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Exploring Occupant Behavioral Intentions in Immersive Virtual Environment to Enhance the Design and Engineering of Sustainable Buildings

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EXPLORING OCCUPANT BEHAVIORAL INTENTIONS IN IMMERSIVE
VIRTUAL ENVIRONMENT TO ENHANCE THE DESIGN AND
ENGINEERING OF SUSTAINABLE BUILDINGS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Engineering Science

by

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December 2019

To my parents and brothers

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ABSTRACT

Accurately simulating occupant behavior is essential to improve our understanding about the future energy performance of the buildings. To date, most of the information related to the occupancy behaviors has been gathered through field observations and/or performing experiments within the lab environments. Even though these common data collection methods are effective and reliable for the existing buildings, using such data to project occupant behaviors in other contexts is likely to lead to uncertainties. The most significant theoretical achievement of this dissertation was to provide the future building occupants with thermal experience of non-physically existent environments. In this dissertation occupant behavior data was generated in an innovative experimental platform, the state-of-the-art, multi-sensory IVE within a climate chamber. This novel data collection approach allows designers to incorporate human sensation in design process and provides the possibility of examining the occupants' thermoceptions and thermally-driven behavioral intentions in pre-occupancy stages of buildings' life cycle. In specific, this dissertation focused on exploring the effectiveness of this new testbed in producing psychological and physiological responses that are comparable to their *in-situ* counterparts. Through the observations from the pilot studies, a well-grounded basis for developing a theoretical framework for the dissertation was formed, and results from the empirical evaluations and hypothesis testing of the proposed theoretical framework of the dissertation provided evidence for the ecological validity of the IVE as a scientific research tool. It was revealed that changing the indoor temperature between 65 °F to 85 °F has the same impact on participants' perception of the thermal environment and physiological responses in both IVE and *in-situ* settings. However, some of the physiological responses at the beginning of the IVE sessions were significantly different from the *in-situ* sessions that could imply the availability of stress or

worry. Also, the analyses of the collected sample of the dissertation showed that the variables age, computer skills and experience with virtual reality, as well as immersive tendency (entertainment) were positively, and the variable cybersickness (nausea) was negatively correlated with the consistency of thermally-driven behavioral intentions across the IVE and *in-situ* settings. The dissertation improved the IVE-based data collection using modeling techniques which are sensitive to the contextual factors such as the spatial, temporal and outside weather conditions. Another considerable finding of this dissertation was that the thermally-driven behavioral intentions in the IVE showed significant independence from the two periods of data collection (colder vs. warmer outside), which opposes the findings of the *in-situ*. Overall, this dissertation showed promising potential for utilizing multi-sensory IVE platforms in the area of occupant energy behavior and laid a subtle groundwork for future research.

CHAPTER 1 INTRODUCTION

1.1 Motivation

Advancements in digital media such as video games and immersive virtual environments (IVE) have provided experiences that are as rich, realistic, and complex as their real counterparts are. Researchers across different disciplines have discovered various benefits of applying the state-of-the-art digital media to their studies. IVEs have been used for human behavior studies, such as virtual reality exposure therapies for anxiety and phobias (Parsons and Rizzo 2008), eating disorders and obesity (Ferrer-Garcia et al. 2013), behavioral neurosciences (Bohil et al. 2011), stress management (Serino et al. 2014), testing delusional beliefs (Freeman et al. 2010a), treating paranoid disorders (Freeman et al. 2008b), acrophobia treatment of fear of flying (Juan et al. 2006), and medical training (Bright et al. 2012; De Leo et al. 2014; Schout et al. 2010; Tichon 2007a). In particular, IVEs are essential where replicating real life experiences is too costly, too risky, or impossible, such as emergency evacuation in tunnels (Kinaterder et al. 2014; Marsh and et al. 2014) or hotels (Kobes et al. 2010), building design and analysis (Mackie and et al. 2004; Reap et al. 2008), the review of different design alternatives (Dunston and Al. 2011; Tutt et al. 2013), and architectural design and analysis (Gerber 2014; Heydarian et al. 2015a; Shen and et al. 2011). More recently, IVE applications to occupant energy behavior studies are emerging, which enables the possibilities for studying the relationship between design and human interactions (Heydarian et al. 2015a; b; Heydarian and Becerik-Gerber 2016; Saeidi et al. 2015, 2016a, 2017a). If proven effective for simulating occupant behavior, this dissertation can address a significant gap in literature the discrepancies between design expectations and buildings' actual performance.

1.2 Problem

Recent studies suggest that occupants play a great role in building energy consumption (Hong and Lin 2012) and the lack of good understanding about occupant behavior has caused many high performance buildings to fail in meeting their design expectations (Janda 2014). So far, information related to occupant behavior is mainly collected through field (*in-situ*) observations, lab experiments, and surveys (Hong et al. 2015). Although these approaches are important for understanding occupant behavior in existing buildings, there are various weaknesses associated with them. For instance, collecting *in-situ* data requires an existing environment; thus, finding an experimental platform that could closely replicate the desired design would be a challenge. In other words, the data that is collected using a specific building might be less relevant to the context of a new design building. Similarly, while collecting data in the lab environments is common, the significance of the contextual factors (*e.g.*, spatial, temporal, and the social) is normally ignored by this approach. Therefore, it is difficult to generalize and apply those results to other buildings or new designs (Mahdavi and Pröglhöf 2008). On the other hand, using survey data in design would be tricky as survey results depend entirely on the respondents' perception and memory, which could be mingled with uncertainties as well. Uncertainties of these kind can cause a significant gap between the estimated performance of a building under design and its actual performance. Consequently, the reliability of the models, which are generated using such data, would be questionable.

1.3 Goal

The main goal of this dissertation is to examine the effectiveness of a novel tool, multi-sensory IVEs, as an alternative approach to study occupant behavior in design context. This approach specifically aims to generate valid data related to individuals' experience of a new

environment. It is intended to determine whether IVEs are able to elicit the responses of individuals in the same way as *in-situ*. In other words, the research aims to gather evidence for the ecological validity of IVEs and their ability to replicate mundane realism by evoking individuals' naturalistic responses to experimental stimuli. The dissertation envisions to utilize a broad spectrum of human sensation within the design process of buildings and putting forward a human-centered approach to investigate the performance of future buildings. It is eventually intended that the IVE-based data enhance our understanding of occupant behavior in design phases and lead us to less uncertain building performance simulations.

1.4 Scope

This research emerges from a combination of four different pilot studies, each of which had a limited scope of occupant behavior in IVEs. Pilot study 1 was designed to explore occupant lighting-use behavior in a single occupancy office, with a minimum level of bodily activity (*i.e.*, rest). This study explored the extent to which occupants' responses to lighting stimuli in IVE accurately reflect those in the *in-situ* condition. This study aimed to examine the possibility of enhancing IVE research designs for measuring occupants' energy-use behaviors and integrating the results with existing energy simulation models to reduce the uncertainties in estimates. Findings of this study specifically revealed that replicating IVEs in order to explore occupant lighting-use behavior experiments was a promising method. Still, since occupants' experience of the buildings includes more than their sense of vision, additional pilot studies were planned to incorporate more senses into experiments. Pilot study 2 tried to understand whether IVEs evoke participants' thermal-related perceptions and experiences differently compared to what is typical in naturalistic environments, or *in-situ*. The study focused on experimenting participants' thermoception and physiological responses with a minimum level of bodily activity

while the indoor temperature was changed. A single indoor environment with a climate chamber was used for performing the experiment. By demonstrating that participants experience similar psychological and physiological states in IVE and *in-situ*, evidence of ecological validity was established. Pilot study 3 was also designed to study the thermoception and physiological responses of participants with a varied level of bodily activity (*i.e.*, cycling) in a lab environment. The findings from this study helped to further expand the feasibility and the effectiveness of using IVE as an apparatus for occupant behavior studies. Participant reflections about their experiences in the study were used to detect errant sources of method bias and to establish the validity of IVE applications. Pilot study 4 pinpointed one of the major critiques about the IVE applications— the difficulty in obtaining extended observations (longitudinal data covering relevant spatial and temporal events) and the fact that this lack of extended observations is necessary for developing quantitative analytical models. This study proposed a Spatial-Temporal Event-Driven (STED) modeling approach to enable IVEs for longitudinal studies. Using a single occupant office as the case study, two sets of occupancy and lighting data (from IVEs and a comparable physical *in-situ* environment) were collected and organized in the form of state transitions at different events. This modeling method demonstrated strong support for viability of IVEs for extended observations and for generating data for effective simulations. The final proposed case study tested a combination of the experimental constructs that were used in the four pilot studies. Two varying periods of the year were selected for data collection and participants' thermoception, physiological responses, and behavioral intentions were measured and recorded in a controlled testing environment— climate chamber at LSU. Yet, due to the inconvenience of performing physical actions under VR conditions, the study focused on the intentions to behave, rather than measuring the actual behavior itself. Participants in all of the

above studies were selected from a pool of university students (undergraduate and graduate students) and staff.

1.5 Significance

If the validity of IVEs for collecting occupant behavior data is proven, this study will put forward a significant improvement in the understanding of the building design and research communities about occupant behavior in buildings under design. Developing high-fidelity experimental platforms that are sensitive to contextual factors will impact the design and engineering of sustainable and energy-efficient buildings. This study specifically proposed the use of a state-of-the-art technology, multi-sensory IVE (combining IVEs within a climate chamber) to investigate occupant thermal states during the pre-occupancy phases of buildings. The key to this research is the capability of IVEs to properly induce individuals' perceptions of the thermal environment and explore their thermally-driven behavioral intention within any design context. This possibility will allow designers to better picture the future performance of buildings and hence improves the development of more sustainable and energy-efficient building designs.

1.6 Methodology

This dissertation introduces an innovative approach to improve building simulations by generating context-sensitive occupant-related inputs. The process of developing the dissertation was as follows. A thorough review of literature was conducted to understand occupant behavior, thermal comfort, and their related underpinning theories, plus the current trend in the IVE applications, *e.g.*, medical care, education, marketing, tourism and building design and operations. The literature review aimed at determining the gaps in the area of occupant behavior as well as identifying the capabilities and the level of the maturity of IVE technologies. This

research used Google Scholar as a major search engine and the IEA Annex 66 research bibliography (<https://annex66.org/?q=biblio>) to collect relevant literature. For occupant behavior literature, keywords such as “occupant behavior”, “building energy”, “building simulation”, “occupant comfort”, “thermal perception”, “thermal comfort”, “lighting”, “window operation”, “blinds adjustment”, “behavior modeling”, “building design and operations”, “occupant behavior theory”, “human behavior”, and “building performance” were used. For IVE applications, the following keywords were used, “virtual reality”, “immersive virtual environment”, “presence”, “immersion”, “affordance”, “phenomenology of VR”, “cues”, “physiological monitoring”, “ecological validity”, “face validity”, “criterion-related validity”, and “construct validity”. The next step was designing and conducting several pilot experiments, to permit preliminary testing and finding micro-validation that could motivate to design larger scale examinations. Micro-hypotheses in each pilot study were used to study a particular aspect of the application of IVE in occupant behavior studies and the combination of them was expected to accommodate a more inclusive view of the subject matter. The diagram below illustrates the methodology of this research (Figure 1.1). Linking the observed findings and the procedures of the pilot studies, a well-grounded basis for developing a theoretical framework for the research was then suggested. The framework structures the path of the study by proposing how the research constructs could relate with each other and underpins the study to the existing theories and anecdotal evidence from the reviewed literature. In essence, it formulates and tests several assumptions about the relationships between the construct variables of the study and aims at drawing conclusive inferences about the viability of the IVEs in replicating naturalistic occupant *in-situ* experiences.

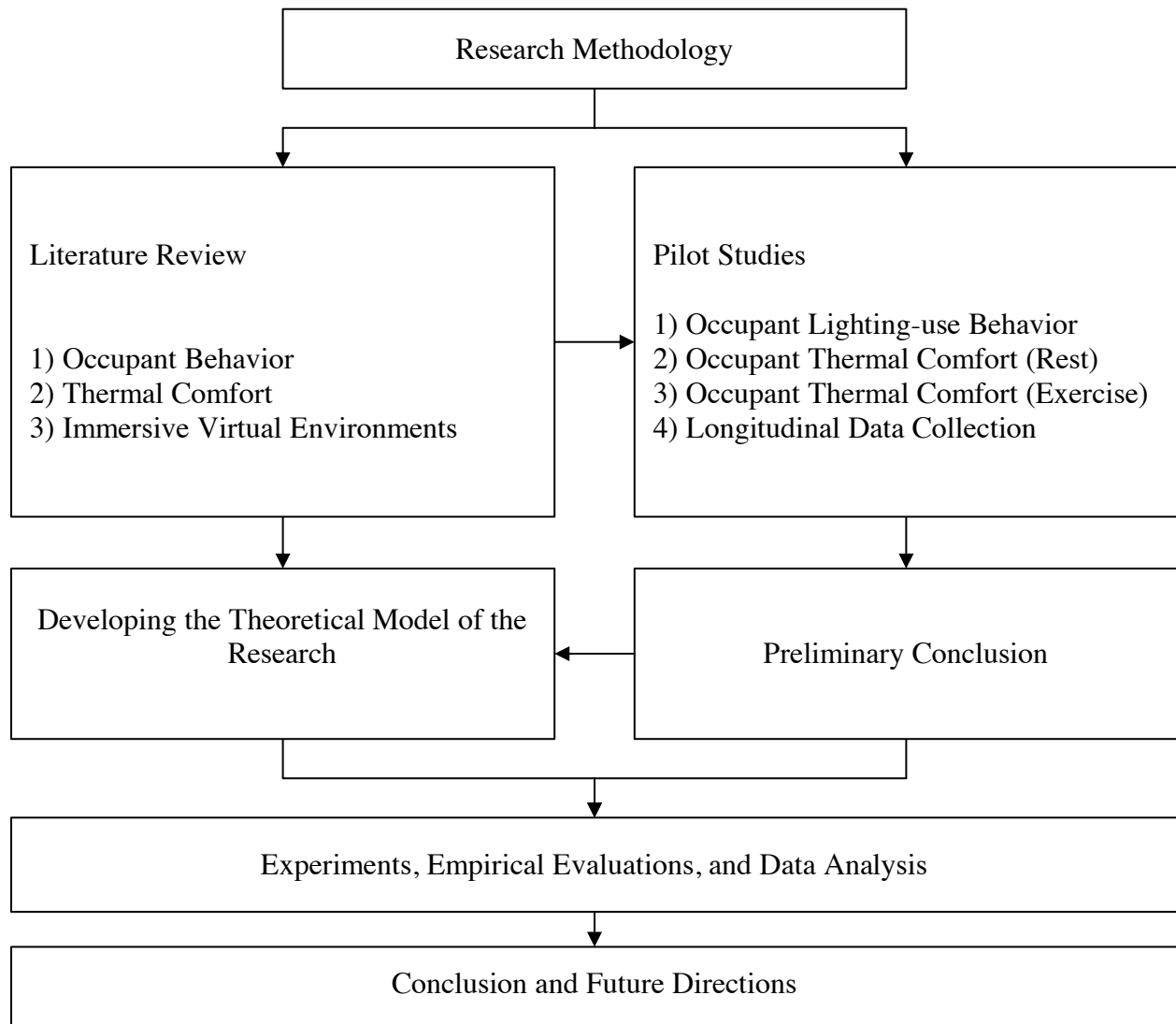


Figure 1.1 Research Methodology

1.7 Organization of Dissertation

This dissertation is organized into five chapters. The present chapter outlines the most prominent elements of the dissertation. It contains a brief discussion about the problem statement, motivation, goal and the scope of the research. The rest of the dissertation is structured as follows:

In Chapter 2, a thorough literature review on topics related to this dissertation is provided. This chapter looks at three different topics, namely: virtual reality and its implications, human and occupant behavior, as well as thermal comfort in indoor environments.

Chapter 3 describes four separate pilot experiments that test the validity of IVEs for investigating occupant behavior. The experiments include investigating occupant lighting-use behavior, thermal comfort, and longitudinal data collection in IVEs. This chapter provides the background and a basis for this dissertation.

Chapter 4 combines the information obtained from chapters 2 and 3 and develops a theoretical framework for exploring occupant thermal comfort and thermally-driven behavior. This chapter is exclusively focused on applying the knowledge gained from literature and the pilot experiments to the proposed model. Several hypotheses are formulated and tested.

Chapter 5 discusses the theoretical and the practical implications of the proposed theoretical framework of the dissertation, the dissertation contribution, the currently existing limitations, as well as the future directions for pursuing this research.

CHAPTER 2 LITERATURE REVIEW

2.1 Occupant Behavior

2.1.1 Introduction

During the past decades, many studies have focused on energy efficiency in the built environment and the demand for more sustainable buildings. Even though the deterministic features of building energy simulations appear to be quite useful (Haldi and Robinson 2008), the complexity of the occupant-related factors make it rather hard to accurately develop building simulations. The accuracy and precision of the building energy simulations are highly dependent upon the inputs related to the occupant's interaction with the building system. A previous study by Clevenger and Haymaker (2006) showed that using various occupancy profiles can change the estimated energy consumption in buildings by more than 150%. Therefore, it is crucial that building energy models apply authentic data which represents their future occupants. In fact, the building designers are required to have a deep insight about the significance of all the factors that might influence how the occupants would perceive the indoors environments. Factors such as temperature, lighting, noise, indoor air quality are closely associated with occupants' comfort, health (Vischer 2007), well-being (Ryan et al. 2014), and work productivity (Gray and Birrell 2014). If buildings do not meet the requirements of the mind and body, alternative approaches are likely to be used to maintain the standards, which could entirely alter the presumptions of the building energy simulation models and causes discrepancies between the simulations and actual performance of the buildings. Therefore, understanding occupants' needs and the way they act/interact with buildings is one of the major contributing elements in building performance estimates.

2.1.2 Human Behavior Overview

A good understanding of human behavior is critical for creating a better living environment. Still, defining human behavior and explaining its driving forces are complicated. Human behavior, at its social level, refers to “the way humans act and interact. It is based on and influenced by several factors, such as genetic make-up, culture and individual values and attitudes” (<https://www.nature.com/subjects/human-behaviour>). There are many theories in literature that conceptualize and describe human behavior. Gestalt and Lewin (Lewin 1951, 1964) portrayed human behavior by the following equation: $B = f(P, E)$, in which Behavior (B) is a function of the Person (P) and his/her Environment (E). Still, this formula is just a heuristic way of looking into behavior. There has to be some additional variables much be considered in the way building design defines human behavior.

Gibson (1966) explained behavior or action as follows. Environmental stimulation leads to sensations (associated with lower order variables *e.g.*, retinal image size) and perceptions (higher order variables, *e.g.*, optical flow variables), whereby this process (detecting information) could be either conscious or unconscious. Perception and action operate as a continuous cycle, whereby “perception obtains information for action, and action has consequences that inform perception about both the organism itself and the events that it perpetrates” (Figure 2.1).

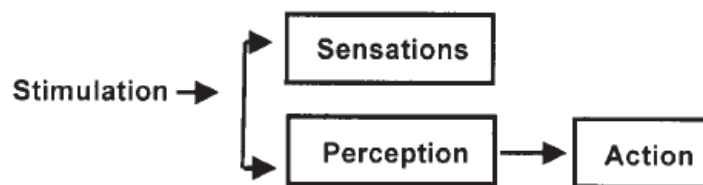


Figure 2.1 Gibson's View of Information and the Theory of Direct Perception (Gibson, 1966)

According to Gibson (1966), action is divided into performatory and exploratory. The former refers to the activities that bring one closer to a goal, while the latter involves activities that aim to reveal information that can help guide one to a goal (Michaels 2000). On the other hand, constructivists such as Gregory (1970) believes that the perception of our environment is a top-down process in which the sensory inputs will be combined with the previously stored information. To date, various theories have been developed to predict human behavior, among which the variables of Theory of Planned Behavior (TPB) have shown to address individuals' energy behavior very well (Vlek and Steg 2007). With that said, the theoretical explanation of human behavior in this research revolves around this theory.

2.1.3 Theory of Planned Behavior (TPB)

Theory of Planned Behavior, developed by Ajzen (1991), is a well-known theory that predicts an individual's intention to engage in a behavior. The major elements of this theory consist of the attitudes toward performing the behavior, the perceived individual and social pressure to perform the behavior, and the belief in one's ability to perform the behavior. A combination of these elements determines the behavioral intention, as well as the final action. Ajzen (2010) clarified that "both deliberative and spontaneous decision making is encompassed in his theory." See Figure 2.2.

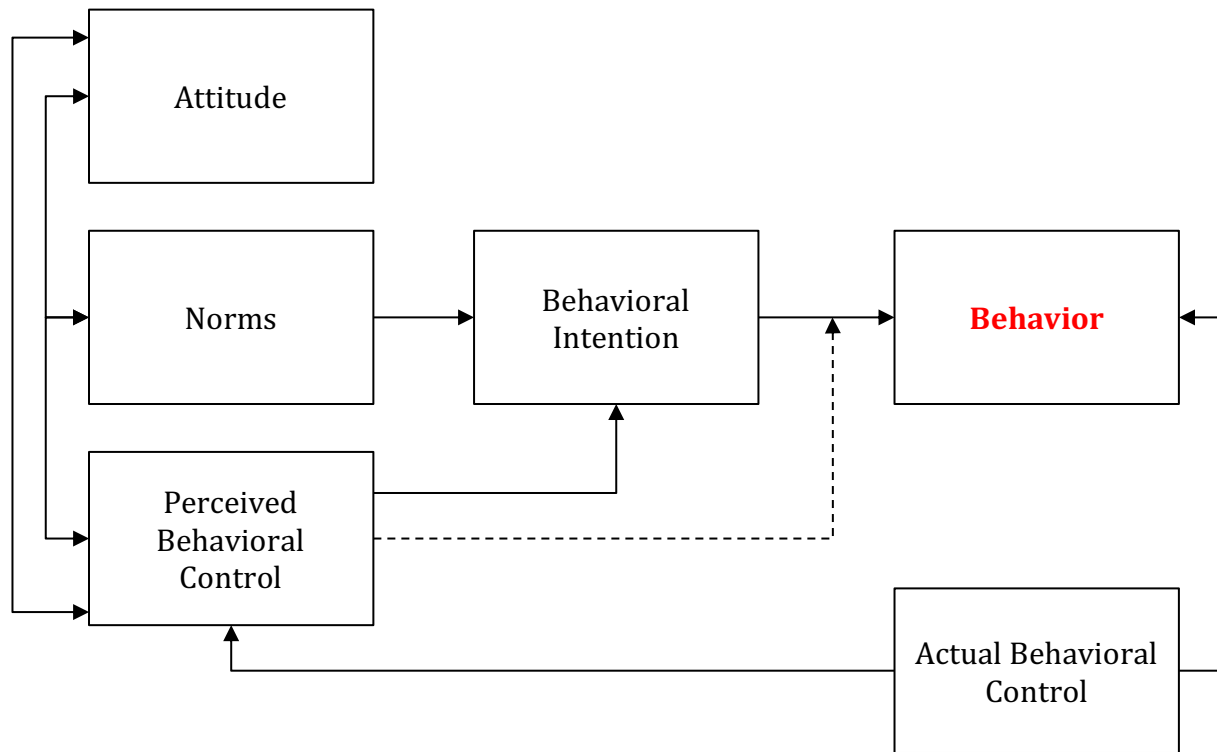


Figure 2.2 Theory of Planned Behavior (Ajzen et al. 1991)

TPB has evolved from the Theory of Reasoned Action (Fishbein and Ajzen 1977) in which the main driving factor is the individual's *intention* to perform a behavior. Ajzen et al. (1991) explained that “intentions are indicators of how hard people are willing to try, of how much of an effort they are planning to exert, in order to perform the behavior.” It is believed that one's intention to perform a behavior is a proximal predictor of his/her actual behavior (Johnston et al. 2004). Therefore, this research finds it satisfactory to examine human behavioral intention as a proximal antecedent of behavior. He rationalizes that “when particular set of beliefs are tied together, the cognitive foundation of decision making and behavior will follow a reasonable and consistent fashion”, however, there are some exceptions that have to be considered; *e.g.*, the impact of culture and background which could inherently cause a behavioral direction change within a specific group of people. Nonetheless, scope of the study determines what factors have

to be controlled for and/or incorporated into the research. Overall, a careful choice of samples can help to mitigate the uncertainties related to the individual differences.

2.1.4 Application of Theory of Planned Behavior (TPB) in Occupant Behavior Studies

Different disciplines have extended TPB and adapted this model for specific purposes. In the domain of sustainable building design, engineering, and operations, TPB has shown a considerable potential in predicting occupants' actions by exploring their attitudes, normative beliefs, and perceived control beliefs (Abrahamse and Steg 2009; Steg and Vlek 2009; Gill et al. 2010; Kientzel and Kok 2011; Wang et al. 2011; Wenshun et al. 2011; Menezes et al. 2012; Claudy et al. 2013). Figure 2.3 presents an extended TPB model combining the major driving factors behind the occupant energy-related behaviors.

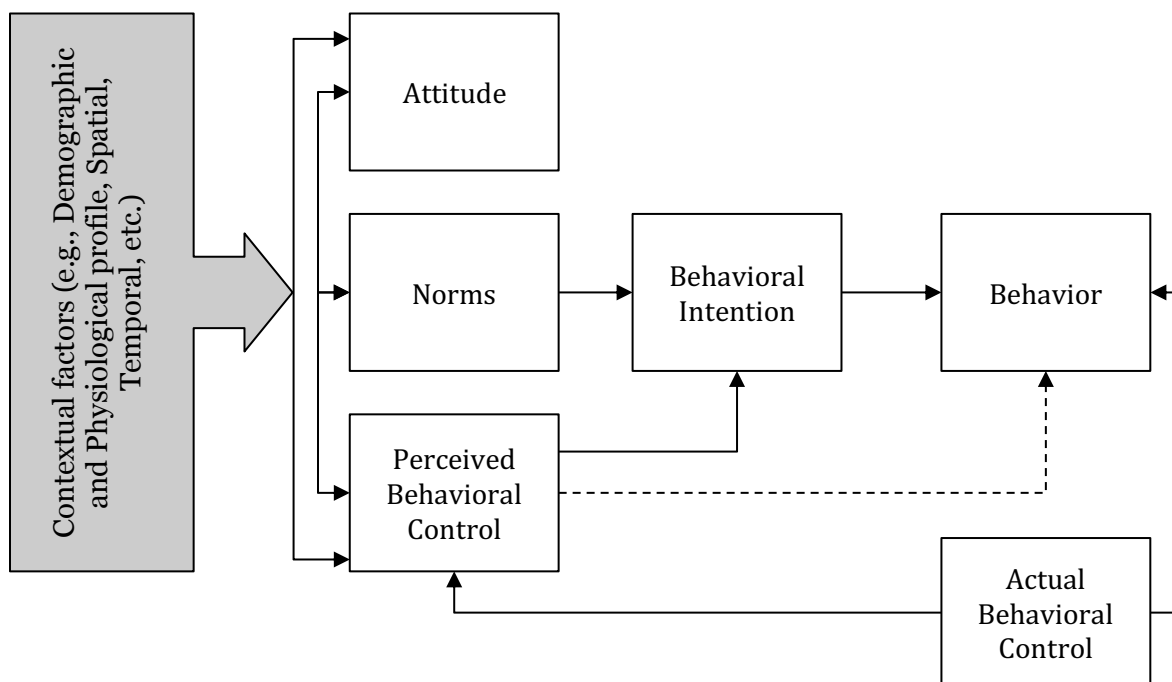


Figure 2.3 Extended Theory of Planned Behavior

Through the review of literature, several occupant-behavior driving factors that have been previously studied, are collected and categorized under the major components of TPB (Table 2.1). As Figure 2.3 illustrated, there is one supplementary driving factor, namely, contextual

factors (*e.g.*, demographic and physiological profile, spatial, temporal, etc.) that has been added to the original TPB model.

Table 2.1 Occupant Behavior Driving Factors Based on TPB Measures

Measure		Occupant Behavioral Driving Factor
Contextual factors	Profile	<ul style="list-style-type: none"> • Age • Gender • Clothing • Medication • Social economic status or income • Ethnicity • Material status • Nationality • History of residency • Highest level of education • Knowledge of energy consumption and environmental impacts • Intelligence
	Physiological drivers	<ul style="list-style-type: none"> • Fitness & health status • Activity level • Food and beverage intake (Fabi et al. 2012) • Anthropometrics – Body mass, height, composition (fat mass/lean mass) • Cardiovascular profile – PWV, BAFMD, HRV • Hot/cold acclimation • Metabolic variables – resting and working metabolic rates, dietary induced thermogenesis, HR, activity monitoring • Heat storage – skin temperature, core temperature, evaporation heat loss, dry heat loss, total heat storage; clothing factors.
Attitudes, normative, and behavioral beliefs		<ul style="list-style-type: none"> • Moods and emotions (Fishbein and Ajzen 2010) • Beliefs based on and about past experiences (Bentler and Speckart 1981) • Environmental considerations & priorities (Steg and Vlek 2009) • Moral responsibility (Abrahamse and Steg 2009b) • Environmental values and adverse consequences (Christina et al. 2014) • Individualism-Collectivism values (Hofstede and Hofstede 2001) • Attitudes and perception of and about • Willingness to save energy (Wenshun et al. 2011) • Economic benefits of energy consumption (Wang et al. 2011) • Sensory experience of temperature, air quality, light, humidity, etc. • Environmental responsibility and energy saving investment (Wenshun et al. 2011) • Impact-income-spending relationships (Peattie 2010) • Norms, the perceptions of personal and/or social pressure to act in an energy-efficient manner, could be classified into the followings. • Shared beliefs about social responsibility & environment (Bar-Tal 2000) • Habits (Peattie 2010; Steg and Vlek 2009)

(table cont'd.)

Measure	Occupant Behavioral Driving Factor
	<ul style="list-style-type: none"> • Lifestyle (Fabi et al. 2012; Peattie 2010) • Family life style (Fritzsche 1981) • Normative concern about environmental impact (Steg and Vlek 2009) • Policy and social propaganda, social interaction (Wang et al. 2011) • Interaction between occupants (Fabi et al. 2012) • Spatial dimensions in socio-economic decision-making (e.g., regional labor markets and economies) (Peattie 2010) • External constraints, institutional constrain, social norms, or availability of fiscal or regulatory incentives (Claudy et al. 2013) • Government expectation, client demand, organizational culture, financial constraints, organizational capacities, inter-professional relations (Kientzel and Kok 2011)
Control beliefs	<ul style="list-style-type: none"> • Cost/benefits of energy behaviors & inconvenience (Abrahamse and Steg 2009b; Wang et al. 2011) • Control and personal efficacy (Peattie 2010) • Sustainability (Kientzel and Kok 2011) • Availability of personal control, accessibility of personal control, complexity and transparency of automation systems, presence of mechanical/electrical system, views and connection with the outdoors, interior design, experience and foreseeable future conditions, visibility of energy use, occupancy pattern and social constraints (O'Brien and Gunay 2014) • Capacity to alleviate environmental threats (Christina et al. 2014)
Actual control factors	<ul style="list-style-type: none"> • Building ownership & authority (Fabi et al. 2012) • Feedback about energy consumption • Physical environment (temperature, humidity, air velocity, noise, illumination, and odor) (Fabi et al. 2012) • Contextual drivers (Insulation of buildings, orientation of façades, heating system type, thermostat type) (Fabi et al. 2012)

2.2 Thermal Comfort

2.2.1 Introduction

Since 1950, the urban population has increased over 40% and it is expected that by 2050, at least 80% of the US population will live in urban environments (Nations 2015). According to the Environmental Protection Agency (EPA), the average American spend 93% of their life indoors, and adults spend about 40 hours per week at work, most of the time at desks and workstations (U.S. Census Bureau 2016). Given the fact that people spend most of their time

indoors and considering the highest rank of thermal comfort among other types of indoor comfort (Frontczak and Wargocki 2011a), it is crucial to have a clear understanding on how the thermal environment could be perceived within different building designs.

2.2.2 Significance of Thermal Comfort

Thermal comfort is one of the most important physical needs of the human beings as well as one of the factors for satisfaction and well-being within an environment (Vischer 2007). ASHRAE defined this term as “that condition of mind which expresses satisfaction with the thermal environment” (Fanger 1970). Thermal comfort in indoor environments is a complex topic, since many factors are involved in how the indoor thermal environment would be perceived. Fanger (1970) categorized these factors into the environmental (radiant temperature, humidity, air velocity) and personal (clothing and metabolic rate) factors. Besides these, there are many indirect factors such as the access to thermostat control that can have impact on occupants' satisfaction with the indoor environment, as well (Williams 1997). Frontczak and Wargocki (2011) conducted a literature review on several studies that investigated the importance of the environmental conditions on building occupants' overall satisfaction with the indoor environment quality. The results of these studies showed that thermal comfort was among the most important conditions for building occupants to derive overall satisfaction from the indoor environment. This could be due to the fact that human body is particularly sensitive to the environment temperature and senses temperature changes in a relatively short time. Logically, if the thermal comfort is not achieved, there will be impulses to change the thermal environment through alternative approaches in order to recover it. Therefore, the lack of proper assumptions about individuals' thermoceptions and thermal comfort set-point could result in future costly design modifications.

2.2.3 Thermoregulation

Human beings respond to the thermal environment, consciously or unconsciously, to keep their body temperature within a certain boundary. The normal human body temperature should remain steady at the range of around 97.7–99.5 °F (36.5–37.5 °C) and human physiological responses show a noticeable variation, even under mild environmental conditions (van Marken Lichtenbelt et al. 2001, 2002). Human body senses the temperature through the thermoreceptors that are described as cutaneous free nerve endings (Waldman 2016), and thermal comfort is directly linked to the signals from the thermoreceptors and the general state of the thermoregulatory system (Hensel 1981; Loomans 1998). The human body has both autonomic and behavioral thermoregulation, and these systems continually interact in order to ensure the thermal comfort and survival (Hensel 1981; Parsons 2003). The perception of the thermal stimuli is, in fact, innate (Cabanac et al. 1971) and the autonomic thermoregulation is controlled by the hypothalamus, (*e.g.*, by shivering, controlling the skin blood flow, respiratory dry heat loss, sweating and respiratory evaporative heat loss), while the behavioral thermoregulations are more related to the conscious sensations about the thermal environment and feelings of thermal comfort (*e.g.*, active movement and adjustment of clothing) (Hensel 1981).

2.2.4 Thermal Comfort Calculation

Thermal comfort in indoor environments is normally assessed through two different approaches; static or classic steady-state (Predicted Mean Vote) model developed by Fanger (1970) and adaptive model (Auliciems and Szokolay 1997; Nicol 1993; Nicol et al. 2012; Robbins et al. 1994).

2.2.4.1 Predicted Mean Vote

The first model which is expressed by Predicted Mean Vote-Predicted Percentage Dissatisfaction (PMV-PPD) is developed based on the combination of metabolism, clothing, indoor air temperature, indoor mean radiant temperature, indoor air velocity and indoor air humidity. This model was the basis of most national and international comfort standards, e.g., ISO 7730 (ISO Standard 1994) and ASHRAE Standard 55 (ASHRAE 1992). “In this static model the person is viewed as a passive recipient of thermal stimuli” (ASHRAE 1997).

2.2.4.2 Adaptive Models

The second school of thought, the adaptive model, stands on three inter-related variables; adjustment (behavioral), habitual (psychological), and acclimatization (physiological) (ASHRAE 1997). See Figure 2.4.

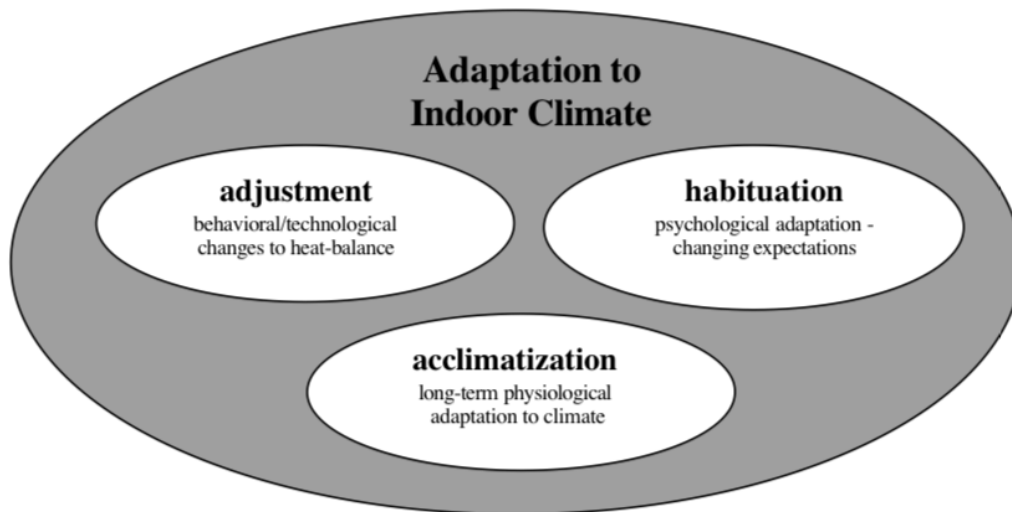


Figure 2.4 The Three Components of Adaptation to Indoor Climate ASHRAE (1997)

Adjustment has three subcategories; personal adjustment which is adjusting to the surroundings by changing personal variables, such as adjusting clothing, activity, posture, eating/drinking hot/ cold food or beverages, or moving to a different location; technological or environmental adjustment which is modifying the surroundings themselves, when control is

available, such as opening/closing windows or shades, turning on fans or heating, blocking air diffusers, or operating other HVAC controls, etc.; and, cultural adjustments, including scheduling activities, siestas, dress codes.

Acclimatization, is defined as “all the changes in the physiological responses which result from exposure to thermal environmental factors, and which lead to a gradual diminution in the strain induced by such exposure” (ASHRAE 1997). Human beings can adapt to the changes of the thermal environment, which helps them to better tolerate heat and cooling exposures.

Acclimatization takes place by both behavioral or autonomic changes in heat production and heat exchange with the environment (Bligh et al. 1976). In literature (Deng et al. 2017; Zhang et al. 2010), human physiological responses are often seen as indicators of thermal sensation.

Acclimatization varies among different people and under different conditions. This approach of assessing thermal comfort needs to account for several complex factors. Individual-related factors (*e.g.*, sex, age, body surface area, body mass, hydration state, metabolic rate, physical fitness, and clothing) are proven to change individuals’ perception of the thermal environment. For instance, a recent study reported that female sex hormones can influence cold perception (Cankar et al. 2016) as well as the heat loss response of cutaneous vasodilation (Kuwahara et al. 2005). Also, food and beverage intake (fasting, under eating, maintenance or overeating) are factors that impact body temperature and thermoregulation. Emotions (*e.g.*, fear, stress, anger, pain, noise) can result in both psychological and physical changes such as skin temperature, galvanic skin response, and heart rate (Kreibig et al. 2007; Lisetti and Nasoz 2004). and affecting body temperature and thermoregulation.

Acclimatization to heat is usually faster than acclimatization to cold (Höppe 2002), and people who are physically fit adapt to the new condition easier and quicker (Ingram and Mount

2012). Acclimatization has been more extensively studied for heating exposure (Givoni and Goldman 1973; Bruce 1960; Berglund and McNall 1973), while in cold there is more of behavioral adjustments (Clark and Edholm 1985). Besides, a global survey suggested that there is a relationship between outside temperatures and indoor conditions required for thermal comfort (Humphreys et al. 2013; Morgan et al. 2002). Therefore, controlling for possible impacts of the outdoor environment would be necessary while studying thermal comfort.

The last component of the adaptive model, habituation, is defined by the way in which experiences and expectations of the indoor climate influence thermal perception (Frisancho 1993; Glaser 1966). This is specifically important when considering the impact of context: be it lab vs. home vs. office environment. Thermal perception may also be different being in an air-conditioned indoor environment vs. naturally-ventilated building (De Dear et al. 1991; Fishman and Pimbert 1982; Heijs and Stringer 1988). Williamson, Coldicutt, and Riordan (1995) and Paciuk (1990) emphasized the role of perceived degree of control on individuals' thermal comfort in office buildings. They found that higher levels of satisfaction are achieved when individuals realized that they have more control over their environment. Also, it boils down to the fact that "A most powerful form of thermoregulation is behavioral; put on or take off cloths, change posture, move, take shelter and so forth" (Nicol et al. 2012). Therefore, having a clear understanding on occupant behavioral choices is critical, since these choices can impact building energy simulation (Yan et al. 2015), building performance prediction (de Wilde 2014), and thus the design of a building (Hong et al. 2016).

2.3 Immersive Virtual Environment (IVE)

2.3.1 Introduction

In computer science and digital media domain two terms Virtual Environments (VE) and Virtual Reality (VR) are used interchangeably, which are also equivalent to “Synthetic Experience”, “Virtual Worlds”, “Artificial Worlds” or “Artificial Reality”(Mazuryk and Gervautz 1996). Burdea and Coiffet (2003) defined VR as “a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels.” The early attempts on VR research and application date back more than 50 years. In 1962, Morton Heiligh invented an immersive multisensory simulator, namely, Sensorama (Figure 2.5). This machine would represent “pre-recorded films in color and stereo, was augmented by binaural sound, scent, wind and vibration experiences” (Burdea and Coiffet 2003; Mazuryk and Gervautz 1996).

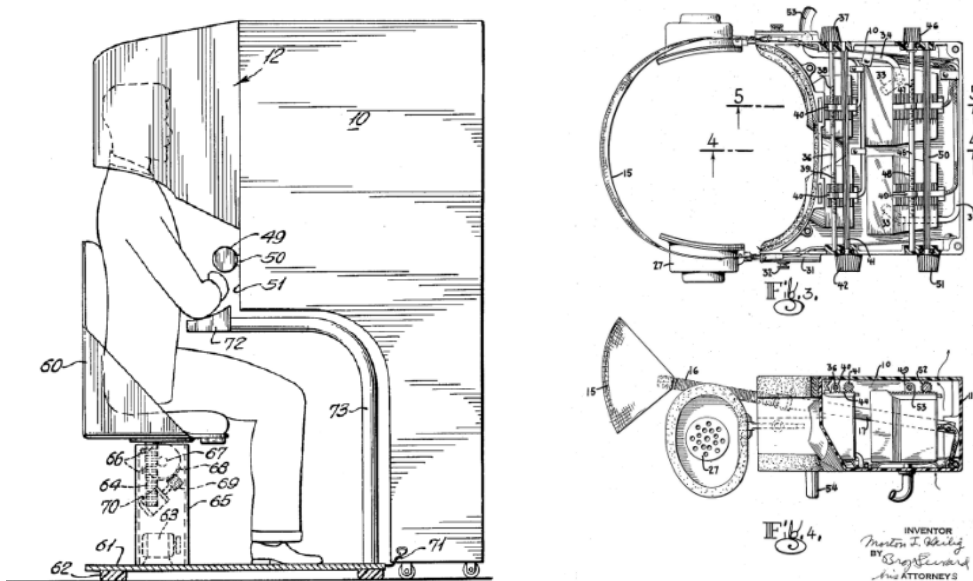


Figure 2.5 Sensorama, Stereoscopic-Television Apparatus (Images courtesy of United States Patent and Trademark Office, Heilig 1962, US Patent #3,050,870)

In 1965 Ivan Sutherland introduced “The Ultimate Display” with the use of interactive three-dimensional computer-generated graphics instead of recorded films. He constructed a

variety of head-mounted displays and paved the way for immersive virtual experiences and real-time simulations (Sutherland 1965, 1968).

2.3.2 Presence and Immersion

There are two fundamental concepts associated with VR simulations, immersion and presence. Presence is defined as the sense of “being there” in a computer-mediated environment (Ijsselstein et al. 2000). Presence is a concept focusing on the subject’s *experience* of being there, while immersion is the quality or qualities that make an inclusive, extensive, surrounding, and vivid illusion of reality (Cummings and Bailenson 2016; Slater and Wilbur 1997). Witmer and Singer (Witmer 1998) recognized immersion as necessary conditions for experiencing presence in a virtual environment and stated that the Quality of the Experience (QoE) depends on the following parameters: 1) graphic frame rate, 2) overall extent of tracking, 3) tracking latency, 4) quality of the images, 5) the field of view, 6) the visual quality of the rendered scene, 7) dynamics, and 8) the range of the sensory modalities accommodated (Slater 2009; Slater and Usoh 1993). The more of the above parameters are incorporated in a system, the higher levels of immersion and presence can be offered (Slater and Wilbur 1997). With that said, virtual experiences are classified into 1) fully immersive or first-order immersive systems that have a lot in common with our everyday experiences. (*e.g.*, using head mounted displays). Lower order systems, semi-immersive systems (*e.g.*, projection-based displays), and non-immersive systems (*e.g.*, desktop stereoscopic displays) complied with fewer immersion capabilities, however, they still offer some levels of presence (Mujber et al. 2004; Slater 2009). Interaction is also a substantial element in VR simulations that augments feedback to one or more senses and produces the sense of being mentally immersed within a virtual world (Sherman and Craig 2003). Hülsmann et al. (2014) developed wind and warmth simulations in VR systems in

different thermal environments, such as desert and volcano. They found that user's presence was significantly higher when the wind and warmth was provided with VR system. They also revealed a few factors influenced on the perception of presence, including distance to the thermal source and time delay between the VR scene and actual perception of it (Mahdavi and Pröglhöf 2009). Slater (2009) believed that evoking realistic response to situations during a VR experiences was contingent upon two orthogonal components: presence or place illusion (PI), and Plausibility (Psi)— the illusion that the scenario being depicted is actually occurring. He indicated that Psi relied on the process of inference from evidence (perceptions) to issues concerning the 'reality' of the situation. He argued that "If you are there (PI) and what appears to be happening is really happening (Psi), then this is happening to you! Hence you are likely to respond as if it were real." For an experiment to have a high Psi, several factors including optimization of QoE needs to be considered in designing IVEs.

Presence is evaluated through both subjective (qualitative) and/or objective (quantitative) measurement tools; qualitative evaluations are typically made by self-reports while the quantitative measurement techniques usually address the physiological and behavioral responses to the presented stimuli. The major advantage of using physiological responses is that they produce continuous and real-time information and they allow for time-varying assessments, as opposed to the questionnaires (Insko 2003). Each of these measurement types have their own positives and negatives which are listed in Table 2.2.

2.3.3 Qualitative Measures

Presence should primarily be assessed using qualitative methods since this concept is a manifestation of mind (Sheridan 1992). There are several widely known and well-established presence measures, such as the ITC-Sense of Presence Inventory (ITC-SOPI), and the Igroup

Presence Questionnaire (IPQ). These instruments subjectively measure the user's experience in a virtual environment. Each instrument is composed of several major sub-categories. For instance, ITC-SOPI contains 44 questions with five-point Likert scale (strongly disagree to strongly agree). It is categorized into 1) sense of physical space (19 items); 2) engagement (13 items); 3) ecological validity (five items); 4) negative effects (six items). This questionnaire also measures a number of important demographic and background variables such as age, sex, occupation, education, self-rated experience with computers and frequency of playing computer games, self-rated knowledge of VR, TV/film production, and stereoscopic image presentation using polarized spectacles. IPQ which comprises 14 items with seven-point Likert scale anchors that vary for each question (<http://www.igroup.org/pq/ipq/download.php>). The major components of it are as follows. 1) spatial presence, which is related to the sense of being physically inside the IVE (five items); 2) involvement, which is intended to evaluate the attention devoted to the IVE (four items); and 3) realness that evaluates the sense of reality attributed to the IVE (three items) (Schubert, Friedmann & Regenbrecht, 1999).

Another common approach to control the individuals' virtual experience is through the Immersive Tendencies Questionnaire (ITQ). This questionnaire is usually used to provide insight about involvement in common activities. It breaks down into four main subcategories, namely: focus, involvement, emotion, and entertainment on a seven-point scale. While presence scales measure the degree of being immersed in the virtual scene, the ITQ evaluates individuals' tendencies to be involved/immersed inside the virtual settings. Witmer and Singer (1998) believe that an "increased involvement can result in more immersion in an immersive environment and they expect individuals who tend to become more involved will also have greater immersive tendencies." Furthermore, several other qualitative measurements (*e.g.*, open-ended question,

interview, interaction analysis and observational methods) can be used to qualitatively explore the quality of the VE experiences.

2.3.4 Quantitative Measures

Behavioral and physiological measures are the most common tools to quantitatively assess the quality of the VR experiences. Behavioral measures such as reflex responses (Held and Durlach 1992), facial expressions (Huang and Alessi 1999), postural responses (Hoshino et al. 1997) can be useful for measuring the presence. However, they can be biased and intrusive if there were side-effects while performing the experiments. For instance, swaying back and forth while watching a video shot from the hood of a rally car, could happen due to both sense of “being there” as well as the poor visual qualities of the virtual scene (Insko 2003).

The most commonly used physiological measurements in VR researches are heart rate (HR), heart rate variability (HRV), skin temperature (T_{sk}), and galvanic skin response (GSR). Meehan et al. (2002) stated that “to the degree that a virtual environment seems real, it will evoke physiological responses similar to those evoked by the corresponding real environment.” They found that HR was strongly correlated with presence and it could be used as an objective measurement of presence. A better physiological assessment tool measuring VE experiences is the HRV (Brogni et al. 2006), which is the variation in the time interval between heartbeats (R-R interval). The wave with the highest amplitude is the R wave (Figure 2.6). While HR is the average beats per minute, HRV analyzes how the beat-to-beat intervals (R-R intervals) change over time. HRV scores are usually based on the root mean square of successive differences between normal heartbeats (RMSSD).

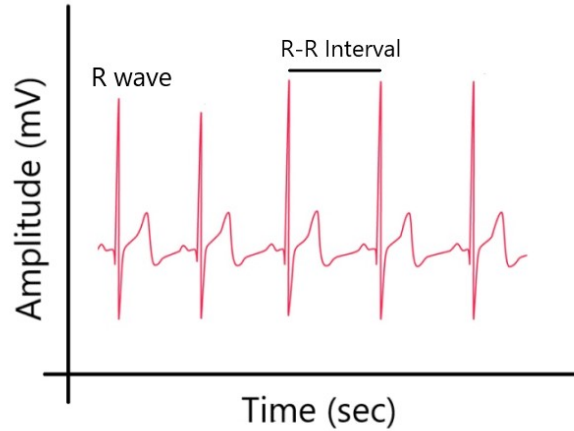


Figure 2.6 R Wave and RR Intervals of an ECG Signal

It is believed that HRV can be an indicator of the balance between sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) outflow in the autonomic nervous system (ANS) (Cardiology 1996; Laborde et al. 2017). HRV is a non-invasive measure of ANS (Sztajzel 2004). The activities of the ANS are reflected in the low frequency (LF; 0.04Hz - 0.15Hz) and high frequency (HF; 0.15Hz and 0.4Hz) (von Rosenberg et al. 2017) (Figure 2.7).

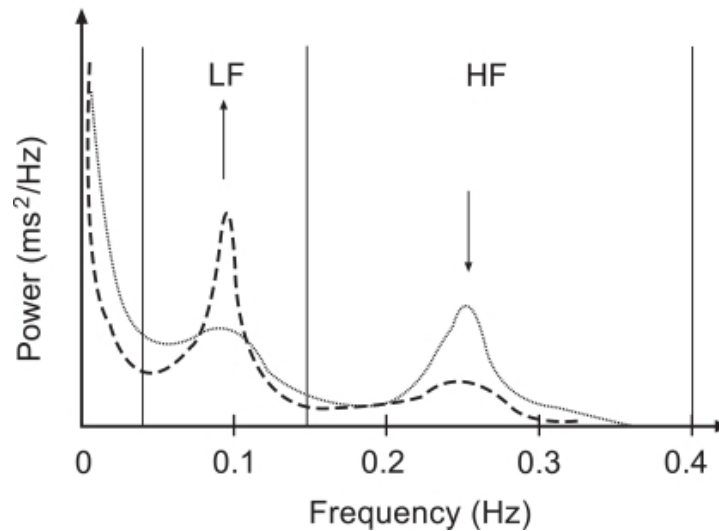


Figure 2.7 Sketch of Short-term HRV Frequency Domain Characteristics According to (Cardiology 1996) Power Spectral Density During Rest (dotted line) and Tilt Load (dashed line). (Günther et al. 2010)

An increase in LF implies a more dominant activity of the SNS while an increased in the HF indicates a stronger influence of the PNS (A. Brogni, V. Vinayagamoorthy, A. Steed 2006; von Rosenberg et al. 2017) (Figure 2.8). In other words, under mental stress conditions, the LF component of a participant's HRV increases and the HF components decreases (Shaffer and Ginsberg 2017). Likewise, in a study by Hjortskov et al. (2004) the LF component of the HRV showed an increase and the HF decreased in stressful situation comparing to the control session.

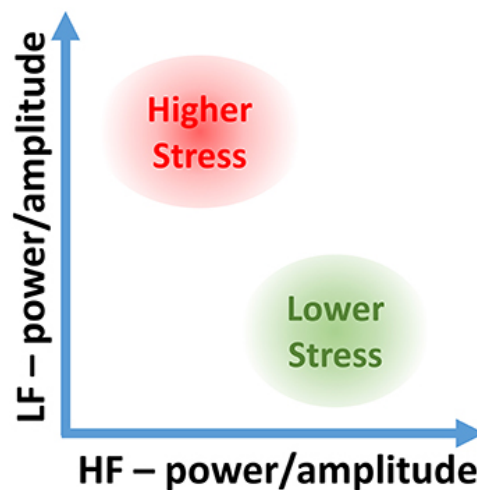


Figure 2.8 Stress Categorization in a 2D LF-HF Diagram: Courtesy of von Rosenberg et al. (2017)

Andreassi (Andreassi 1980) declared that stressful conditions can cause an increase in HR and electrodermal activity (EDA) activities, a decrease in skin temperature (T_{sk}) and can induce rapid and shallow breathing. In a study by (Tierl et al. 2017) T_{sk} was measured in two cases of observing a full virtual limb vs. more abstract models of the hand. They found lower temperature changes in the real hand compared to the other conditions. According to (Insko 2003), the change in T_{sk} are slow and can take up to five minutes to reach a peak, and this has to be considered while using physiological measures using average skin temperature.

The other representative measure is GSR, which refers to the electrical properties of the skin. The increase of GSR indicates that the skin conducts electricity improves. GSR reflects the

intensity of human psychological arousal and it is assumed that participants with higher GSR levels feel more present in a VE scene (Lo Priore et al. 2003; Yuan and Steed 2010).

Each of the measurement types has its own advantages and disadvantages. Table 2.1 summarizes the full extent of the advantages and disadvantages of the two presence measurement methods. When measuring presence, situational decision has to be made in order to diminish or lose one quality, quantity or property of a set or design in return for gains in other aspects. Table 1 summarizes the presence measurement methods and their pros and cons.

Table 2.2 Presence Measurement Positives and Negatives

	Applied Method	Positives	Negatives
Qualitative Measures	<ul style="list-style-type: none"> • Questionnaires • Continuous Assessment • Qualitative Measures • Psychological Measures • Subjective Corroborative Measures 	<ul style="list-style-type: none"> • High face validity • Easy to administer, analyze and interpret 	<ul style="list-style-type: none"> • Unable to measure the time-varying qualities of presence (Insko, 2003) • Retrospective and therefore relies on participants' memories • Fatigue or boredom in prolonged exposures influences the responses (Insko, 2003) • Prone to several biases and recency effect
Quantitative Measures	<ul style="list-style-type: none"> • Psychophysiological Measures (e.g., Heart Rate, Eye reactions) • Neural Correlates (e.g., EEG, fMRI) • Behavioral Measures • Task Performance Measures 	<ul style="list-style-type: none"> • They are not influenced by the participant's subjective interpretation • Relatively unobtrusive 	<ul style="list-style-type: none"> • Challenge to validity (not always clear what is being measured) • Also sensitive to factors that do not influence presence (IJsselsteijn, 2004) • Different stimuli can produce the same physiological response (Insko, 2003)

2.3.5 Cybersickness

Cybersickness is the side-effect of exposure to virtual environments (Rebenitsch 2015). The symptoms of cybersickness may vary from eyestrain, headache, nausea or even vomiting (Davis et al. 2014). Kim et al. (2005) revealed some link between the automatic nervous system (ANS) and cybersickness and Ohyama et al. (2007) noticed increases in (sympathetic nervous system) SNS activity during virtual reality exposure.

The simulator sickness questionnaire (SSQ) by Kennedy et al. (1993) is a widely used instrument for measuring cybersickness. The SSQ standard quantifies the severity of several symptoms. The Symptoms are categorized into nausea (*e.g.*, nausea, stomach awareness, increased salivation, etc.), oculomotor (*e.g.*, blurred vision, eyestrain, headache, etc.), and disorientation (*e.g.*, vertigo, dizziness, etc.) and they are on a scale of 0 (none) to 3 (sever). Cybersickness can be associated to some other variables; for instance, Jang et al. (2002) reported that in driving VE, older participants felt sickness more than younger.

2.3.6 Designing IVEs

Designing effective IVEs that are capable of producing high PI and Psi is complex. Virtual settings, by nature, are not capable of offering the same levels of affordance as in the real-world conditions. Therefore, as mentioned in the previous section, a wide range of the sensory modalities have to be accommodated within VEs to support individuals' sense of being there. Adding perceptual cues to virtual spaces is a method to compensate for such shortcomings (Bowman et al. 2008; Bowman and McMahan 2007; Chertoff et al. 2008; Todd 1997). Cues in virtual spaces play a significant role in conveying messages and enhancing cognitive/perceptual affordances. For instance, the application of cues has proven to be promising in changing of nicotine craving or behavior (Lee et al. 2003). Similarly, Gallagher et al. (2016) worked towards

the understanding of embedding cues (*i.e.*, auditory cueing, visual cueing, feedback, and directed attention) in a virtual environment to promote exercise. In another study by (Ferrer-Garcia et al. 2013) cue exposure therapies have been used as an effective intervention for provoking changes in craving for foods and reducing binge eating behavior. Using certain types of cues in any IVE is essential to enhance the process of realizing the surroundings—situation awareness (Endsley 1988). Paes and Irizarry (2016) define situation awareness as “the perception of the elements in the environment within the volume of time and space, the comprehension of their meaning and the projection of their status in the near future.” Cues can be classified into two main groups, stimulatory cues and instructional cues (Saeidi et al. 2017b). Stimulatory cues are pertaining to the structural, spatial, and temporal configuration of the IVEs. Stimulatory cues (both verbal and/or visual) are used to inform participants about the general design characteristics of the IVE (*e.g.*, time, type, size and function of the space, temperature) using sensory stimulation. Instructional cues guide participants navigating and interacting with virtual objects in the IVE. Instructional cues facilitate the use of IVEs and the flow of experiment procedures. Most of the IVE studies employ a narrative-along-the-experiment method to assist participants to follow all steps of an experiment without the need to break his/her connection with an IVE. Cues not only help participants to understand the design characteristic of IVEs, but also play a significant role in reducing the imposed cognitive load on participants for decision-makings. They can be used to expose participants to different stimuli while representing intended real-life experiences. Cues, in fact, are an integral part of any virtually created experimental setting that aims at inducing the naturalistic emotional, behavioral, and physiological responses.

2.3.7 Practical Applications

IVE applications have shown great promises in creating experimental constructs in a wide range of research contexts. Social scientists have used this tool to simulate life-like scenarios to study human behavior and evaluate this technology's capability in changing real-world attitudes and behaviors. In studies of this kind, participants had a chance to take over the ownership of a specific virtual avatar and walk in his/her shoes. Some examples include reducing energy consumption (Bailey et al. 2015; Bailey and Bailenson 2013); increasing saving behavior for retirement (Hershfield et al. 2011); promoting physical exercise (Fox and Bailenson 2009); reducing negative stereotyping of the elderly (Yee and Bailenson 2006); reducing social prejudice toward out-groups (Farmer and Maister 2017). Furthermore, in the field of health care and clinical research many successful interventions have been made for stress management (Serino et al. 2014), testing delusional beliefs (Freeman et al. 2010), treating paranoid disorders (Freeman et al. 2008) and acrophobia (Rothbaum et al. 1995).

Education and training are another domain that has greatly benefitted from VR and IVE. This tool was able to replicate risky or costly educational material such as operating complex industrial equipment. Tichon (2007b) in his study of high-stress training of train drivers in a virtual environment, reported that simulators were effective in generating a "reasonable fit with the real world." Various VR training prototypes have been developed and repeatedly tested by NASA for performing hazardous tasks by astronauts in the space (Cater and Huffman 1995). Similarly, the U.S. Army simulation-based training has made great contributions in developing adaptive tools and methods to automate the authoring and training soldiers (Goodwin et al. 2015; Whitney et al. 2014), and more recently, schools in the US are using VR to train teachers, staff, and administrators to respond to armed intruder threats. In a research by Stinson and Bowman

(2014), it was assumed that using high-fidelity VR settings can prepare athletes for real-world high pressure situations. Their work revealed that “VR sport-oriented system can induce increased anxiety (physiological and subjective measures) compared to a baseline condition.” Bideau et al. (2004) found that the reaction of goalkeepers to ball throwers are similar between real-life and a VR setting. In another attempt by Fels et al. (2005), swimming in the ocean was simulated by suspending participants in the air and representing computer generated visuals and sound. VR simulation in surgical education has proven to be effective in teaching, transferring technical skills, and engaging learners (Cannon et al. 2014). Several research studies have been done on remote robotic microsurgery such as operations of the eye surgery (Hunter et al. 1993) and some other practiced surgery simulation of body parts—leg surgery (Pieper et al. 1991). Bootvong et al. (2010) assessed the feasibility of virtual models for orthodontic plaster models and their study revealed that the analysis performed on the virtual model was as valid as traditional plaster models. VR can also be used for the representation of objects and environments that do not exist yet. Several applications have been carried out in industrial prototyping and assembly in manufacturing (Jayaram et al. 1997). In a similar fashion, buildings that have not been yet constructed, have been visualized and remodeled as many times as required, in a shorter time and in the cheapest way. With the use of VR goggles, designers were able to experience a real-time demo of scenes wherein they could observe and investigate future design adjustment. Dunston et al. (2011) studied an IVE mock-up tool for reviewing the design of space and equipment functionality through added interaction capabilities of the mock-up tool. In a study of modeling traffic patterns, using virtual reality was demonstrated as an effective technique to observe the way people show specific patterns of interaction, and to identify the indicators for how to establish rules in empirical procedures for decision-making (Nabijiang et al. 2019; Saeidi et al. 2019; Tan and De 2000).

For studies of building occupant role-playing and behavior, IVE provides participants with the opportunity to vividly experience specific environments under controlled laboratory circumstances. Application of this technology has been leveraged to study human behavior in design, engineering and construction. Examples include building design and analysis such as home design (Mackie and Cowden 2004), architectural daylighting design (Hong and Michalatos 2016), emergency situations such as evacuation from tunnel fire (Kinatader and Warren 2016), construction safety (Lu and Davis 2016), and human movement and spatial behavior in urban environments (Natapov and Fisher-Gewirtzman 2016; Zacharias 2006).

The virtual experiment platform provides users with a close approximation to the real-life representation. Kuliga et al. (2015) showed the potential of virtual environments as a research tool for human-environment interactions (Fabi et al. 2012). They showed that it is possible to achieve effective end-user feedback from the system and concluded that VR had a strong possibility as a research tool in psychological and architectural researches.

More significantly, designers can benefit from detailed observations on occupant behaviors in IVEs and run simulations that are more accurate. For example, Heydarian et al. (2014) were interested in the impact of alternative design properties including, spatial geometries, material and finishes, lighting and environmental factors on human behavior. They used an IVE to investigate occupant's lighting use preferences when manual and semi-automatic control systems were offered and realized that IVE serves well for collecting data instead of using traditional approaches such as the use of surveys or field observations. Literature suggested that lighting-use behavior in indoor environments might be a habitual behavior that it is largely non-reflective, and so theoretical predictors such as the variables of the TPB may explain little variance in this particular occupant behavior (Bamberg and Schmidt 2003; Steg and Vlek 2009).

However, there is still a big gap in literature with respect to the validity of applying IVE-based data collection to studies of occupant behavior in buildings. Ample evidence is needed to more strongly support that IVEs are capable of eliciting humans' naturalistic sensations and behavior and to suggest under what conditions the bottlenecks can be overcome.

2.3.7 Validation of IVE Applications to human Behavior Studies

There have been many studies focusing on the validity of VR operationalization and its constructs in order to determine its value as an empirical measuring tool. The major validity types that should be considered in any IVE study are listed as follows.

2.3.7.1 Ecological validity

Ecological validity implies a close link between the challenges imposed by the assessment procedures and the challenges that the subject has to confront in real life situations (Wasserman and Bracken 2003). In a broad sense, ecological validity of a test refers to its capacity to provide similar results with those expressed in real life situations (Chaytor and Schmitter-Edgecombe 2003; Wasserman and Bracken 2003) (Loomis, Blascovich, and Beall (1999) believe that "IVE technology is a highly promising tool for the study of basic psychological processes. One of its primary advantage is affording more ecological validity without compromising experimental control and allowing the decoupling of variables that naturally co-vary." When it comes to measuring ecological validity, presence or sense of "being there" becomes an inevitable concept to consider. The term presence is generally used to address the human feelings and perceptions of a virtual environment (Barfield et al. 1995). The reason behind finding participants' sense of being there is that the more a person feels present in a virtual environment, the more his/her response to the stimuli would match those in the physical environment (Villani et al. 2012). Along with testing the level of presence in IVE, the face

validity of the experiment has to be confirmed as well, *i.e.*, the experiment material should look like they are measuring what they intend to measure and be designed to be as respondent-friendly as possible (Oppenheim 2000). Content validation in IVE is considered another requirement for determine the value of IVE, which is referred to as the appropriateness of the simulator as a testing modality (Lyons et al. 2013).

2.3.7.2 Internal validity

“Internal validity is possibly the most important strength of IVE studies since the entire virtual experimental setting can be easily controlled (Loomis et al. 1999).” Internal validity aims to establish a cause-effect relationship between the major variables of the study and tries to figure whether the observed outcome (occupant behavioral intention) can be attributed to the experiment intervention (*i.e.*, IVE intervention) and not to other possible/alternative causes (Trochim 2000).

2.3.7.3 Construct validity

Trochim (2000) defines construct validity “as the approximate truth of the conclusion that our operationalization accurately reflects its construct”. Construct validity for an IVE can be assessed by comparing the applied measures in two different IVE and *in-situ* settings. If both test settings produce similar measurements (*e.g.*, physiological responses to similar stimuli) and path coefficients, then construct validity can be supported. Alternatively, many researchers tend to test validity of the simulators or IVE scenes by comparing the performance of the experts vs. novices. In operationalizing IVE scenes and simulators, researchers expect to distinguish between different groups for which they assess data.

2.3.7.4 Criterion-related validity

In this type of validity, VR's ability will be tested in that whether VR can predict something, which should theoretically be predictable. In essence, demonstrating comparable levels of prediction in behavioral intentions between the two settings could provide evidence for predictive validity (Trochim 2000).

2.3.7.5 External validity

Supposing that in this experiment there is a causal relationship between the constructs of the causes and their relevant effects, to provide support for external validity of the research, researchers should be able to generalize the results of this study to other persons, places or times. Besides, "General knowledge can only be produced through application of theory and no findings based on any research methodology can have external validity in the absence of theory" (Lucas 2003).

This study mainly focuses on testing the ecological validity of the IVEs, while finding threats to the other forms of validity (i.e., internal, construct, criterion-related, and external validity) will be a future study to this dissertation.

2.4 Chapter Summary

This chapter identified the major components of the research, which include occupant behavior, thermal comfort, IVEs, and validation methods for application of IVEs in occupant behavior studies. The systematic review of the literature enabled to discover some gaps in the above areas and identify a research question for this dissertation. The main research gap in the literature was the feasibility of the application of multi-sensory IVEs to improve our understanding about occupant behavior during the design phase of the buildings. That is, if occupant energy-use related behavior in IVE can be mapped to their *in-situ* counterparts, many

shortcomings of the occupant behavior studies performed in the *in-situ* or in the lab environments or using surveys would be overcome. In particular, are we able to use IVEs as a replica that can provide the opportunity to construct and contextual (*e.g.*, temporal, spatial, physical, social) factors for testing various types of occupant behavior, such as thermally-driven behavior, lighting-use behavior, acoustics-related behavior? Even though IVEs have been previously used for lighting-use behaviors, the validity of applying IVE-based data collection for predictions has yet to be proven. The most critical achievement of this chapter was to intertwine the existing gaps together and offer a logical stream of thinking for the dissertation. This chapter also identified the major threats to different aspects of experiment validity (*i.e.*, ecological, internal, construct, criterion-related, and external validity). So, the requirements to tackle each of the validity types was assumed to be met to ensure that the data collected from IVEs could be considered valid and comparable to the data collected from the *in-situ* experiments.

CHAPTER 3 PILOT STUDIES

In this chapter, gaps in the literature were specifically identified and several micro-hypotheses were formulated and tested through four pilot studies. They were basically designed to examine the feasibility of IVE application for making interventions and hypothesis testing. Various research methods were selected in each pilot study to accommodate different aspects of occupant behavior (*i.e.*, lighting-use behavior, visual and thermal comfort, longitudinal data collection) in IVEs. The pilot studies explored the validity of IVE-based collected data in support of making occupant behavior predictions in design context. Using the conclusions derived from the pilot studies, the major research constructs of the proposed theoretical framework of the dissertation were determined and the relationship between them were explained as a set of hypotheses.

3.1 Pilot Study I, Occupant Lighting-use Behavior

3.1.1 Introduction

Buildings' actual performance is largely influenced by the occupant behavior during the post-occupancy phase; yet, the diverse and complex nature of humans has not been fully understood to allow designers to have a realistic prediction of their behaviors (Yu et al. 2011). Obviously, little understanding or poor prediction of occupant behavior causes significant discrepancies between an energy prediction during design and the actual consumption during occupancy, which if remains, will continue to prevent designers from achieving design goals. Consequently, many technological advances for energy efficient buildings are still unable to fulfil their true potential and in particular the effectiveness of passive designs is often in question after the occupancy phase of a building starts (Hoes et al. 2009).

3.1.2 Purpose

This study looked into the consistency of occupant energy behavior in IVE and *in-situ* environments. Better predicting occupants' behavior is a critical factor that can reduce the discrepancies in energy consumption predictions between design and post-occupancy phases. The study employed an office environment and its corresponding IVE to examine individuals' perceptual and behavioral responses in using artificial lighting. As a matter of fact, the ultimate goal of this study was to optimize the understanding of occupant and building interactions during the design phase of the building life cycle.

3.1.3 Methods

This study considered established predictors of volitional behaviors in order to control for them and demonstrate the ability of IVE to model *in-situ* behaviors. A number of theories predicting the major influences on human behavior exist in the literature; among which, Theory of Planned Behavior (TPB) by Ajzen (1991) was the main basis of the proposed model in this study. It was hypothesized that IVE is capable of producing a comparable level of perception to what is typical in physical environments and can be designed in a way that can induce similar behavioral intentions. To that end, an experiment was designed in that the participants' visual comfort and their lighting-use behavioral intentions were examined. The main dependent variable of the experiment was the occupant behavioral intention of using window-blinds over the artificial lighting, in the *in-situ* vs. in the IVE conditions. It was intended to understand whether the occupant lighting-use behavioral intention in IVE is capable of being mapped to *in-situ* behavior, and more specifically, to explore what variables would succeed/fail to map.

3.1.4 Participants and Procedure

A total of 28 undergraduate students participated in this study and the study employed a within-subject design (participants were randomly assigned to both the IVE and *in-situ* conditions). Experiments were conducted in an office environment (Figures 3.1 and 3.2) over a total of three months from January to March 2016. Participants were asked to report to the lab at least two weeks after the completion of the web-based pre-experiment questionnaire. Half of the participants completed the IVE in their first visit and the other half performed the *in-situ* experiment first. In the IVE trial the experiment began after a 5-minute familiarization session. It was intended to let the participants get accustomed to the VR tools and the experimental setting. All the experiments were conducted in the afternoons, and only if the weather was sunny. The amount of the indoor light was measured with a lux-meter and it remained consistent between the IVE and the *in-situ* trials. There were four lighting choices in each experiment, namely P_1 , P_2 , P_3 and P_4 , which respectively represent the experiment environment with only natural lighting, natural and artificial lighting together, only artificial lighting and finally no lighting source at all. The experimental conditions are illustrated in Table 3.1. The experiment procedures started by performing a reading task in a dimly lit condition (P_4).



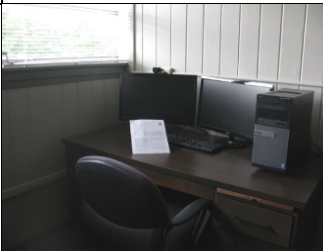
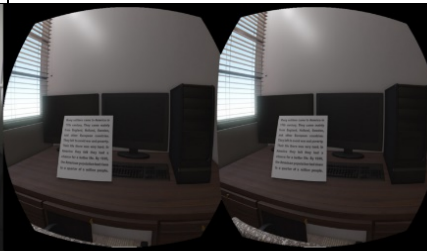
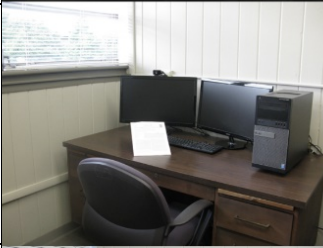
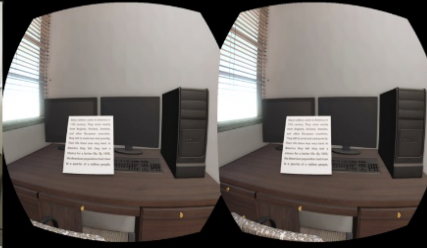

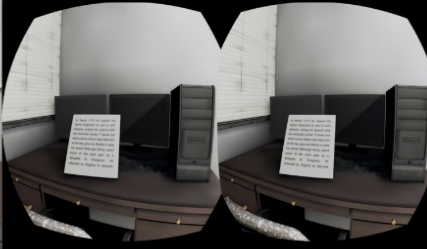

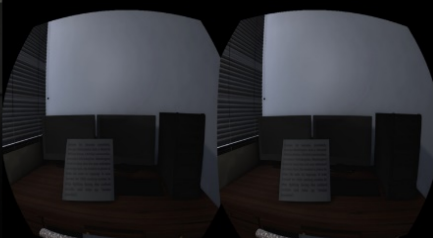
Figure 3.1 IVE Experiment View



Figure 3.2 IVE Experimental Setting

After performing the reading task in P_4 condition, participants answered to a satisfaction questionnaire and they were given the chance to pick their preferred lighting source to improve their visual comfort. They could either select to use the natural light by pulling up the window-blinds (P_1), turn the artificial light (P_3) on or select both (P_2). After the selection was made, participants answered another questionnaire, to report their perceived control beliefs and actual control to adjust the light and blinds in the experimental environment.

Table 3.1 Experiment Environments and Lighting Conditions

	Room Condition	<i>In-situ</i>	IVE
P_1	Blind open/ Light off		
P_2	Blind open/ Light on		
P_3	Blind closed/ Light on		
P_4	Blind closed/ Light off		

Participants were asked to come back for performing the second round of the experiment, in at least 2 weeks. Spacing between the two trials of the study helped to minimize the carryover effect. The same set of questions (*i.e.*, satisfaction with lighting, perceived control beliefs, and actual control perceptions) were asked in the other experimental conditions. Moreover, if the trial involved IVE, the level of presence that IVE evoked in the participants was measured using the scale of ITC Sense of Presence Inventory (ITC-SOPI). It contained participants' Engagement with the virtual setting, their Spatial Presence, Ecological Validity of the virtual scene as well as the Negative Effects of the IVE on participants. In addition to the collected data from questionnaires one-on-one interviews were conducted with participants.

3.1.5 Results

Ecological validity of the IVE setting was evaluated through the self-reports on the ITC-SOPI questionnaire. For the naturalness of the scenes, participants reported an average of 76%, ranging from 48% to 92%. Noticeably, the lowest recorded measure referred to a participant who experienced the highest negative impact in the IVE. Almost all of the participants reported being negatively impacted due to the imperfection of the resolution of the VR goggle. In this exercise the IVE test received high rating on engagement and spatial presence, respectively 76% and 78%. It is worth mentioning that ITC-SOPI questions were designed with careful considerations to support the face validity (Lessiter et al., 2001). The threat to the internal validity of the study was eliminated by developing completely comparable experimental scenes, plus by providing adequate and step-by-step explanation about every single stimulus control and experimental stimulus manipulation in both test settings. Construct validity was assessed by comparing the mean performance of the tested satisfaction variables (*i.e.*, visual comfort, visual stimulation and mood) in two IVE and *in-situ* settings. Except for the participants who experienced high negative

impact from the IVE, both settings produced similar measurement and path coefficients. That is to say, the lighting stimulus in the IVE was able to produce similar perceptual and behavioral responses as in *in-situ*. However, in terms of emotional aspects, IVE showed that it cannot represent constant and reliable responses. For instance, majority of the participants felt relax, cozy and pleasant in the dimly lit physical environment, but results showed that none of them felt the same in the corresponding dimly lit IVE condition.

The criterion validity in this study was tested by demonstration of similarly observed measurements of the Theory of Planned Behavior (TPB). The TPB measures which consist of attitudes and beliefs, norms, control beliefs and actual behavioral controls have been used as predictor of the behavioral intentions in two experimental settings. The TPB measures in this study established a great potential to be the evidence of the criterion-related validity as the participants' lighting behavioral intentions closely matched their self-reports on their attitudes and beliefs, norms, control beliefs and actual behavioral control. Indeed, the applied measures were likely to predict the behavior of 70% of the participants. The observations revealed that the predictive capacities could be reduced when the participants experience strong negative effect of the IVE.

Before examining the consistency of participants lighting-use behavior across the two experimental settings, we sought to establish that the IVE was well designed and provided participants with the perceived ability interact with the environment. We first confirmed that participants had equivalent perceived control beliefs and perceptions of actual control to adjust the artificial lighting and the window-blinds in both experimental settings. The Kolmogorov-Smirnov test was employed to compare these variables across the test settings. Perceived control beliefs and perceptions of actual control did not show a statistically significant difference across

the *in-situ* and IVE ($p\text{-value} > 0.05$). In other words, individuals' responses to these variables in IVE closely matched their responses in *in-situ* setting. This indicates that the control beliefs and the actual control factors were perceived as comparably easy/difficult in the two varying settings. Therefore, scores on these two variables in IVE were likely to reflect the scores from the *in-situ* settings.

Internal reliability coefficient (Cronbach's alpha) were computed for each of the four ITC-SOPI factors. Alphas were pretty good and comparable to a similar research (Lessiter et al. 2001). The alpha and the mean score of the four factors are respectively given as follow: Spatial Presence (19 items) = 0.89, 3.36 ± 0.67 ; Engagement (13 items) = 0.79, 3.58 ± 0.55 ; Ecological Validity (6 items) = 0.80, 4.16 ± 0.77 ; Negative Effects (6 items) = 0.82, 2.38 ± 0.72 . Given these statistical tests and comparing the results with other similar studies (De Leo, Diggs, Radici, & Mastaglio, 2014; Nisenfeld, 2003) we conclude that the presence level in IVE was sufficient for replicating a real-world experiment.

Correlation tests were also used to explore the relationship between the ITC-SOPI variables and the dependent variable of the study—observed lighting-use behavior match (binary). The results indicated a fairly strong correlation between the lighting-use behavior match across the two environments and individuals' level of Computer Experience ($p\text{-value} = .001$) and Spatial Presence ($p\text{-value} = .002$). It can be concluded that users who were not sufficiently engaged with the IVE and/or are negatively impacted by its side effects are more likely to behave inconsistently across the experimental settings. Similarly, correlation tests were used to examine the statistical significance of the association between the choice of using/not using the window-blinds in the *in-situ* vs. in the IVE setting. The results revealed a strong correlation of lighting-use behavior across both environments ($p\text{-value} < .001$), this

correlation was even stronger after the control factors (TPB factors) were included. In short, the IVE setting was shown to be a promising tool for predicting this type of behavior.

In this pilot study, the external validity could not be assessed due to the small sample size. Therefore, further studies are required so that authors can generalize the findings of the research to and across other groups of people, time and place.

3.1.6 Discussion and Conclusions

Estimating building energy performance range widely from optimistic assumptions and experts are convinced that the randomness of occupant-related factors is one of the main reasons for it. Findings of this study indicated that replication of IVE with field experiments appears to be a promising method to improve the existing predictive models. Undeniably, the new adaption will be a useful and effective adjunct to any building project. Besides, the study considered that comparing various design alternatives with specific energy behavioral information can assist designers and engineers to optimize the design process. Yet, this pilot study remains to be inconclusive due to its explorative nature and the small sample size.

3.2 Pilot Study II, Occupant Thermal Comfort (Rest)

3.2.1 Introduction

The potential of IVEs in mirroring real-life experiences and inducing individuals' psychological and physiological responses (Felnhofer et al. 2015; Meehan et al. 2002; Serrano et al. 2016; Vilar et al. 2014) has inspired this study to adopt this tool to investigate human thermal states. For exploring the design of the future of a building design, it would be best if users could experience all properties of the environment (*e.g.*, thermal, acoustic, air quality) in addition to the visual features of it. Fricoteaux et al. (2009) presented the concept of an informed virtual environment by which any thermal feedback could be displayed to perceive cold or warm

differences in virtual rooms. Similarly, Hülsmann et al. (2013) developed a system for creating wind and warmth simulations within a virtual platform, they stated that “one possibility to make virtual worlds more immersive is to address as many human senses as possible.” Thermal sensation and interactions with thermostats is a significant factor which cannot be not well-understood and predicted during the design phase of the buildings, which can causes misinterpretations about the future of the buildings. There are numerous studies focusing on the significance of occupant thermal comfort and energy-related behaviors and building performance (*e.g.*, Al-Mumin et al., 2003; Dietz et al., 2009; Raaij, 1983). When occupants are uncomfortable with the indoor environmental qualities, they are very likely to choose other alternative means to satisfy their comfort. The uncertainties associated with occupant interactions with building systems can cause discrepancies between designers’ initial assumptions about the building and its actual performance. This study tries to determine the feasibility and the effectiveness of using IVEs as an apparatus for replicating real-life experiences of an indoor environment and studying occupant thermal comfort and their thermally-driven behavior. The study makes changes to the environment temperature and assesses individuals’ psychological and physiological responses. Thermal comfort studies are normally conducted in two standard approaches, either in resting mode or during exercise states (Asmussen 1967; Gagge et al. 1967). This study has chosen the rest mode; still, there is an essential need for solid evidence of validity to accredit more intensive occupant behavior studies using IVE.

3.2.2 Purpose

The purpose of the study was to explore participant perception and experience of temperature variation in IVEs. By comparing the construct measures gathered in the IVE and in-situ, the study tried to see how different the environmental factors could be perceived in the two

experimental settings. Eliciting similar psychological and physiological responses to temperature, in comparable IVEs and in-situ environment was believed to produce evidence for the construct validity of the experiment. Given that, it was hypothesized that IVE is able to replicate mundane realism with regards to setting, stimuli, and response.

3.2.3 Methods

The study employed a within-subject design and participants were assigned to the experimental settings in random order. Experimental setting, IVE vs. in-situ, and the environment temperature are the independent variables of this study. Dependent variables were divided into both subjective and objective measures. Subjective measures included the participants' thermal comfort, thermal sensation and satisfaction with the temperature as well as their level of presence. Objective measures consisted of the physiological responses of their bodies—skin temperature and heart rate. Participants' chest was selected as a representative spot to measure the skin temperature. This selection was made with consideration of convenience for sensing and adoption rate in previous 16 thermoregulation models (Choi et al., 1997). Each test involved two sessions, *in-situ* and the IVE which both took place in a climate chamber located in the University of Southern California (USC), School of Architecture. Experiments were conducted over a total of two months, March and April 2016. All participants took part in both two sessions, one for the *in-situ* and one for the IVE. The sessions were carried out on the same day, one immediately after the other. The experiments were carried out with counterbalancing to tackle the order effect; half of the participants started with the in-situ, and the other half started with the IVE.

3.2.4 Participants and Procedure

The experiment was conducted with 17 participants, 6 females, 11 males; they were all undergraduate and graduate students in USC. They attended the experiment voluntarily. Their age ranged from 21 to 28 (median=24) years old. Participants were recruited using flyers and word of mouth on USC campus. Data analysis relevant to the questionnaire surveys were performed with the collected data from all of the participants. However, the carried out physiological data analyses was based on the data acquired from only 12 participants (5 females, 7 males) due to a sensing system issue, but the sample size is still meaningful to use t-statistics. The entire experiment, both the in-situ and the IVE sessions, was performed in the climate chamber. The USC climate chamber relies on a heat-balance that provides a carefully controlled environment which is capable of making its occupants shiver or perspire. The air speed in the chamber was controlled at less than 0.2 m/s by ASHRAE-55. A chair and a desk were placed in the center of the room, and data collection equipment was installed. To collect indoor environmental data, the indoor temperature was monitored in the center of the chamber and maintained at 1.6 m high. Relative humidity and CO₂ densities were measured as well in order to sustain consistent experimental conditions. The surface wall temperature and mean radiant temperature were also monitored to prevent radiant asymmetry, based on the ASHRAE-55. The relative humidity and CO₂ density were maintained around 30~40% and 700~900 ppm during the monitoring experiment. In order to build the virtual environment of the experiment, 3D model of the interior of the climate chamber was created in AutoCAD and then imported into a game engine—Unreal Engine 4. Most textures were created externally within an image-editing application (Photoshop) and then imported into Unreal Editor and applied onto the objects and surfaces. Lights and shadows were essentially placed into the model in UE4. The virtual reality

headset of Oculus Rift DK2 was used which had resolution of 960 x 1080 per eye and was the latest version of the head mount display of the time of this research. The created IVE of this study was sufficiently realistic and almost comparable with the physical version of it (Figure 3.3).



Figure 3.3 IVE View of USC Climate Chamber

Physiological monitoring in this study was limited to heart rate and skin temperature monitoring. Polar wireless heart rate instrument was used because of its accuracy and ease of the use (Figure 3.4). Skin temperature data was collected by using Vernier surface sensors (Model: STS-BTA), which measured skin temperature on direct contact with the skin surface. The collected heart rate and skin temperature were automatically transmitted to the DAQ system in the computer and recorded as a data file through an interface developed by the research team (Figure 3.5).

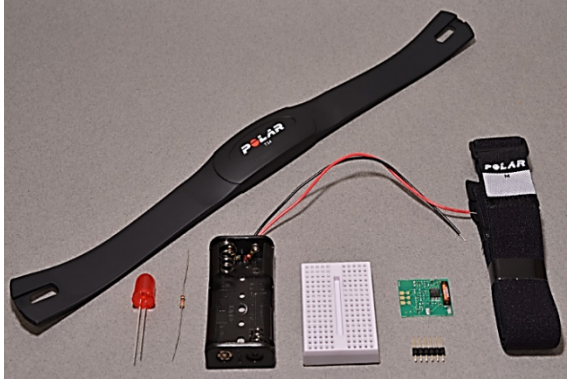


Figure 3.4 Heart Rate Monitoring Tool

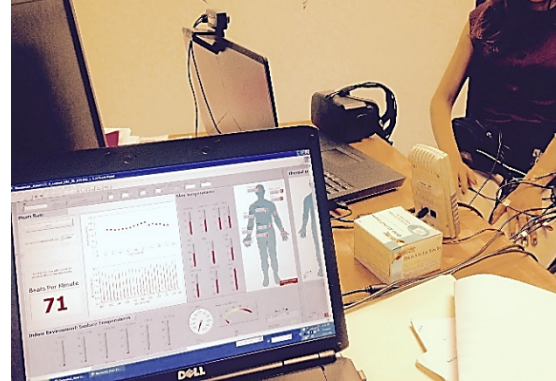


Figure 3.5 Environment and Skin Temperature Monitoring System

On the day of experiment, participants were provided with the informed consent; the consent form was read to the participant and her/his signature was obtained. The research assistant then signed and dated the form. Only after the participant has given her/ his written consent the experiment could began. They were then given a demographic questionnaire. This questionnaire was a part of ITC-SOPI questionnaire asking for information such as age, gender and occupation, plus for information on the participant's knowledge and level of computer experience as well as their prior experience with 3D images and Virtual Reality. Each experiment had two sessions, one in the IVE and one in the in-situ setting. The duration of each session was between 30 to 40 minutes. Both sessions took place in the climate chamber. The in-situ context was in fact the chamber's interior, while the IVE was the virtual representation of the chamber's interior (Figure 3.6 and Figure 3.7). In both tests, participants sat on a chair, relaxing and listening to a very soft background music. Once ready, experimenters assisted them to put on the heart rate sensor on their chest and adjust the length of the chest strap, if necessary. Afterwards, skin sensor wires in 9 parts of participants' bodies were taped onto the surface of their skin; forehead, upper arm, wrist, hand, chest, belly, waist, back neck and neck. Experimenters were told to be sure to tape the thermistor end (the tip) of the sensor directly to

the right position on the skin surface. After reassuring that the heart rate sensor, wiring and the software were working correctly, they would click the collect button on a computer to start collecting data. In the beginning of each session, there was 15-20 minutes standby at around 75F for the adjusting process and consistency by minimizing any variant condition of a metabolic rate and a preceding thermal status across the participants before the test. With the start of the session, temperature began to gradually increase and once the indoor temperature was stabilized, inquiries concerning the Thermal Sensation and Thermal Satisfaction were collected every 5 minutes along the experiment. Participants were assisted by the experimenters when answering the questions, *i.e.*, in both in-situ and IVE, questions were read to the participants and their answers were recorded. The ASHRAE thermal sensation numerical was used for the purpose of measuring the subjective physiological sensory related to the environment temperature.

The other commonly used scale which was administered to this study was the satisfaction with the environment temperature (7-point thermal satisfaction scale ending with choices: “Very Satisfied” and “Very Dissatisfied”). Besides, participants were allowed to explain their dissatisfaction by answering open-ended questions. Participant’s physiological responses, skin temperature and Heart Rates, were logged every minute for the duration of experiment. When the temperature reached 85F, collecting data would be over.



Figure 3.6 Thermal Sensation Inquiry in In-Situ Setting



Figure 3.7 IVE Experimental Setting

When an IVE test was involved the presence questionnaire, ITC-SOPI, was administered immediately after the IVE trial. The ITC-SOPI questionnaire measured the subjective quality of individuals' experience in IVE which included 44 items with five-point Likert scales. It breaks down into the level of Engagement with the virtual scene, Spatial Presence, Naturalness of the virtual scene as well as the Negative Effects of the virtual scene on participants.

3.2.5 Results

All of the participants were able to fully complete the sessions. The collected physiological data was imported from the database and integrated with the subjective recorded data. To examine the impact of IVE and determine the relationship between the collected data in the in-situ setting and IVE, pairwise comparisons of the dependent variables across the experimental setting in different temperatures were performed. To establish the relationship between the participants' subjective votes on their thermal sensation and their level of satisfaction with the temperature across the two experimental settings, data was initially plotted using clustered column charts (Figure 3.8 and Figure 3.9).

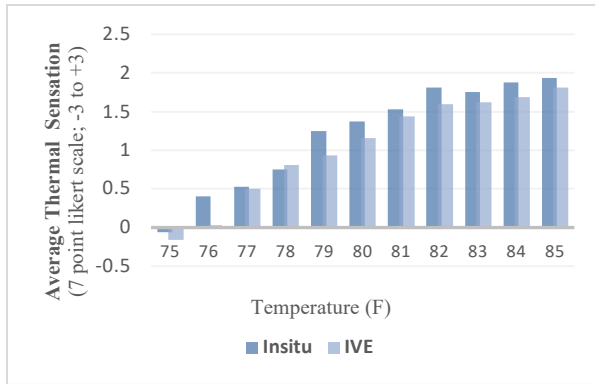


Figure 3.8 Thermal Sensation

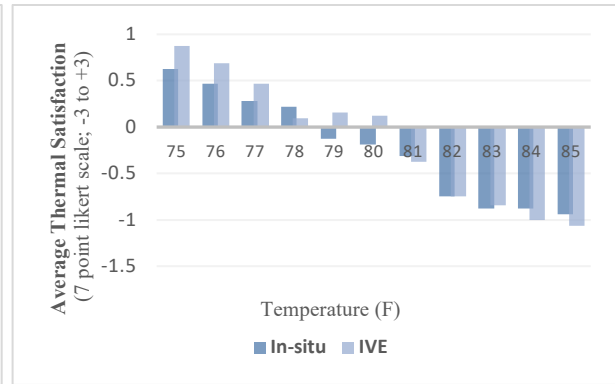


Figure 3.9 Satisfaction with Temperature

The plotted data (Figures 3.8 and 3.9) revealed a very similar pattern in both settings and Mann-Whitney U test results revealed that there was no significant difference among the recorded measures across in-situ and IVE. The average heart rate of the in-situ group was slightly lower than the recorded average heart rate in the IVE. However, this difference is not statistically significant ($p=0.91$). In contrary, the measured skin temperature of the in-situ group was slightly higher than that of the IVE group, nonetheless, this difference was not statistically significant as well ($p=0.70$). Therefore, these comparisons based on the aggregated data could not reveal any significant difference between the two test settings. Figure 3.10 & and 3.11 shows the mean and range of the data for these two variables.

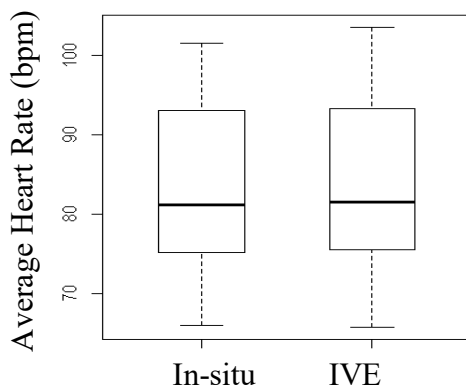


Figure 3.10 Comparison of the Heart Rate (bpm)

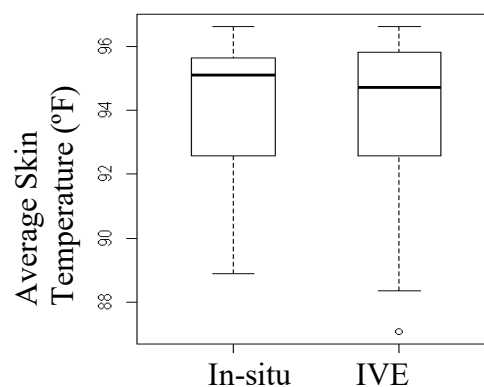


Figure 3.11 Comparison of the Skin Temperature (°F)

Paired sample t-tests examined whether there was significant difference between the physiological variables of the study across the in-situ and IVE experimental settings. The t-tests were performed using the average recorded heart rate and skin Temperature and the results are shown in Table 3.2.

Table 3.2 T-test of Heart Rate in the IVE vs. *in-situ* Settings

Setting	Heart Rate (bpm)					Skin Temperature (F)				
	N	Mean	St.Dev.	t	<i>p</i> -value	N	Mean	St.Dev.	t	<i>p</i> -value
<i>in-situ</i>	12	82.54	11.21	-0.12	0.91	12	94.05	2.40	0.38	0.70
IVE	12	83.09	12.03			12	93.62	3.04		

Association between the measured subjective dependent variables (thermal sensation and satisfaction with temperature) and the physiological variables of the study (heart rate, and skin temperature) has not been reported completely, due to some missing data in some certain temperature points for heart rate and skin temperature— minor data collection errors must have happened due to a participant’s quick movement, abrupt gesture, dry skin, etc.

Additionally, for assessing the quality of the IVE and participants’ level of presence, the responses to the ITC_SOPI questionnaire was analyzed and compared with the previously conducted studies. The internal reliability coefficient (Cronbach’s alpha) were calculated for each of the four ITC-SOPI items. Alphas were pretty close to Lessiter et al.’s (2001) study. There was no statistical inconsistency among the items and they had almost similar loadings. The alpha and the mean score of the four factors are respectively given as follow: Engagement (13 items) = 0.84, 3.44 ± 0.48 ; Spatial Presence (19 items) = 0.93, 3.37 ± 0.55 ; Naturalness (6 items) = 0.86, 3.52 ± 0.61 ; Negative Effects (6 items) = 0.79, 2.61 ± 0.62 . The above statistical tests were also compared with the results of other similar studies (e.g., De Leo et al., 2014; Nisenfeld, 2003).

3.2.6 Discussion and Conclusions

In this study, participant responses to the experiment experience were used to assess the ecological validity of the experiment. The subjective votes for thermal sensation and satisfaction with the temperature revealed that, except for the beginning of the sessions, there was a high correlation between the recorded votes across the test settings. More prominently, the physiological responses, as control factors, strongly supported the hypothesis of the study. It is revealed that neither the heart rate nor the skin temperature difference between In-situ and IVE were statistically significant. To sum up, the analyzed data indicated that being exposed to IVE and having a head-mount display on face, does not cause interference with the thermal comfort of human participants in the IVEs. Nonetheless, further studies on more physiological factors are essential, and additional human participant experiments are required to more confidently validate and generalize the findings of this study. Given the results of the presence questionnaire along with the comparable physiological measures (as another commonly used factor of the quality of virtual environments) between the two experimental settings, the authors conclude this study's IVE was able to replicate mundane realism and evoke enough level of presence. Moreover, the similarity of the subjective reports on the thermal sensation and Satisfaction with Temperature across the test settings indicate that the IVE setting did not make change in individuals' thermal comfort. The conducted experiment puts forward the IVE as a viable way to study the real world human thermal comfort related experiments. The findings from this study provide useful insight that can be leveraged to replicability of human thermal comfort and occupancy behavior studies in IVE.

3.3 Pilot Study III, Occupant Thermal Comfort (Exercise)

3.3.1 Introduction

In line with the potential of IVEs in evoking psychological and physiological human responses, this study takes a further step and investigates human thermal states during exercise. In general, there are two standard approaches to study thermal comfort, either in resting mode or during exercise states (Asmussen 1967; Gagge et al. 1967). While Study 2 examined individuals' thermal comfort in the rest mode, this study tries to understand possible discrepancies between human participants' physiological and psychological statements in a high energy expenditure mode of bodily activity.

3.3.2 Purpose

This study aims at exploring if IVE induces different participant experiences from what is usual in in-situ environments, while performing an intense physical activity. In fact, it is intended to determine whether the virtual replica of the lab environment, as the proposed testbed for studies of occupancy behavior, has a significant impact on participants' physiological and psychological responses. To that end, it is needed to gain insight into human participants' perceived thermal comfort and their physiological responses in both low (rest) to high (moderate exercise) energy expenditure modes of bodily activity, in IVE and compare it with the corresponding typical measures in the physical environment, in-situ.

3.3.3 Methods

Experiments were conducted over a total of three months, March to May 2016 and were performed in a lab in which the air temperature and humidity were properly consistent. All the participants took part in two sessions in a randomized, counterbalanced, crossover design— IVE (wearing a head-mount display) and in-situ (wearing no headset). Experimental setting, IVE vs. in-situ, was the independent variables of this study and dependent variables contained the aforementioned psychological and physiological measures. The sessions were carried out on two

different days within a week. The applied devices included a stationary bike, a computer set and a head-mounted display, and the equipment related to measuring the physiological data including telemetric heart rate monitor with capacity to measure breathing rate, activity levels, and skin temperature, a tympanic thermometer, metabolic cart capable of measuring oxygen uptake (VO_2), carbon dioxide production (VCO_2) and respiratory exchange (RER), and an infrared skin thermometer. Respiratory values (VO_2 , VCO_2 , and RER) were collected via Parvo Metabolic Measurement System (TruOne 2400, ParvoMedics, Inc., Sandy, UT) and HR was collected via telemetry using the BioHarness BH3 (Zephyr™, Performance Systems. Annapolis, Maryland).

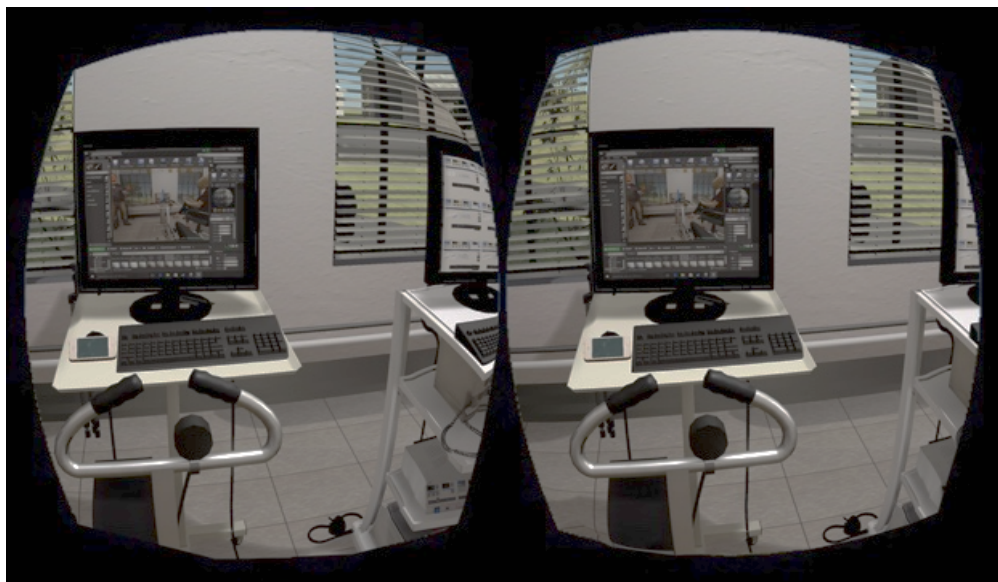


Figure 3.12 IVE View_Physiological Lab of School of Kinesiology

3.3.4 Participants and Procedure

Fourteen healthy, college-aged LSU students (age= 21.8 ± 1.9 y; 9 men, 5 women) participated in the experiment. All participants gave their voluntary, written consent prior to any assessments. All participants were screened through a medical history questionnaire and Physical Activity Readiness Questionnaire (PAR-Q). Participants at increased risk for cardiovascular, metabolic, pulmonary, or renal diseases were excluded from the study.

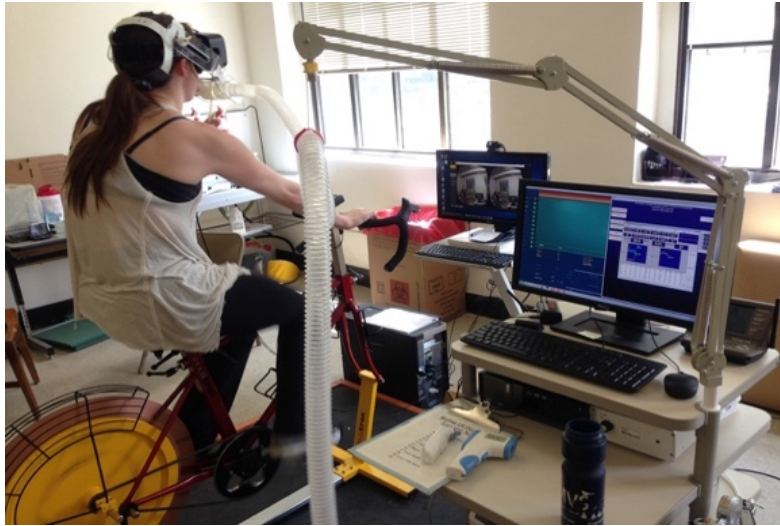


Figure 3.13 In-situ Experiment Environment_ Physiological Lab of School of Kinesiology

On the day of experiment, participants showed up in the Clinical Exercise Testing Lab in the school of Kinesiology at LSU. Basic demographic information of the participants, their body weight and height and their daily physical activity habits, were collected after completion of the consent. The IVE and in-situ trials consisted of 15 minutes of seated rest followed by 20 minutes of cycle exercise at a work rate equal to an estimated 50% of their age and sex predicted $\text{VO}_{2\text{max}}$ according to previously published literature. The estimated exercise capacity was measured in metabolic equivalent tasks (METs; VO_2 in $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ divided by $3.5\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) (Gulati et al. 2005; Morris et al. 1993) and the formulas below have been extracted from previous researches and were used to determine the workload for male participants ($\text{MET}=18.1 - 0.16 [\text{Age}]$) and for female participants ($\text{MET}=14.7 - 0.13 [\text{Age}]$).

Upon entering the laboratory on trial days, participants would be assisted to put on the HR sensor on their chest and adjust the length of the chest strap. Respiratory gases were monitored during the exercise sessions using an integrated oxygen/carbon dioxide analyzer calibrated with standard gas mixtures. Stoichiometric equations were used to determine fat and carbohydrate oxidation rates as well as caloric expenditure rates. Respiratory exchange ratio was

calculated as VCO_2/VO_2 . To collect skin temperature (T_{sk}) from each participant, upper arm was selected as a representative site and tympanic temperature (T_t) was repeatedly measured in the ear using Braun Ear Thermometer. All exercise testing was completed in accordance with the American College of Sports Medicine's Guidelines for Exercise Testing and Prescription as well as the American Heart Association. Participants' thermal comfort vote (7-point ASHRAE thermal sensation and satisfaction with temperature) was recorded in the beginning and at the end of the experiments (ASHRAE 2013).

3.3.5 Results

All of the participants were able to fully complete the sessions, however, the HR and VO_2 data for two participants did not transmitted/recorded properly and they were excluded from the analysis. Table 3.3 present the descriptive statistics of the physiological data in in-situ and IVE experimental setting, respectively. The mean of the last 5 minutes of resting and exercise physiological data, the steady-state values, are reported.

Table 3.3 Descriptive Statistics of the Physiological Data.

Variable	N	Min		Max		Mean		Std. Dev.		<i>p</i> -value
		<i>In-situ</i>	<i>IVE</i>	<i>In-situ</i>	<i>IVE</i>	<i>In-situ</i>	<i>IVE</i>	<i>In-situ</i>	<i>IVE</i>	
HR (bpm)	12	137.7	123.2	193.4	186.5	161.2	149.9	15.20	18.41	0.73
VO_2 (ml·kg ⁻¹ ·min ⁻¹)	12	17.93	16.53	27.81	28.36	23.87	23.18	3.03	3.92	0.76
T_{sk} (F)	14	91.90	91.40	96.40	96.80	94.06	97.50	1.77	1.14	0.67
T_t (F)	14	94.10	95.80	99.10	99.70	97.50	98.08	1.14	0.99	0.25
RER	14	0.94	0.89	1.09	1.01	1.00	0.96	0.44	0.03	0.025*

Min, Max and Std. Dev. respectively indicate minimum, maximum and Standard Deviation

To examine the impact of IVE and to determine the relationship between the collected data in the in-situ setting vs. IVE, pairwise comparisons of the corresponding dependent

variables across the two trials were carried out. Two-sample paired t-tests revealed that the mean for HR, VO_2 , T_{sk} and T_t variables have no statistically significant difference across in-situ and IVE experimental settings. That is, the hypothesis testing formulation declared $p > 0.05$ meant fail to reject the null hypothesis of no experimental setting difference ($\alpha = 0.05$).

The only variable with significant difference between in-situ and IVE was RER ($p = 0.025$, $\alpha = 0.05$). Participants oxidized less carbohydrate and more fat for energy while wearing the head-mounted display and did the exercise while in the virtual version of the lab. To explore the relationship between the participants' subjective votes on the thermal comfort items across the two experimental settings, non-parametric data analysis was performed. Mann-Whitney U test results showed that there was no significant difference between the ranks of the subjective votes on their thermal sensation in the beginning ($p = 0.30$, $\alpha = 0.05$) of each trial and also at the end of it ($p = 0.07$, $\alpha = 0.05$). Likewise, participants' satisfaction with temperature in the beginning ($p = 0.10$, $\alpha = 0.05$) as well as at the end was not statistically significant ($p = 0.19$, $\alpha = 0.05$). Moreover, the quality of the IVE and participants' level of presence was examined, the answers to the ITC_SOPi questionnaire were analyzed and compared with the previously conducted studies and was found quite comparable (*e.g.*, De Leo et al. 2014; Nisenfeld 2003).

3.3.6 Discussion and Conclusions

This study gained useful insight into the individuals' perception on thermal comfort as well as their physiological responses in high energy expenditure mode of bodily activity in IVE vs. in-situ experimental setting. Analyses revealed that participants' thermal comfort votes (thermal sensation and satisfaction with temperature) were not significantly different between the two trials. This suggests that being exposed to IVE and having a head-mount display on face, does not cause interference with the thermal comfort of human participants in the IVEs.

Additionally, majority of the physiological reactions (HR, VO_2 , T_{sk} and T_{t}) remained consistent across the settings; even though RER was statistically different between the two trials, it appeared that it did not affect the thermal sensation and satisfaction based on this study's sample. Considering that there were no differences in the other physiological responses, the difference between the measured values of RER between two trials might be due to the calming environment for the participants as a lower sympathetic nervous system activity may explain the lower carbohydrate use in IVE comparing to the lab setting in in-situ. Further investigations are required to confirm this statement.

Therefore, authors suggest that IVE is capable of replicating mundane realism in participants' body and mind responses. Obviously, participants' evoked perceptions and experiences from what was usual in in-situ environments was not significantly different. That is, this innovative method is a viable alternative tool for examining occupant behavior related to thermal comfort. The findings of this study can be leveraged to greater and more intensive occupancy prediction studies in wider range of activity modes.

3.4 Pilot Study IV, Spatial-Temporal Event-Driven Occupant Behavior Data Collection

3.4.1 Introduction

Longitudinal data are critical to modeling occupant energy behaviors, however, creating such models requires sufficient information to enable establishing and examining the patterns in the data, which can only be achieved through extended observations (longitudinal data).

Longitudinal studies supposedly contain a balanced coverage of observations based on the needs of the research. Using a conceptual framework, this study was able to design a systematic approach to generate large amount of data that could be useful for enabling IVEs for extended observations. The framework adopted four basic elements related to occupants and building

energy performance, to describe the conceptual framework of a STED model, i.e., “State”, “Context”, “Event”, and “Human (H)-Building (B) Interaction.” In this study, State ($s_i, s_{i+1}, \dots, s_{i+n}$) was defined as the collective status of operations in different building spaces at a certain point of time, especially the conditions of building systems and components that are operable by human beings and have energy efficiency consequences. An example of the state of a building can be the light-use condition of an entire building at 8:00 am on a normal working day. Contexts are situational factors that are associated with and describe the state of a building, but not necessarily a part of it. For example, a contextual factor can be the season for describing the light-use state of a building at 8:00 am, because the daylight condition in the winter can be significantly different from the summer at the same time point. Event ($e_1, e_2 \dots e_k$) is an occurrence that triggers the change of a state or sets the foundation for future events to change a state. Thus, there are state changing events and non-state changing events. Finally, H-B Interaction refers to a particular type of occupant actions to mitigate a thermal, visual, indoor air quality, or acoustic discomfort of an occupant such as turning on artificial lighting at 8:00 am by an occupant, which is associated with a state change event. At a higher level, states and events are interconnected, forming a constant loop between them (Figure 3.14). State i is the initial status of a given set of spaces at a specific time point along the time span of a study. State i will change to state $i+1$ upon the occurrence of an event.

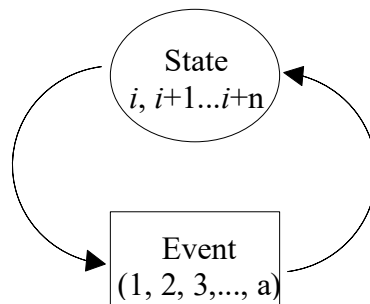


Figure 3.14 State-Event Model

This structure allows researchers to connect space conditions and time, which is critical to designing experiments for longitudinal data collection in built environments. Figure 3.15 displays a more extensive model of the state-event diagram that incorporate “occupant need”, and “H-B interaction” into the state-event model. Occupant needs are defined as human motivation under the context preceding the occurrence of an event, and consequently trigger H-B interactions. In fact, the occurrence of an event can impact occupant's overall comfort and generate a desire for H-B interactions, which leads a state change. Thus, a state transition, the change in the collective status of a building and its component will take place.

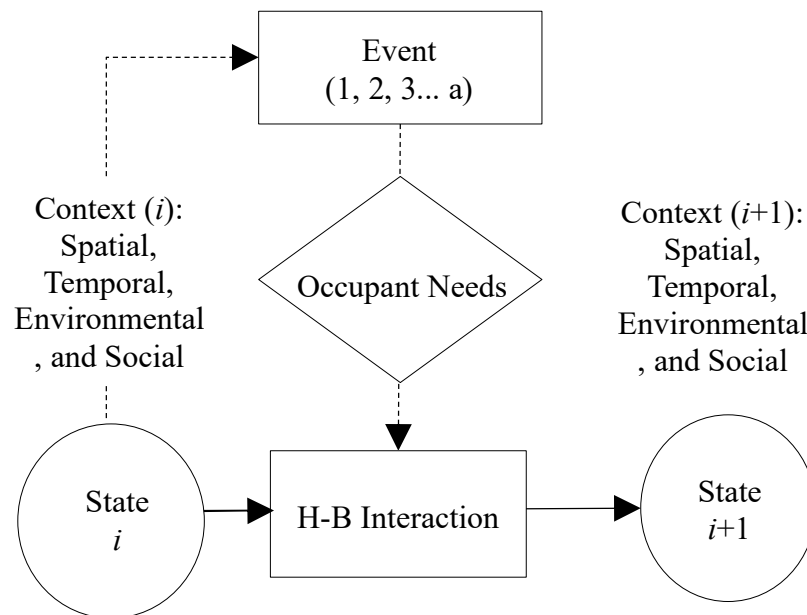


Figure 3.15 STED Model

Window-opening, shade control, lighting control, thermostat control, electric equipment usage, and space occupancy status are among the most common H-B interactions people perform to maintain or pursue their general comfort indoors.

3.4.2 Purpose

The main purpose of this study was to obtain initial evidence that IVEs have potential for supporting longitudinal experimental studies. While acquiring longitudinal data is not a problem

in *in-situ* studies, it represents a significant challenge to IVE applications. This study aimed at suggested a novel technique for generating and examining high-fidelity occupant-related longitudinal data which could further help developing context-sensitive occupant behavior models. The study tried to replicate certain events and state transitions across the IVE and its corresponding *in-situ* experimental conditions.

3.4.3 Methods

The study applied STED modeling in developing a case study in order to emulate extended observations in IVEs. The validity of the collected IVE data was tested through comparing state transitions with data gathered from a comparable *in-situ* environment. Therefore, case study involved two data collection methods, namely sensor (*in-situ*) and IVEs. The authors selected an on-campus single occupancy room in an office building at LSU. The office occupant (male, age: 30-40) was a faculty member of the university, who agreed to have sensors installed in his office for in-situ data collection and participate in the virtual reality experiments as well. The layout of the testing office and the place of the sensors are illustrated in Fig. 5. The testing office had a south-facing window with operable window-blinds as well as ceiling lights. The interior design of the office is shown in Figure 3.16. The STED modeling is to model critical events in a chronological order, representing long observations of states in reality. In the study, the basic measurement is the operations on a lighting switch to determine the occupancy/lighting state transition, which is a snapshot of a space at two different time points representing the initial and subsequent status of a space. Considering the current limitation of virtual reality technologies, the authors selected a single occupancy office in the case study in order to reduce the effect of the extraneous variables.

The spatial dimension of the STED model depicts the physical configurations of the single occupancy office space, whereas the temporal aspect of it simulates the sense of time and captures a series of state transitions within a specific time frame, such as a day. Events are determined based on research needs and the likelihood of state changes. Since most lighting adjustments during a day happen upon arrival and/or before departure (Hunt 1979), this study has selected six typical events representing the arrivals and departures and investigated the response variable of occupancy/lighting status of the office space at those time points. Therefore, events in this study are broken down into: e_1) arrival at the office; e_2) intermediate (short) leave; e_3) return from intermediate short leave; e_4) intermediate (long) leave; e_5) return from intermediate long leave; e_6) departure (see Figure 3.16).

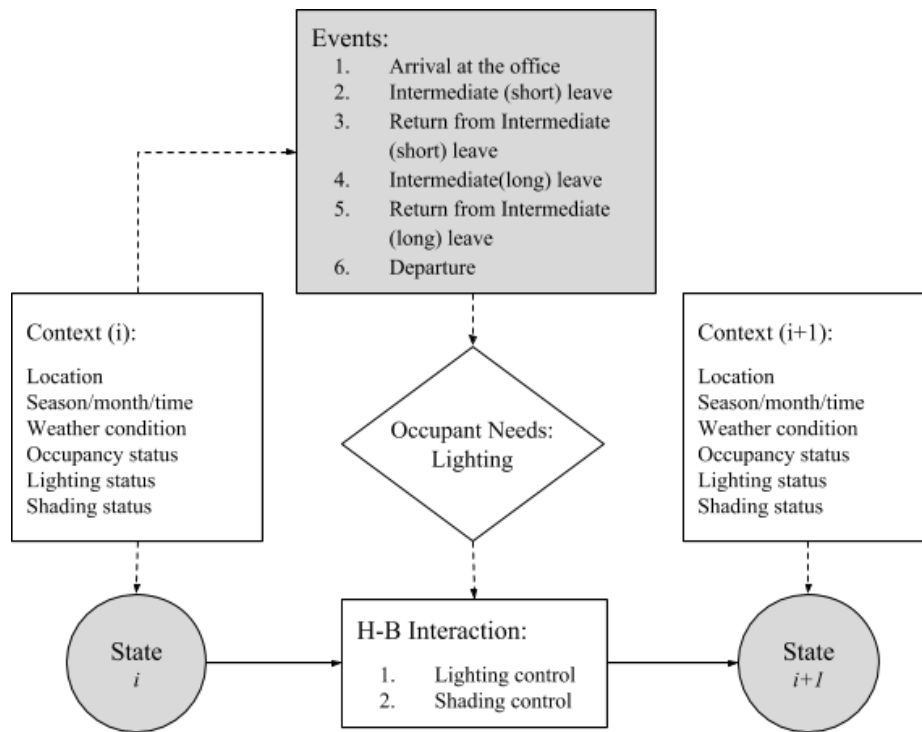


Figure 3.16 STED Model (Case Study)

On the other hand, states are defined based on the combination of the occupancy and lighting status of the testing environments, which leads to four types of states: s_0) non-occupancy

without artificial lighting; s_1) non-occupancy with artificial lighting; s_2) occupancy without artificial lighting; and s_3) occupancy with artificial lighting (see Figure 3.17).

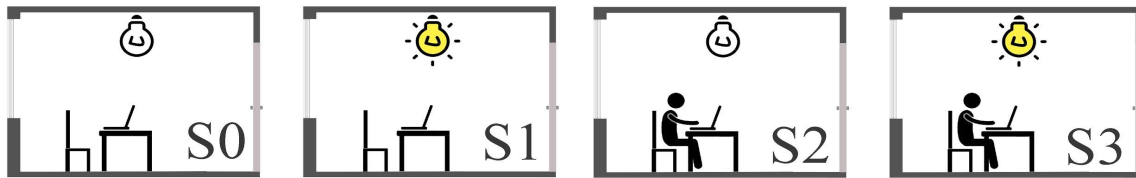


Figure 3.17 Occupancy/lighting states (case study).

This study used a single occupancy room in an office building located at LSU campus. The room had a southern facing window with operable and accessible window-blinds. However, due to the limited time and funding resources, the case study included only one participant (male, age: 30-40). This study consisted of two major phases of data collection; 1) field observation or *in-situ* (Figure 3.18), 2) IVE experiment (Figure 3.19). The metrics that were used in this study include lighting status change and the occupancy state of the office.

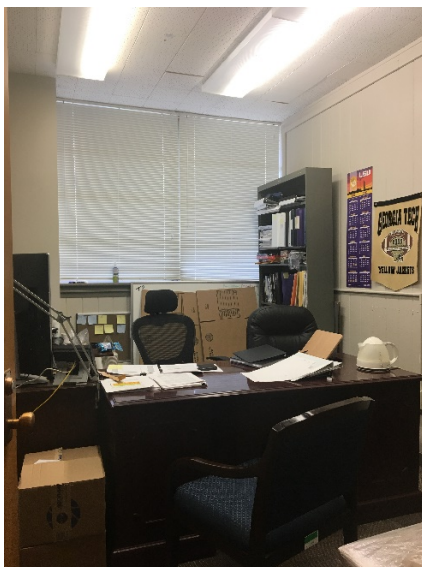


Figure 3.18 In-situ Environment

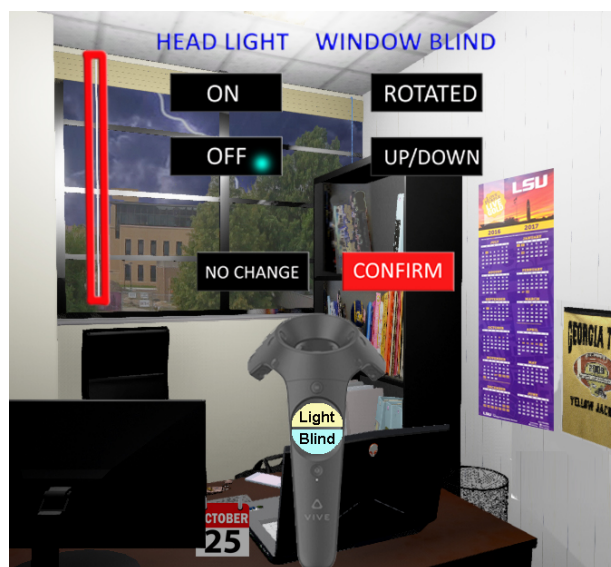


Figure 3.19 Sample Cues in the IVE Scene

3.4.4 Participants and Procedure

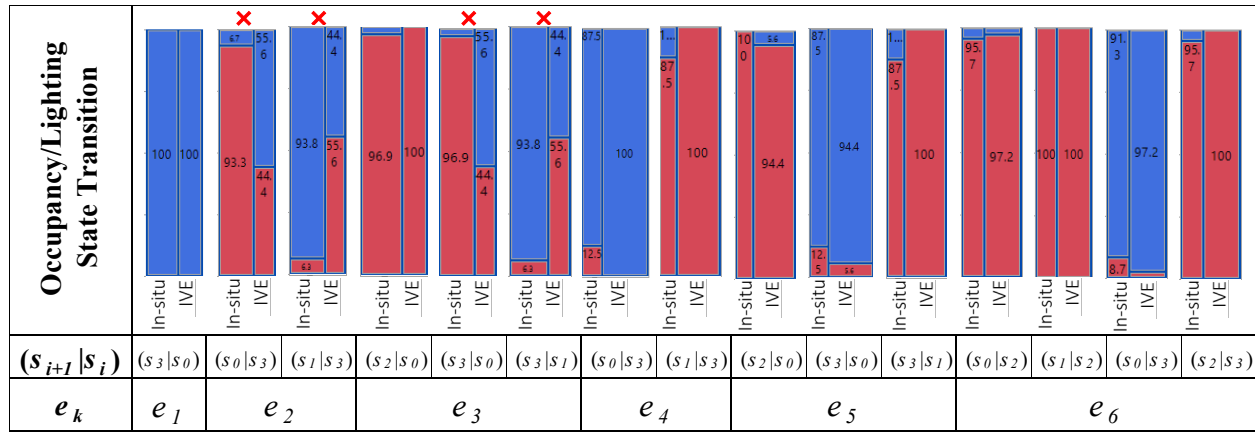
The experiment started with signing the written consent form followed by the pre-experiment questionnaires including the demographic information, knowledge of computer, and VR experience inquiries. Furthermore, the constructs of the Theory of Planned Behavior (TPB) were incorporated in the study to obtain information about the participant's behavioral intentions as for the use of the lighting in the office. The *in-situ* data collection was performed using two occupancy and two lighting sensors (*i.e.*, HOB0 UX90-005 and HOB0 U12-02) and it lasted for 35 days, September 23 through October 27, 2016. The IVE experiments, on the other hand, were carried out in two separate days in November 2016. Before every IVE sessions, the participant attended a familiarization session (~10 minutes), so that all the necessary IVE functions (*e.g.*, navigating through the menu and within the IVE itself, selecting the lighting choices, and responding to the virtual stimuli) could be mastered.

The end result of the IVE experiments was a dataset related to the occupancy/lighting state change transitions which happened at 126 events, in total; 18 events of arrival at the office (e_1), 18 events of intermediate short leave (e_2), 18 events of returning from the intermediate short leave (e_3), 18 events of intermediate long leave (e_4), 18 events of returning from the intermediate long leave (e_5), and 36 events of departure (e_6). The initial occupancy/lighting state of the virtual office, in the beginning of the experiment was always set to s_0 and the succeeding state of each event became the initial state of the second event. Events in this study were established and ordered in a continuous chronological succession (*i.e.*, starting with the arrival at the office in the morning) without an interruption. The duration of each event in the IVE experiment did not exceed 2 minutes, and after every 12 events there was a 5-10 minutes break. Each session lasted about 70 minutes in total and there was 10 days gap between the IVE sessions.

At the end, participant's subjective votes about their VR experience was investigated using the ITC-SOPI instrument. The second session of the IVE experiment was conducted after 10 days and the procedure of it was the same as the first session. However, there was an additional post-experiment TPB questionnaire, investigating the perception of the behavioral control factors in the IVEs.

3.4.5 Results

This study used a nonparametric statistical test, namely, Fisher's exact test of independence to find out if there is any nonrandom association between the studied variables of the research. This test is applicable when the variables are nominal and it is more accurate than other independence tests (e.g., chi-square), when the sample is small. The null hypothesis of this test is that there is no association between the two variables of the research, such that the proportions for the first variable are different among values of the other variable. In the case of this study, that is, the probability of the occupancy/lighting state transitions are not influenced by being in any of the two experimental settings ($H_0: p(s_{i+1}|s_i) = p'(s_{i+1}|s_i), i = 0, 1, \dots, n$). Fisher's exact test of independence analyzes the two-by-two contingency tables and examines the equivalence of the probability distributions of the state transitions in the IVE and *in-situ* experiments. The p -values greater than 0.05 would retain the null hypothesis, suggesting that the two applied methods of data collection generate similar outcomes (at the 0.05 level of significance) and the data is independent from the studied tools, *i.e.*, IVEs vs. *in-situ*. Statistical analysis of this study was performed in SAS 9.4 (Statistical Analysis System) and JMP 13 (Figure 3.20).



✗ Statistically significant (p-value less than 0.05)

■ Probability of occurrences

■ Probability of non-occurrences

Figure 3.20 Proportion of State Transitions in All the Events

The results of the Fisher's exact test of independence illustrated in Figure 10 clearly shows that the majority of the occupancy/lighting state transitions between the IVE and *in-situ* environments were statistically comparable. In e_1 , the only possible state transition was (s_3/s_0) which was also the only occurred state transition and the result of the statistics revealed a complete consistency in the outcomes across two experimental settings (p -value=1). That is, regardless of being in IVE or *in-situ*, s_0 always led to s_3 at the event of the arrival at the office. Similar to the e_1 , e_6 showed that the IVEs were able to closely match *in-situ* observations. The reported p -values from the statistical significance test for comparing (s_0/s_2) , (s_1/s_2) , (s_0/s_3) , (s_2/s_3) and their counterparts, were greater than 0.05, which suggest that there was no experimental setting effect on any of the occupancy/lighting state transitions at e_6 .

Additionally, the case study investigated the intermediate leaves (short and long) and returns to the office. In the event of the long leaves (e_4) and returns to the office from the long leaves (e_5) the observed occupancy/lighting state transitional probabilities in IVEs perfectly corresponded with their counterpart *in-situ* (p -value> 0.05). Yet, there were inconsistencies in

the event of the short leaves (e_2) and returns to the office from short leaves (e_3). At e_2 , the probabilities of transition from s_3 to s_0 and from s_3 to s_1 in IVEs was statistically different than those *in-situ* (p -value<0.05). More specifically, in IVEs the tendency of turning the lights off upon the short leaves was significantly higher. Consequently, the occupancy/lighting state transitions at e_3 , which was essentially dependent on the chosen lighting status in e_2 , were different from the *in-situ* (p -value< 0.05) and could not follow the same pattern as *in-situ*. However, in this case study, the cumulative record of the arrivals at the office (regardless of the initial lighting status) clearly showed that “ s_3 ” was the most probable office status in both the *in-situ* observation and IVEs. Considering that the only observed discrepancy between the IVE and the *in-situ* occupancy/lighting state transitions occurred at e_2 and e_3 , the authors believe that the IVE design or the associated cues might not have been able to properly characterize those events. The cues that were used to represent e_2 and e_3 , *intermediate (short) leaves and returns from/to the office*, were mainly auditory cues, such as a voice message on the phone, asking the participant to assist a student in the next-door office, or asking the participant to stop by the secretaries’ office for a quick business affair. However, the duration in which the participant was expected to be involved with such activity was not directly stated throughout the message. As a matter of fact, open-ended messages of this kind could be personally interpreted, and the participant might draw his/her own conclusion about it. That is to say, the messages could be delivered and perceived in a different way rather than what the study planned to; thus, when the message is not clearly understood, the participant’s response could be totally conditioned based on his/her subjective interpretation.

The perception of being present is crucial in IVEs, since the more a person feels presence in a virtual environment, the more his/her responses would match those in the physical

environment (Villani et al. 2012; Witmer 1998). Thus, the authors administered a well-known presence instrument, ITC-SOPI, in order to take this factor into account. To determine if the IVEs are effective, the authors compared the results with previous studies (Table 3.4).

Table 3.4 Presence Measurement Score Comparison (Mean \pm Standard Deviation)

Presence Measurements	Pilot Study I (22)	Pilot Study II (23)	Pilot Study III (24)	Pilot Study IV
Engagement	3.58 \pm 0.55	3.44 \pm 0.48	3.15 \pm 0.29	4.38
Spatial Presence	3.36 \pm 0.67	3.37 \pm 0.55	3.06 \pm 0.49	3.95
Naturalness	4.16 \pm 0.77	3.52 \pm 0.61	3.04 \pm 0.62	4
Negative Effects	2.38 \pm 0.72	2.61 \pm 0.62	2.55 \pm 0.74	3.33

The factors and items contributing to this instrument consist of Spatial Presence, Engagement, Naturalness, as well as the Negative Effects. Comparing with previous studies, the IVEs in this study have the following characteristics:

- The high scores of the “Spatial Presence” and “Engagement” were strong indication that the IVE setting of this study provided an adequate sense of attachment to the displayed environment, which afforded some sort of interactions.
- This IVE was successful in drawing the participant’s attention in terms of the “Naturalness” of the scenes and believability of its contents.
- Even though the factor of “Negative Effect” scored the lowest in this study, it was higher than that of in the other studies conducted by the authors. The authors tried to minimize negative effects by allocating a five-minute break between each sub-session of the experiment.
- The TPB survey, on the other hand, provided useful insight about the participant’s tendency in the use of artificial lighting. The pre-experiment survey covered all the necessary measurements of the TPB (i.e., attitude, social norms, personal norm, perceived control belief, and actual control belief) were included in the questionnaire to study the participant’s general behavioral intention. Thus, experimenters learned the exact way the participant tends to interact with the lighting in his

real life (surveys are attached in the appendices). In the post-experiment survey, TPB measurements were designed and translated into the context of the IVE (*e.g.*, social norms: “Even though I was in a virtual setting, I would still consider how my decision on the use of light would be evaluated by others”). The goal of using the TPB survey was to discover any existing causes of discrepancies in the occupancy/lighting behavioral patterns across the two testing environments. Indeed, the pre-experiment TPB survey was used to shed light on the participant attitudes, norms, and perceived behavioral control factors on a daily basis. Interestingly, the answers to the post-experiment TPB survey showed that the major control factors (*e.g.*, the ease/difficulty of operating the window-blinds and light switch, also the impact of glare on the use of window-blind) in IVE were perceived the same way as in *in-situ*. This is in line with the authors’ previous research (Saeidi et al. 2016a) indicating that the control beliefs and actual control factors could be perceived as comparably easy/difficult as in the *in-situ*, if the design of the virtual setting upholds a fair ecological validity.

3.4.6 Discussion and Conclusions

The study explored a data collection method applied to IVEs using the STED modelling approach. IVE data from a single occupancy office were collected in a few hours to compare with one-month field observation. One hundred twenty-six IVE data that were classified into six event categories were compared with one hundred twenty-eight *in-situ* data. State transitions as a result of human building interactions were used to test if the proposed STED modeling approach is effective in simulating longitudinal data collection in IVEs. The hypotheses of the study was that the probabilities of the occupancy/lighting state transitions in a given event across the two experimental environments (*i.e.*, IVE vs. *in-situ*) are not statistically different. Results were, indeed, promising in producing comparable patterns of data across the two environments at the

majority of the events. This finding suggested that the application of STED can potentially alleviate IVE's weakness for producing predictive models. It should be noted that the goal of this study was not to generalize the results of this case study across other samples such as different people, but it was intended to initially discover the capability of IVEs representing extended observations, using STED.

Even though there were some limitations in the case study (*i.e.*, technology limitation), several important findings could be drawn based on the results of the data analysis. First, regarding the STED modeling approach, the case study shows that the flexibility of the event and spatial-temporal structures allows researchers to organize data based on the need of a study. The results hold good potentials to support not only conventional validation studies, but also collecting longitudinal data for predictive modeling. These potentials, with further proofs, can transform IVEs as an experiment platform. However, since the STED modeling approach is intended to cover a long-time study span in IVEs for longitudinal data collection, there often exists a time mismatch between IVE scenarios and experiments. For example, an IVE scenario is about winter conditions and the experiment might be carried out in summertime. Thus, more research is needed to understand the impact of a participant's actual physiological and psychological state on IVE experiments in order to collect data in IVEs within a limited timeframe. Previous researches found evidence that a conventional IVE is capable of eliciting human responses to stimuli such as lighting (Heydarian et al. 2015c; Saeidi et al. 2015), but for an IVE to be able to fully support occupant energy consumption behaviors, more complex IVE systems with additional sensory modalities as well as considering more careful participant inclusion criteria would be necessary. The authors conducted some pilot tests (Saeidi et al. 2016b, 2017a) to explore the feasibility of IVE's in inducing individuals' naturalistic

physiological and psychological responses to temperature as the stimulus. Even though in a sample wise comparison, no statistical difference was found between the studied measures across the IVE and the *in-situ*, measurements of some participants varied significantly between the two settings. It is still unknown that what variables contribute the most to the mismatch of the in-situ experiences comparing to those in the IVE. Apparently, responses to the visual stimuli (e.g. lighting) can be provoked relatively faster and more naturalistic than some other sensory stimuli (e.g. thermal and air flow). Knowing the fact of how different various sensory systems function, one can accommodate the experimental design accordingly.

Furthermore, the study also shows that the accuracy of IVE cues is very important. It seems that IVEs support salient events more strongly. Constructing IVEs with an intention to elicit a range of responses relies on the effectiveness of the details in the design of the IVEs, especially cues. Since it is not practical to replicate every single in-situ details in IVEs, a careful design of cues is required to be able to elicit a variety of event/states even in less distinguishable events. Currently, a systematic study of cues on eliciting occupant behaviors does not exist and thus requires further research. Finally, pilot study 4 demonstrated the potential of the STED modeling approach to support IVEs as an experiment apparatus and a predictive model in the future. Studies in the same vein often only focus on validating IVE experiments with in-situ observations, without further explanations of factors that contribute to discrepancies between in-situ and IVEs experiments. As an alternative to predictive modeling using in-situ data, it is important to show the reliability of any predictions using IVE data. Algorithms to calculate such reliability need to be developed.

3.5 Chapter Summary

This chapter reported on four pilot studies that were designed to explore the feasibility of IVE for collecting valid occupant behavior data. The pilot studies investigated several micro-hypotheses that altogether provided useful insight about the extent to which IVEs could replicate *in-situ* occupant behavior studies. The constructs which were used in the pilot studies were identified through the review of the literature. Each of the conducted pilot studies investigated a particular set of responses and stimulus modality. Pilot study 1, used lighting as the main experimental stimulus and tried to explore whether individual's lighting-use behavior in IVE could be mapped to those in *in-situ*. The study investigated the potential of the IVE in replicating the *in-situ* observation through a collection of various types of evidence (*e.g.*, ecological validity, face validity, construct validity, criterion-related validity, internal validity). Pilot 1 posed the following major question to pursue: “could behavioral choices investigation be extrapolated to apply to broader contexts—*e.g.*, when thermal triggers are also involved?”

Pilot study 2 and 3 were designed to understand two general aspects of thermal comfort, *i.e.*, environmental and personal factors. Pilot study 2, occupant thermal comfort (rest), focused on the impact of the environmental factors (temperature specifically) while keeping the activity level of participants constant. A cross-sample analysis of thermal sensation/satisfaction, heart rate and skin temperature did not show significant differences between IVE and *in-situ* experiments, but statistical differences also existed at individual level. Further analysis confirmed that the heart rate measurements of some participants showed significant difference between IVE and *in-situ*. Pilot study 3, occupant thermal comfort (exercise), focused on personal factors, exploring the question, when environmental factors (indoor temperature and humidity) remain constant will the changes in human activity levels lead to different thermal sensation

between IVE and *in-situ*? Results show that except RER, the sample mean of other parameters had no statistical difference between IVE and *in-situ* experiments. However, a within-subject comparisons, again, showed that measurements of some participants varied significantly between IVE and *in-situ*. Pilot studies 2 and 3 initiated the thought that “would thermoception measurements still be comparable if some of the physiological responses vary between the IVE and *in-situ*?”

Moreover, pilot study 4 developed a conceptual structure as a new data collection method called a spatial-temporal event driven (STED) model. The model was used to collect a pair of (*in-situ* and IVE) lighting-use behavior datasets to examine the possibility of longitudinal observations in IVEs. Still, it is crucial to find evidence whether “this model could still be applicable for thermally-driven behavioral studies?”, since applicability of the STED model to experiments in which thermal stimulus is involved depends on having a proof that temporal and environment temperature mismatches do not significantly alter the responses in IVEs. That is, whether the simulated IVEs of a colder season could be used to collect thermal state and behavior data while the actual season is different (warmer). Thus, the pilot tests raised the need for a more comprehensive IVE-based data collection structure that could address the abovementioned questions, alongside. Performing these four pilot studies was a pivotal step in the process of developing the main theoretical framework of this dissertation (discussed in chapter 4).

CHAPTER 4 EMPIRICAL EVALUATION OF OCCUPANT THERMALLY-DRIVEN BEHAVIORAL INTENTION MODEL

4.1 Introduction

The main purpose of this dissertation is to explore the effectiveness of a multi-sensory IVE (combining an IVE within a climate chamber) for occupant thermal comfort and thermally-driven behavior research. The pilot studies have shown cases in which IVEs had the potential of eliciting responses that were closely comparable to their *in-situ* counterparts. This possibility supported the idea of examining a wider range of stimuli in IVEs and taking advantage of such efficient and safe experimental setting for performing experiments. Yet, it is crucial to find out the contributing factors that could cause discrepancies between the two corresponding measurements (IVE and *in-situ*). The major experimental interventions in this study consist of heating and cooling exposures in IVE and *in-situ* experiments. The key to this study is the capability of multi-sensory IVE to induce individuals' naturalistic thermoceptions (thermal sensation, comfort and acceptability) and thermally-driven behavioral intentions in a design context. In this study, participants experience heating and cooling exposures, as experimental stimuli, in a climate chamber. The thermoception measurements, physiological responses (*i.e.*, skin temperature, heart rate variability and galvanic skin response), as well as the behavioral feedbacks in the multi-sensory IVE are compared with those of the *in-situ* experimental setting.

4.2 Research Constructs and Theoretical Model

The theoretical terms of this study are either extracted from the literature or adopted from the results of the conducted pilot studies. The major variable of interest in this study is the experimental setting, multi-sensory IVE, which itself breaks down into visual and thermal stimulus modalities. IVE replaces individuals' real-world visual experience with a synthetic experience through a technologically-mediated platform; meanwhile, a temperature stimulus is

used to elicit responses through cooling or heating exposures. In fact, the study aims to examine its impact on human thermal sensation or thermoception in IVEs. Thermoception is defined as “the process in which different levels of heat energy (temperature) are detected by living things” (Hensel 1981). In this study, visual perceptions and thermoception play the role of the manipulated variable while many other stimulus modalities (*i.e.*, auditory, olfactory, somatosensory) are assumed to remain consistent.

Thermoceptions and thermally-driven behavioral intentions, as the other significant construct variable of the research, play the role of the main dependent variable of the research. Behavior is intrinsically inseparable from perception of the environment. This research tries to explore if participants’ behavioral choices for reaching thermal comfort would change in IVEs and what are the contributing factors for the possible changes. Some of the typical thermally-driven behaviors examined in literature (Langevin et al. 2015) are listed as follows: clothing adjustment, personal fans on/off, personal heaters on/off, thermostat up/middle/down, windows open/closed, drink water, internal coping and so forth. Moreover, for investigating the thermally-driven behavior, the constructs of the Theory of Planned Behavior: attitude, norms, perceived behavioral controls, and actual control factors, which shown to be a strong potential for predicting occupant behavior, were studied as well.

In the literature review section, the significance of the quality of presence in virtual experiences was extensively discussed and highlighted (Slater 2009). Thus, this study found it necessary to keep track of participants’ votes on those measures as well. It is believed that maintaining a satisfactory level of presence, would evoke comparable emotional, physiological and behavioral responses to what is natural in real-life.

The construct variables of this study are organized into independent variables, dependent variables, and covariates, as shown in Table 4.1. As discussed before, the major manipulators (independent variables) of the study include experimental platforms (IVE vs. in-situ), thermal stimuli (heating vs. cooling), and thermoceptions (thermal sensation, thermal acceptability, and thermal comfort votes). Moreover, since human thermal states vary seasonally (Liu et al. 2017), this variable is also considered as another independent variable of this study. Seasonal mismatch refers to situations where the IVE simulates one season, such as winter, in order to collect thermal state or behavior data, while the actual season is different and especially contrasting, such as summer. It is still unknown if using simulated IVEs of one season while the actual season is different can be a source of discrepancy in collecting thermally-driven occupant behavior data. In this study, the collected data was classified into two contrasting outdoor temperatures— *i.e.*, 20°F different.

The major response or dependent variables of the study are Thermoceptions (Thermal Sensation, Thermal Acceptability, and Thermal Comfort Votes), Physiological Responses (*i.e.*, Tsk, HRV, GSR), Thermally-driven Behavioral Intention. Some of the variables (such as physiological responses) can have overlap in their roles, depending on the assumptions of the hypothesis.

Furthermore, according to literature, individuals' responses to the IVEs also depend on variables such as demographic information, VR experience, immersive tendencies and cybersickness; these variables can have considerable impact on individual responses to certain stimuli or setting. They are called covariates which could possibly explain the response (dependent) variables of the study.

Table 4.1 Research Constructs and their Roles

Construct Name	Independent Variable	Dependent Variable	Covariates
Experimental platforms (IVE vs. in-situ)	X		
Thermal stimuli (Heating vs. cooling)	X		
Period 1 (colder) vs. period 2 (warmer)	X		
Thermoceptions (Thermal Sensation, Thermal Acceptability, and Thermal Comfort Votes)	X	X	
Physiological Responses (<i>i.e.</i> , T_{sk} , HRV, GSR)	X	X	
Thermally-driven Behavioral Intention		X	
Body Mass Index/body component information			X
Demographics			X
VR Experience			X
Immersive Tendencies			X
Cybersickness			X
Presence			X

Figure 4.1 presents the research constructs that were used to develop the theoretical framework of the dissertation. It explains the path of the study by proposing how the constructs could relate with each other and connects and underpins the study to the existing theories and anecdotal evidence from the reviewed literature. It essentially demonstrates the assumptions that are made about the relationship between the variables and helps to formulate hypotheses regarding those relations.

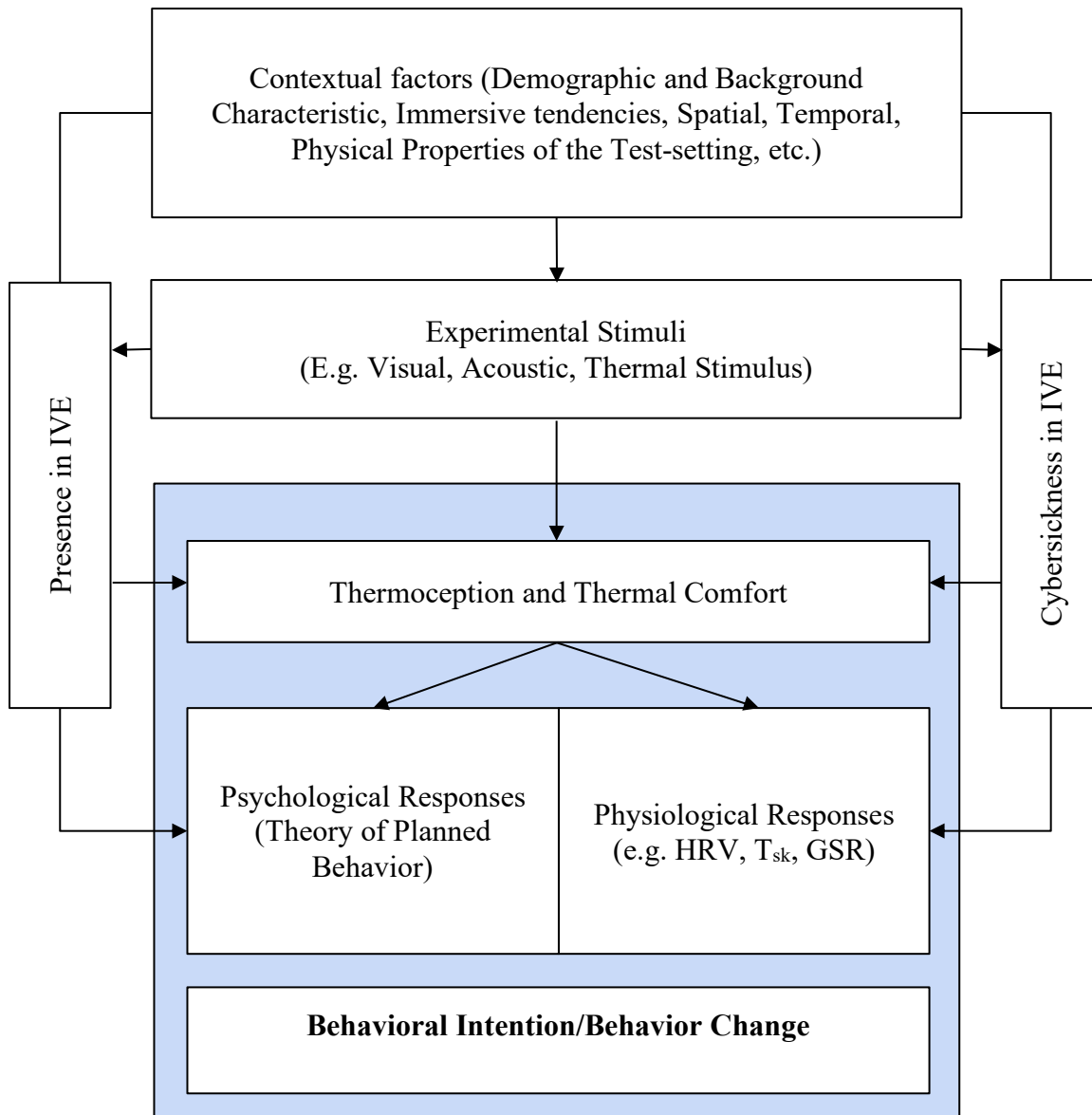


Figure 4.1 Illustration of the Conceptual Framework of the Research

4.3 Research Hypothesis

This study formulated different sets of hypotheses to postulate relationships among the construct variables listed in table 4.1, make statistical inferences, and answer the major questions of the research. Every hypothesis is a clear proposition that aimed to test the effectiveness of multisensory IVE from a different specific dimension. The experiments in this study were used

as data-gathering methods to confirm or reject the hypotheses; they are listed as follows (Table 4.2).

Table 4.2 Research Hypothesis

H1	There is a similar pattern between temperature and thermal comfort in IVE and in-situ (thermal comfort in IVE is not statistically different from thermal comfort in in-situ).
H2	There is a similar pattern between the variables “physiological responses” and “indoor temperature” in the in-situ and IVE experimental settings (physiological responses in IVE are not statistically different from the physiological responses in in-situ).
H3	There is a relationship between thermoception differences and the variability of thermally-driven behavioral intentions across the in-situ and IVE.
H4	Individual-related variables (demographics, immersive tendencies, prior VR knowledge, cybersickness, presence) are related to the variability of thermally-driven adaptive behaviors across the in-situ and IVE experimental settings.
H5	Seasonal mismatch will not significantly alter the thermoception and thermally-driven behaviors of participants compared to seasonally matched IVEs.

Experiment environment, thermoception and thermally-driven occupant behavior were the three core concepts of the proposed theoretic framework (Figure 4.2). In the two experiment environments, multi-sensory IVE was the virtual reality replica of *in-situ* experiments inside climate chambers. The main contextual factors in this study were individual-related factors (e.g., demographics and background, Immersive tendencies, prior knowledge, cybersickness, presence). These factors were considered to study their impact on the outcomes in using multi-sensory IVEs. The three thermoception measurements (sensation, comfort and acceptability) have been used to measure individuals’ different thermal conditions (Zhang and Zhao 2008). Thermal acceptability represents the physio-psychological threshold for action to restore thermal comfort. In addition, the degree to which a mismatch between IVE-simulated and actual season

influences participant responses on thermoceptions and thermally-driven occupant behavior was examined.

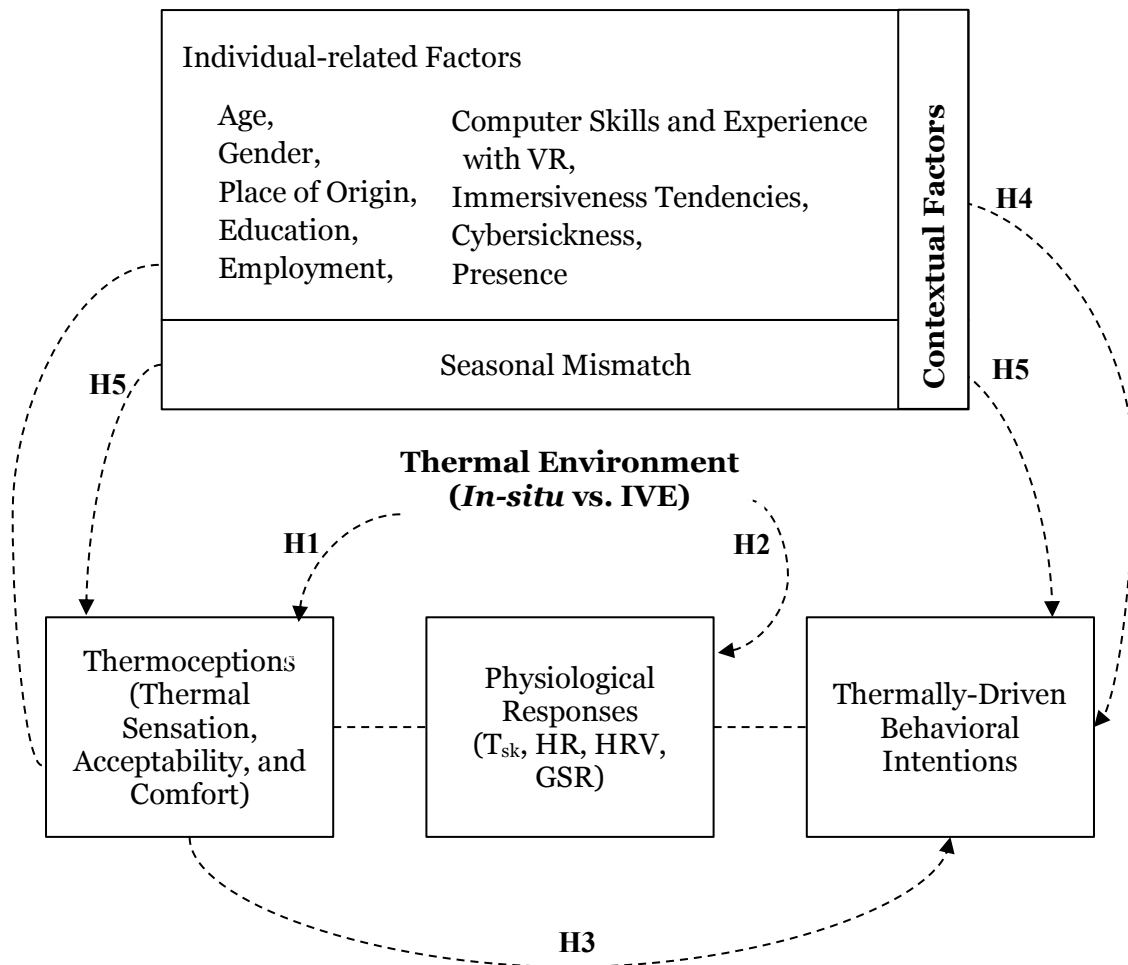


Figure 4.2 Hypothesis Testing Schema

4.4 Research Setting

4.4.1 Experiment Environment

The laboratory within which the experiments of this study are performed is a climate chamber located in the Engineering Laboratories Annex Building (ELAB) at LSU campus. This climate chamber is a renovated indoor environment which is specifically built for occupant behavior thermal studies. The basic layout and the ceiling plan of the climate chamber can be seen in Figure 4.3.

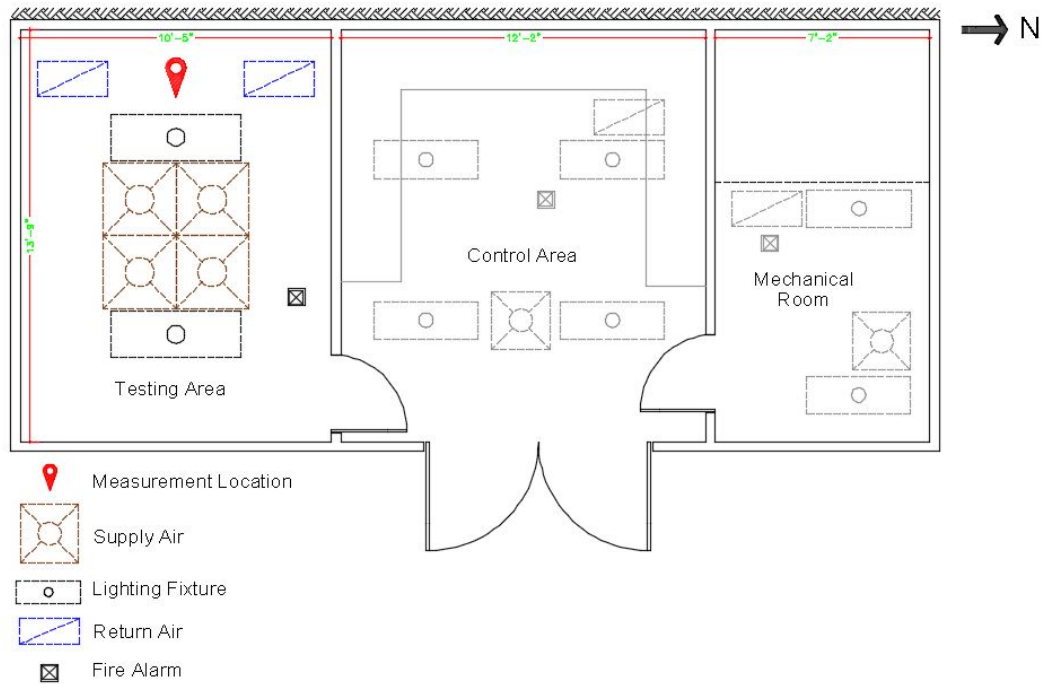


Figure 4.3 Climate Chamber Plan

This facility consists of 3 enclosed spaces including the main testing area (Figure 4.4), the control area (Figure 4.5), and a mechanical.



Figure 4.4 Climate Chamber Testing Area



Figure 4.5 Climate Chamber Control Area

Wood joist framing is used in the construction of the walls and the ceiling of the test area, and plywood decking is used on top. Moisture resistant gypsum boards are used on the interior side of the wall. All ceiling cavities are filled with 5” min heatlok soy’ 200 plus spray-applied polyurethane foam insulation from interior ceiling with epoxy. This climate chamber can simulate a broad range of environmental conditions. It is equipped with temperature, humidity, and CO2 sensors for the purpose of monitoring and keeping the experiment condition under control. Metasys®, which is an industry's leading building automation software, is used to provide coordinated control over the chamber’s system. The Metasys graphical display system helps to adjust the environmental control sequence of the testing area (Figure 4.6). The chamber is able to adjust the temperature to certain levels (increase and decrease) and participants would experience gradual heating and cooling exposure. When the test chamber is “enabled” the fan remains on at all times.

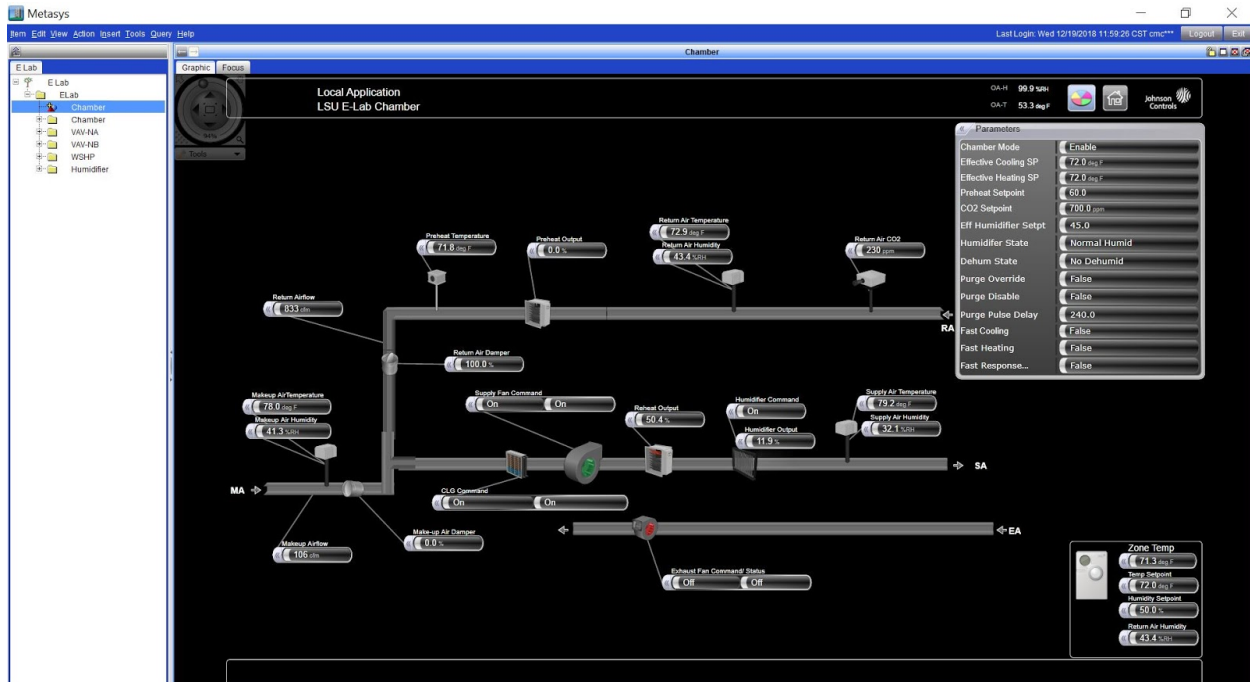


Figure 4.6 Climate Chamber Control System

On a signal of high temperature or high relative humidity, the water-cooled direct expansion coil is enabled to control zone temperature at the setpoint (adjustable). Because of the excessive hunting involved with small spaces, cooling stages are on continuously and reheating is used to control zone temperature, except when in fast heating mode. On a signal of low temperature, the electric reheat coil modulates to control at the setpoint (adjustable). On a signal of low humidity, the humidifier modulates to control at the setpoint (adjustable).

The system is equipped with a purging system in two modes: 1) Purge enable-fast cooling mode, which engages when the chamber temperature is higher than or equal to 78 °F, and when the change of the setpoint is equal to or greater than 6 °F. The electric reheat is disabled when the temperature is within 2 °F of the setpoint. The purge exhaust fan is enabled to evacuate warm chamber air. The chamber parallel box, which contains that warm chamber air, opens to allow the outside air into the chamber to decrease the time it takes to lower chamber conditions. The purge runs for a maximum of 4 minutes (adjustable).

2) Purge enable-fast heating mode, which engages when the chamber temperature is lower than or equal to 67 °F and when the change of the setpoint is equal to or greater than 6 °F. The cooling coil is disabled when the chamber temperature is within 2 °F of the setpoint. The purge exhaust fan is enabled to evacuate cold chamber air. The chamber parallel box opens to allow the outside air into the chamber to decrease the time it takes to change the chamber temperature. The purge runs for a maximum of 4 minutes (adjustable).

The electric preheat modulates to maintain minimum load on the cooling coil when cooling or dehumidification is required, and the load is too low to operate the system. Throughout the experiments, the environmental conditions (*i.e.*, indoor air temperature, relative humidity, and air velocity) of the chamber are carefully monitored. In order to record this information, various sensors are used. All the sensors in this study meet the requirements for measuring range and accuracy given in ASHRAE Standard 70-19915 or 113-19906 or in ISO 7726,1 and referenced sources shall be so identified.

4.4.2 Indoor Air Temperature and Relative Humidity

The air temperature within the testing area is measured by Vernier Surface Temperature Sensors (Figure 4.7). The Surface Temperature Sensor has an exposed thermistor that results in an extremely rapid response time.



Figure 4.7 Surface Temperature Sensor

Three of these sensors were installed at the 0.1, 0.6, and 1.1 m (4, 24, and 43 in.) levels as the experiment involved sedentary activity (levels are recommended by ASHRAE 52-2010).

Among them, the sensor at 24 in. was selected to represent the air temperature near the participant (Figure 4.8). Temperature data transmits in 1-second intervals and was logged with Logger Pro 13. Temperature range of this tool is -25 to 125°C (-13 to 257°F) with a precision of $\pm 0.2^{\circ}\text{C}$ at 0°C , $\pm 0.5^{\circ}\text{C}$ at 100°C .

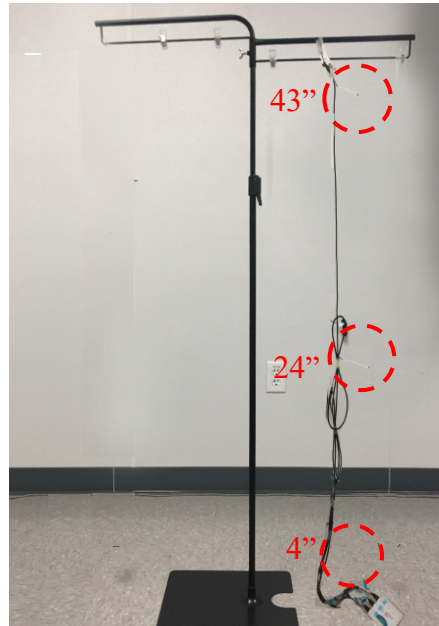


Figure 4.8 Environment Temperature Sensors

Experiments for this study were conducted in the testing area of the climate chamber facility (Figure 4.4). The testing area provided the thermal manipulations needed to examine individuals' thermoception and thermally-driven behavioral intentions. This facility works at its highest efficiency within the temperature range of 60°F to 90°F and humidity of 40% to 90% RH. Figure 4.9 shows the duration it takes to decrease (between 30-40 min) and increase (15 min) the temperature of the testing area from $90/60^{\circ}\text{F}$ to $60/90^{\circ}\text{F}$, while keeping the humidity of the room consistent at 50% RH.

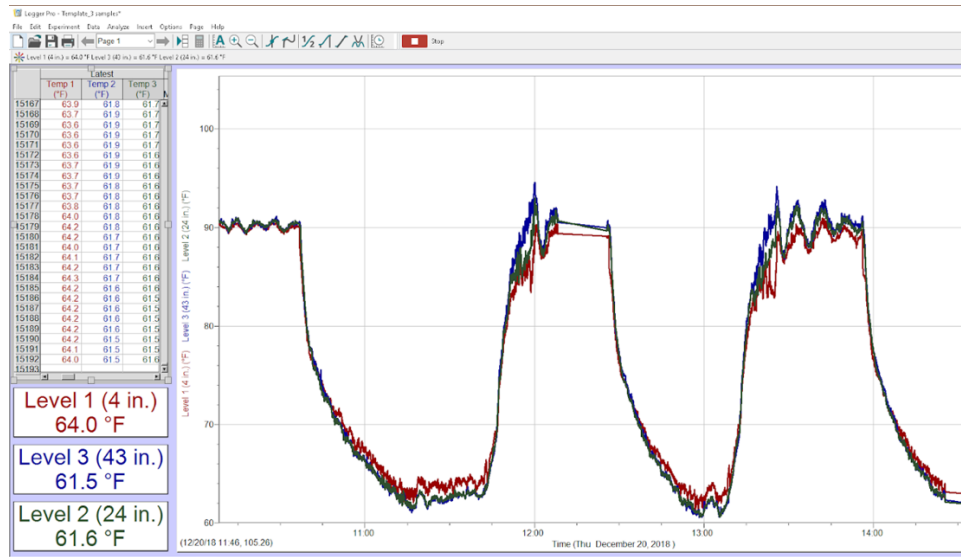


Figure 4.9 Climate Chamber's Temperature Range

Figures 4.10 and 4.11, respectively, represent the stabilization process of the heating (at 65 °F, 75 °F, and 85 °F) and cooling (at 85 °F, 75 °F, and 65 °F). It is noteworthy that in both heating and cooling exposures, the HVAC system of the chamber had a couple of thermostat overshoots before reaching the set-points (specially at 75 °F).

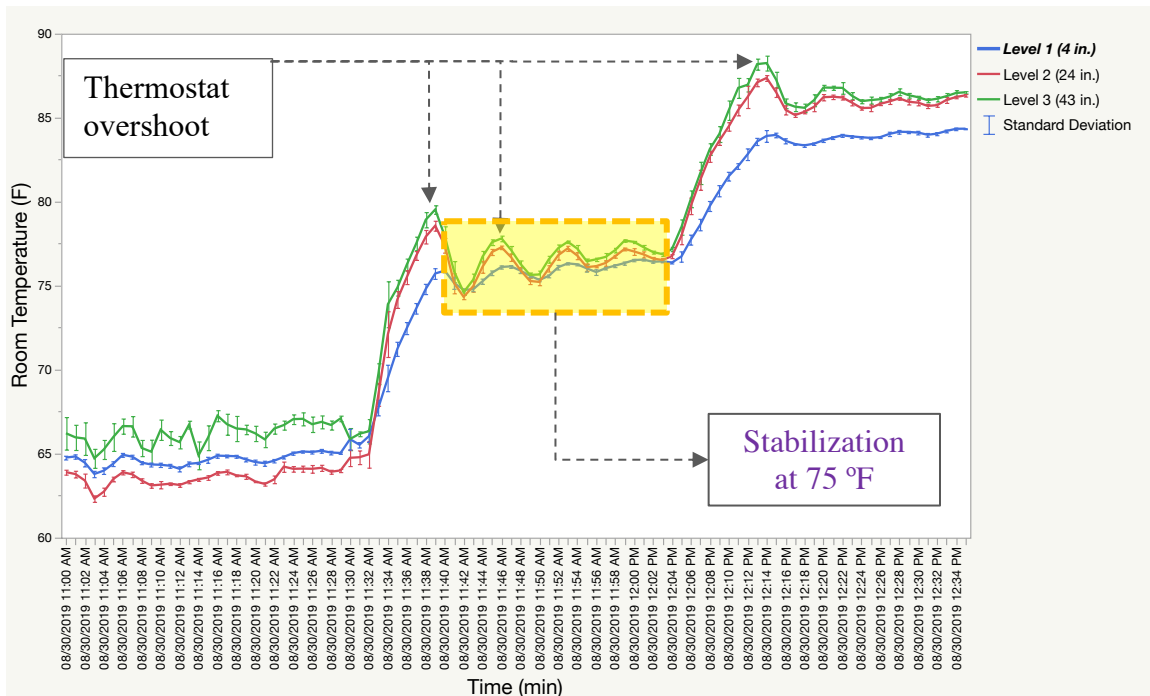


Figure 4.10 Indoor Temperature Trend in Heating Exposure

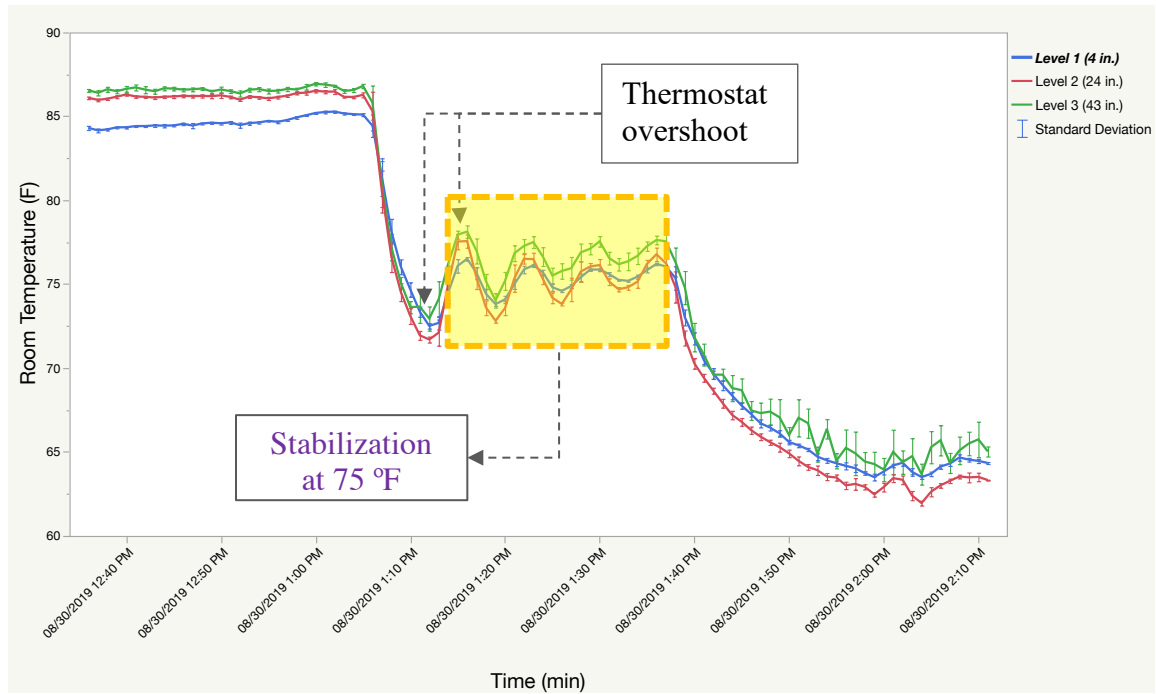


Figure 4.11 Indoor temperature trend in cooling exposure

For instance, if the current temperature is 65 °F and the chamber is then set to reach 75 °F, the chamber temperature would overshoot to ~80 °F first, and then drop down to ~72 °F, and again to ~78 °F again. After that, the fluctuations gradually decrease (Figure 4.10). A similar process takes place for the cooling exposure (Figure 4.11). The error bars (Standard Deviation) shown on the charts are graphically representing the variability of the data. The range of the data which was covered for assessing the precision of the facility in each zone (*i.e.*, 65°F, 75°F, 85°F) was about ~20 min after the end of the largest (first) thermostat overshoot that included several smaller thermostat overshoots (see the yellow box in Figure 4.10 and 4.11). In fact, this range of the data refers to when the indoor temperature was stabilized around the target temperature. For instance, in the dataset shown in Figure 4.10, the assessments for testing the precision of the chamber when reaching 75°F during a heating exposure was performed on the data from 08/30/2019 11:46 AM through 08/30/2019 12:04 PM. The stabilization process at 75°F was more tedious in both heating and cooling exposures as this zone involved with more fluctuations.

Therefore, testing the precision and the reliability of the facility in generating stable data was merely performed in this zone. The descriptive statistics and the Cumulative Distribution Function (CDF) plot of this assessment are respectively shown in Figure 4.12 and Table 4.3. The CDF plot shows the distribution of the sample among the values of the measured variable (chamber temperature). For the heating exposures the major proportion of this data ranges between 73.5°F and 75.5°F. And, as discussed before, small variation in the ambient temperature (<3°F) is considered undetectable by humans.

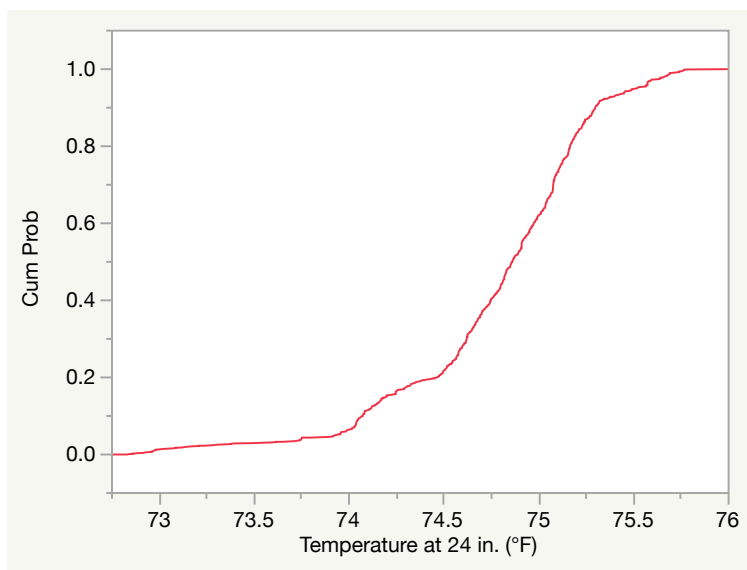


Figure 4.12 Chamber Temperature (n=1) Stabilizing at 75 °F (Heating Exposure)

Table 4.3 Chamber Temperature Data Stabilizing at 75 °F (Heating Exposure)

Mean	74.77
Std Dev	0.52
Std Err Mean	0.01
Upper 95% Mean	74.80
Lower 95% Mean	74.74
N	1186

This process was repeated several times (n=10) for both heating and cooling exposures to ensure the reliability of the above result. The mean value of the indoor temperature in each of the 10 experiments was examined during the stabilization process at 75°F. As the CDF plots (Figures

4.13 and 4.14) illustrate, there was no more that $\sim 2^{\circ}\text{F}$ (heating) and $\sim 3^{\circ}\text{F}$ (cooling) variation within that scope of the data.

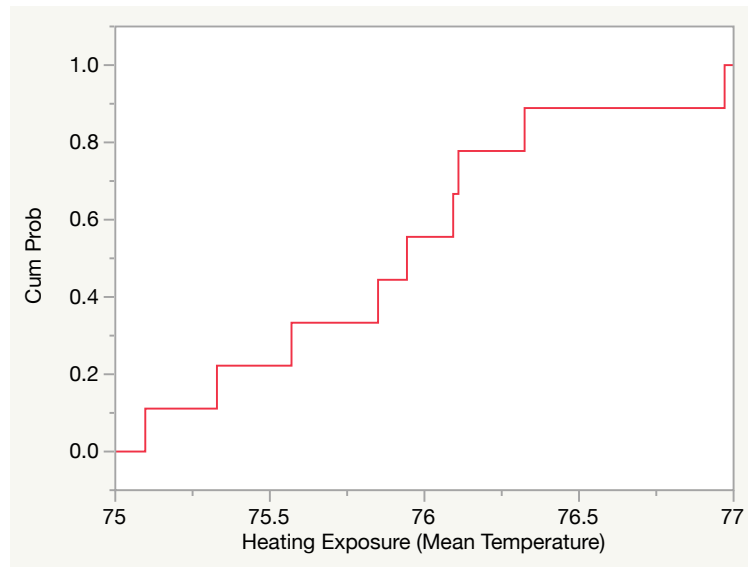


Figure 4.13 Chamber Temperature (n=10) Stabilizing at 75 °F (heating exposure)

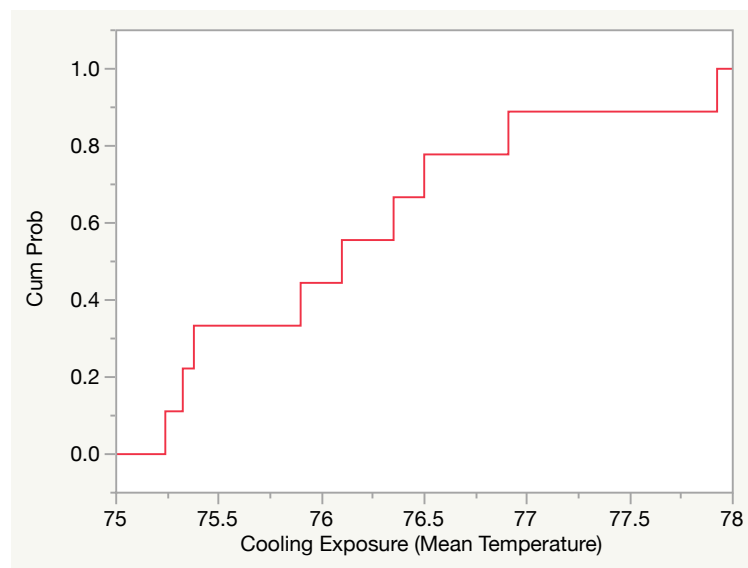


Figure 4.14 Chamber Temperature (n=10) Stabilizing at 75 °F (cooling exposure)

The control system of the chamber was also equipped with a humidifier and a dehumidifier to control the indoor relative humidity throughout the experiments. Relative humidity is the ratio between the actual water vapor present in the air to the maximum amount of

water vapor needed for saturation at a given temperature, it was continuously measured and ensured to be ~50% RH.

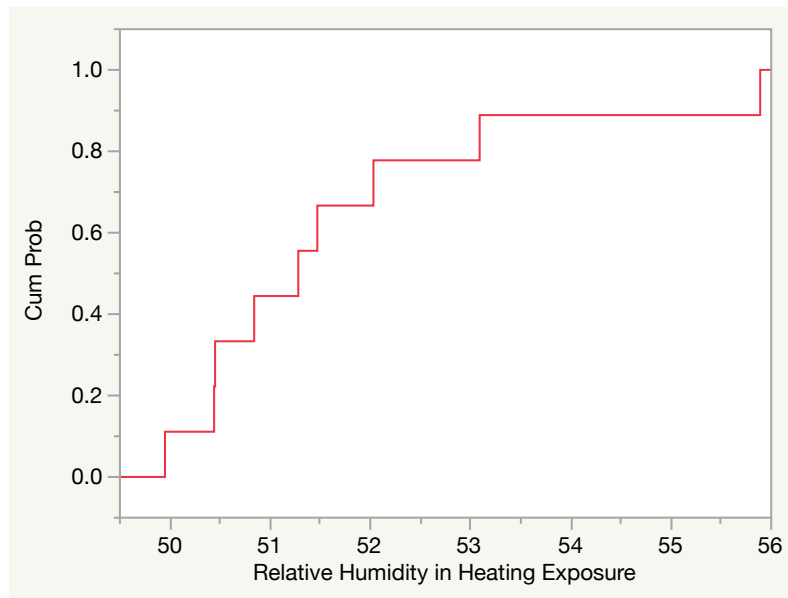


Figure 4.15 Chamber Relative Humidity in Heating Exposure (n=10)

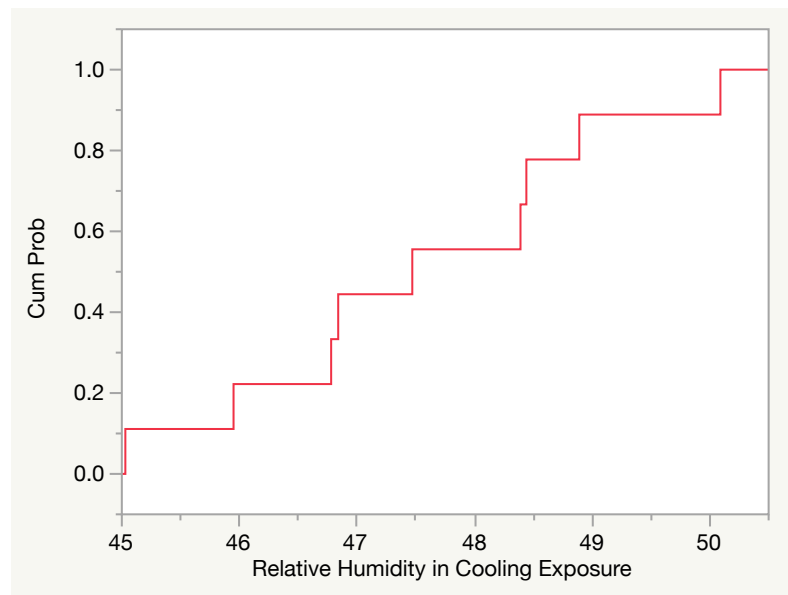


Figure 4.16 Chamber Relative Humidity in Cooling Exposure (n=10)

Similar to testing the temperature precision, this process was repeated 10 times for both the heating and cooling exposures to ensure that this variable was not so far from the expected

range. Figures 4.15 and 4.16 illustrate the CDF plot of the relative humidity of the indoor environment of the chamber during the experimental sessions. It shows that this measurement was between ~50-56 RH% in the cooling and ~45-50 RH% in the heating sessions.

4.4.3 Indoor Air Velocity

Another important environmental condition to control is the indoor air velocity which is described as the rate of the air movement across the occupant. This measure has an important contribution to the (convective) heat transfer from the body and is required to be kept still throughout the data collection. In thermal comfort studies, the air speed should not be greater than 0.20 m/s (40 ft/min) and the measuring period for determining the average air speed at any location shall be three minutes (ASHRAE 55-2010). This study used ABM-200 Airflow & Environmental Meter to ensure the stillness of the air during the experiment. The tool covers the readings of 42 – 12,320 ft/min with the accuracy of $\pm 0.5\%$ (Figure 4.17).



Figure 4.17 ABM-200 Airflow & Environmental Meter

4.4.4 CO₂

The content of carbon dioxide in the indoor air are one of the significant indicators of air quality in a closed space. A wireless carbon dioxide sensor was installed on the ceiling of the chamber to measure the amount of CO₂ in ambient air surrounding the participant. The National Institute for Occupational Safety and Health (NIOSH) considers indoor air concentrations of carbon dioxide exceeding 1,000 ppm as poor air quality air. The control system of the climate

chamber was set to alarm if indoor CO₂ level reaches 700 ppm, and in that case the system purge would automatically run to bring fresh air in and clean the indoor air.

4.4.5 Outdoor Air Temperature and Relative Humidity

In this study, online datasets were the main source of recording outdoor weather information. The most commonly used databases for this purpose include NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) of the NOAA-CIRES Climate Diagnostic Center or NCDC's ISHD (Integrated Surface Hourly Database).

4.5 Other Research Instruments

4.5.1 IVE Apparatus

The climate chamber interior was the experiment environment throughout the study both for the *in-situ* and the IVE experiments. IVE sessions involve wearing a head mounted display (HMD) and seeing a real-time 3D version of the interior of the chamber through the HMD (Figure 4.18). The 3D model of the chamber was created and rendered in 3D Studio Max. The final model, along with the texture and light maps, were then exported into the Unreal Engine for the required programming of necessary auditory and visual cues (Figure 4.19).



<https://www.vive.com/us/product/vive/>

Figure 4.18 Vive-HTC HMD

HMD is a display device or a goggle, worn on the head of a participant, that has a small display optic in front of each eye (a binocular HMD). It is used to project computer generated scenes and intends to provide the maximum approximation of the reality. The HMD that is used in this study is the HTC-Vive, which supports a 2,160 x 1,200 resolution on a dual-AMOLED 3.6” panels with 90Hz refresh rate and a 110-degree field of view. This HMD works with a “room scale” tracking system that offers 360-degree head-tracking, and the two motion-tracked handled controllers allow users to interact with the virtual objects in the 3D environment. The only interacting virtual components in this study were the questionnaire boxes that would pop-up with a click meant for the purpose of the data collection.



Figure 4.19 IVE Experimental Setting View

4.5.2 Physiological Monitoring

4.5.2.1 Heart Rate

In this study a wireless electrode-base heart rate monitoring tool, namely, POLAR Ft7 (Figure 4.20) was used to measure the Heart Rate (HR) of participants. The sensor data was read and recorded through an application called HRV Logger. The time between the beats was calculated in milliseconds (ms), which is called an “R-R interval”. Heart Rate Variability (HRV) was analyzed through this measure. HRV is an important objective variable in this study, because it is deeply connected to the individuals’ nervous system, which controls and responds to many important body processes.



Figure 4.20 Heart Rate Sensor

4.5.2.2 Skin Temperature

The Vernier Surface Temperature Sensors were used in this study to provide the measurement of skin surface temperature (Figure 4.7). The real-time data was recorded and logged through a stand-alone software, namely Logger Pro. This was the same sensor, which was used for measuring the indoor temperature (see section 4.4.2).

4.5.2.3 Galvanic Skin Response

This study used the Qubit GSR sensor to measure the psycho-galvanic reflex of the body (Figure 4.21). This reflex generates a change in skin resistance during the time of stress, excitement, or shock, and is used as a measure of sympathetic nervous system (SNS) activity. This sensor monitors the conductivity of the skin between two disposable tab electrodes that are placed on two adjacent fingers of one hand. This sensor can monitor both rapid and slow changes

in skin conductivity, making it ideal for studies involving shock, arousal, and biofeedback.

Accuracy of the tool is 0.5% of full-scale range. The unit of this measure is μS (microsiemens)

and this study used low range (0–5 μS) of its resolution.



Figure 4.21 Galvanic Skin Response Sensors

4.5.2.4 Body Sensor Deployment

Figure 4.22 demonstrates the body sensor deployment for measuring the physiological responses during the experiments.

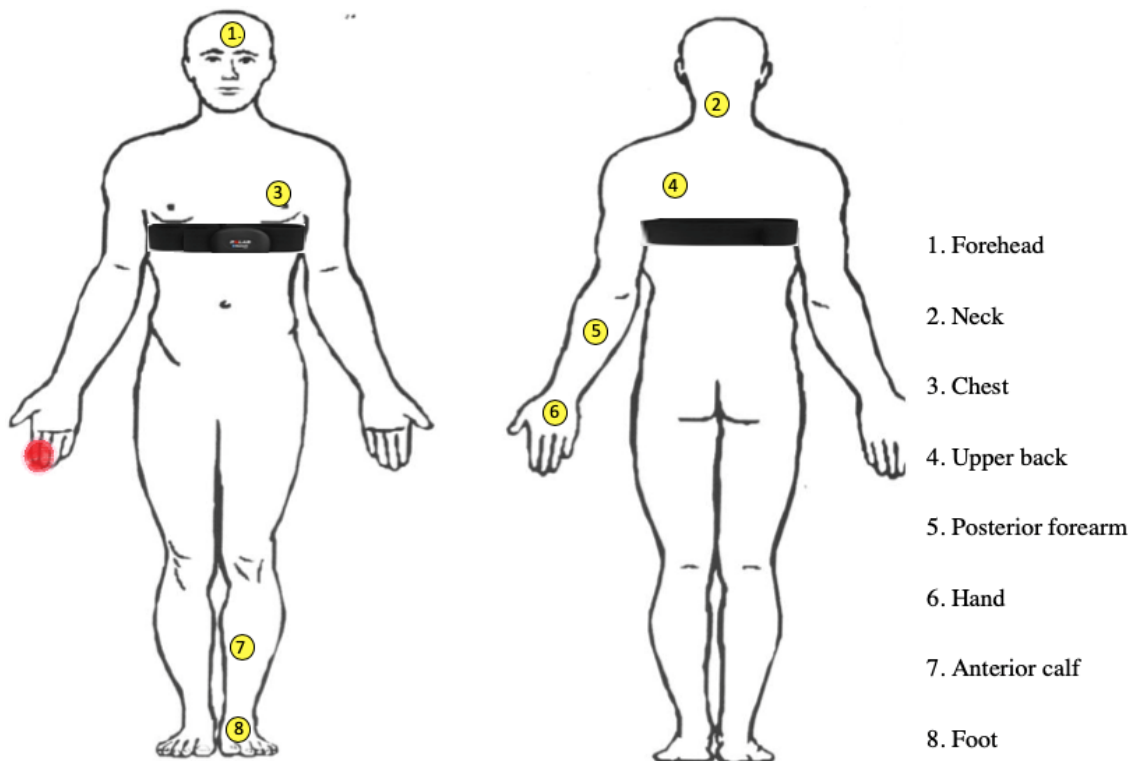


Figure 4.22 Body Sensor Deployment

The yellow circles show the body locations from which the skin temperature and thermoceptions were sampled, and the red circle shows the GSR sampling spots— the tip of index and middle fingers. The black strap on the chest holds the HR monitoring sensor.

This skin temperature measurement locations on the body of the participants were selected based on the sensitivity of the body parts and the weighting factors of the mean skin temperature equations (Liu et al. 2014; Matsumoto et al. 1999; Xiong et al. 2016). This study used a chest strap HR monitor since its accuracy has already been confirmed in several studies (El-Amrawy and Nounou 2015; Laukkanen and Virtanen 1998), while the accuracy of wrist-worn, optically based HR monitors is less certain, at the time of writing this dissertation.

4.5.3 Psychological Monitoring

In this study, several different questionnaires were used and each of them was adopted for a specific purpose. All the questionnaires were created in an online software platform, namely Qualtrics. The use of the online survey tool helped to speed up the data collection and data entry process. Furthermore, the timeline of the recorded questionnaires was used as a benchmark to synchronize with other recorded data (*i.e.*, physiological).

4.5.3.1 Background Information

This questionnaire was administered only on the first visit. It consisted of the following information: socio-demographic characteristics (*i.e.*, age, gender, place of origin, birth and last 5 years living place, education, and occupation, prior knowledge and experience of using virtual reality. The information taken from this questionnaire would be useful to develop possible interpretations of some of the findings of the study.

4.5.3.2 Immersive Tendencies Questionnaire (ITQ)

The ITQ questions were embedded within the background information inquiry. The information obtained from this questionnaire was used as a covariate to the dependent variable of the study. This questionnaire was used to measure the impact of the individuals' differences in their tendencies to experience presence (Appendix A).

4.5.3.3 Theory of Planned Behavior (TPB)

In order to understand participants' intention to take a specific action, the study applied a TPB inquiry in the pre-experiment phase of the data collection. This instrument measured 1) participants' behavioral beliefs and attitude, 2) perceived social pressure or subjective norm, and 3) presence of factors that may facilitate or impede performance of the behavior (TPB; Ajzen, 1988). Theoretically, "the more favorable the attitude and subjective norm, and the greater the perceived control, the stronger should be the person's intention to perform the behavior in question (Ajzen, 1988)." This study utilized a well-established TPB that had been used in the area of predicting pro-environmental behaviors (Macovei 2015) (Appendix B).

4.5.3.4 General Information

This questionnaire was designed to acquire some additional information that could have immediate impact on participants' thermal comfort states, including 1) body weight and height; 2) food intake within the past hour; 3) beverage intake within the past hour; 3) cigarette within the past hour; 4) alcohol intake within the past 12 hour; 5) intense physical activity within the past 12 hours; 6) departure location (off-campus, on-campus, in building); 7) mode of travel (walking, cycling, motorized means); 8) menstrual cycle; and 9) clothing. This questionnaire was applied before all the sessions and the information from that was used as control variable.

4.5.3.5 ASHRAE Standard 55 Thermal Comfort

In this study, participants' votes on their thermal states was measured using the descriptive (7-point Likert) scales of ASHRAE Standard 55 Thermal Comfort (ASHRAE 2013; de Dear and Brager 2002). The questionnaire included the overall body Thermal Sensation (Table 4.4), Thermal Comfort, and Thermal Acceptability (Table 4.5). Also, since the thermal judgments about the overall body could be biased, various local body sites (n=8; see Figure 4.22) which were used for physiological monitoring, were also used as sampling areas for the subjective thermal comfort inquiries.

Table 4.4 ASHRAE Thermal Sensation Scale

Value	Thermal Sensation
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

Table 4.5 ASHRAE Thermal Acceptability and Comfort Scale

Value	Thermal Acceptability	Thermal Comfort
+3	Perfectly Acceptable	Very Comfortable
+2	Acceptable	Comfortable
+1	Slightly Acceptable	Slightly Comfortable
-1	Slightly Unacceptable	Slightly Uncomfortable
-2	Unacceptable	Uncomfortable
-3	Totally Unacceptable	Very Uncomfortable

4.5.3.6 Adaptive Behavior

This questionnaire was designed and used to discover participants' thermally-driven behavioral intentions at the end of the experiment when the temperature was beyond normal individuals' thermal comfort zone (65 °F and 85 °F; 50% RH). Several choices were presented to

allow participants select their most preferred approaches to restore their thermal comfort. The choices were as follows: adjust clothing; change posture; change activity; eat hot/cold foods; drink hot/cold beverages; move to a different location; open/close windows; open/close windows blinds; use handheld fan; turn on/off fans or heating; blocking air diffusers; operating other HVAC controls. It was also possible that the participant may offer any other adaptive behavior he/she would consider. It was always mentioned that there was not any sort of constraints at the time of selecting the behavioral choices. Constraints included economic factors, social customs (*e.g.*, a dress code), occupation (*e.g.*, inability to change the location), and/or design related constraints (*e.g.*, accessibility to the control system, thermostat, and switches, etc.).

4.5.3.7 Igroup Presence Questionnaire (IPQ)

The IPQ questionnaire, one of the many different presence questionnaires, was used (Schubert, Friedmann & Regenbrecht, 1999). This data was collected after all IVE sessions, and participants were asked to answer these questions based on the quality of their experience within the IVE. The information gained from this questionnaire was used as covariates to the response variables of the study (Appendix C).

4.5.3.8 Simulator Sickness Questionnaire

This study applied SSQ which was developed by Kennedy and his colleagues in 1993 (Kennedy et al., 1993) as a post-experimental follow-up that help to gain insight about the possible side-effects that the IVE interventions would pose on the participants during or after the experiments. The information gained from this questionnaire was also used as covariates to the response variables of the study (Appendix D).

4.6 Methods

4.6.1 Experiment Design

To test the hypotheses, experiments were designed to assess the capability of a multi-sensory IVE in replicating building occupants' naturalistic thermoceptions and thermally-driven behavioral intentions. The major manipulations of the experiments included the experimental platforms (IVE vs. *in-situ*), the type of the thermal stimuli exposure (heating vs. cooling), and the outdoor temperature impact—period 1 (colder) vs. period 2 (warmer). The experiments were primarily laid out to find whether any of the independent variables of the study produces significant effect on individual responses (*i.e.*, thermoceptions and thermally-driven behavioral intentions). Moreover, the other constructs of this research were incorporated in the study to enable describing how they were related to each other and what was the nature of their relationships. The experiments were essentially designed to confirm or reject the research hypotheses listed in section 4.3 (Hypothesis testing). Figure 4.23 demonstrates the experimental sessions, the type of data to be collected, and the estimated timelines for each steps of the experiments. The period 1 (colder) data of this study refers to the data, which was collected from December 2018 through the first week of February 2019, and the data, which was collected in April and May and June 2019 was considered period 2 (warmer) data.

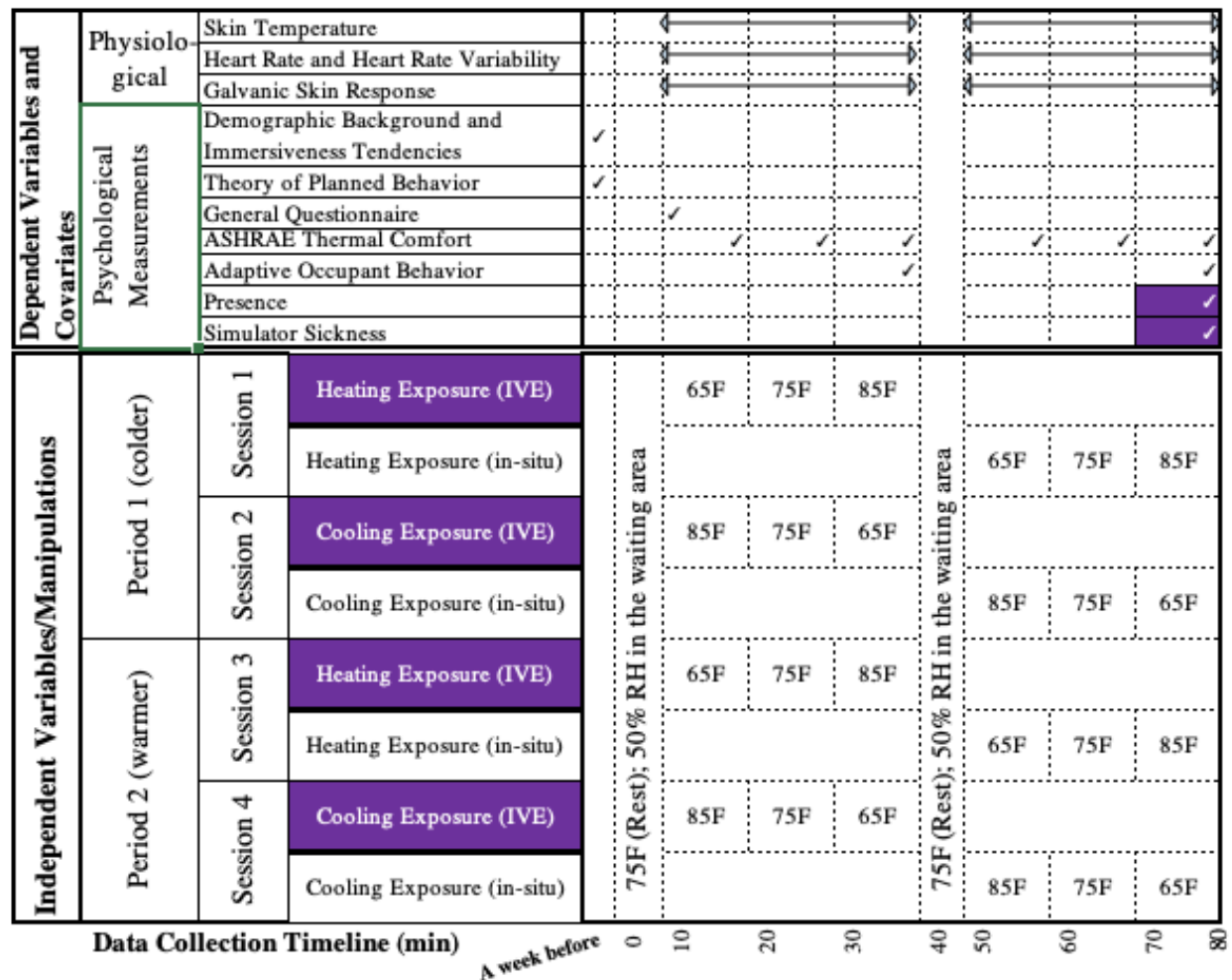


Figure 4.23 Experiment and Data Collection Procedure

4.6.2 Participant and Procedure

Word of mouth and the use of flyers on LSU campus were chosen for recruiting participants. The total number of 30 undergraduate and graduate students, and also a few staff members partook in this research. 28 of them finished all the experimental sessions (4 sessions). Upon meeting the inclusion criteria, the consent form was given to the experiment volunteer. This document described the experiment purpose, procedure, benefits compensation, etc., so that participants had a clear picture about the whole study and procedure in order to decide accordingly. This phase of the study was completed electronically. Besides, the pre-experiment

questionnaires (*i.e.*, demographic characteristics, prior knowledge and experience of using VR, immersive tendencies and theory of planned behavior questionnaires) were sent and administered to the participants via a web-based system one week before the experiment. Once the participant agreed to sign the written consent form, the first session was scheduled.

Participants were asked to avoid strong caffeine, alcohol, smoking, and intense physical activity at least 12 hr. prior to each of the experimental sessions. Otherwise, they were excluded in the pre-experiment screening. At the beginning of each session, their height and weight were recorded for further investigations on the impact of BMI and the changes it had on the response variables of the study. Participants were instructed to come to the lab with predefined set of clothing in all the sessions; shoes, socks, underwear, light pants, and a light long-sleeved shirt/T-shirt. The aforementioned clothing insulation (0.5-0.6 clo) was considered as the standard clothing insulation in some studies of office buildings (de Dear and Fountain 1994; Schiller et al. 1988). There was always an ~20 minutes resting period in the observation area, after a participant arrived at the lab. This ensures that the participant is acclimatized to the indoor condition. Afterwards, they were asked to get into the chamber and sit down on a chair so that the experimenters could start attaching the sensors (*i.e.*, HR, T_{sk} , GSR) to their body. As discussed in before, the surface skin temperature sensors were directly taped on the skin, the heart rate monitoring sensor was attached to the chest, and the GSR sensor was attached to the tip of the index and middle finger for sampling data. The study used 8 body sites for sampling, since inquiries into the overall thermal comfort were mainly based on the participants' subjective judgement and perception, which was affected by participants' temporal emotional function.

Participants' tasks in this study was limited to sedentary or near sedentary physical activity levels—seated at rest, while the study examined a heating exposure (*i.e.*, from 65°F to

85°F) and a cooling exposure (*i.e.*, 85°F to 65°F), each two times for different conditions. In particular, the heating exposure test used a heating sequence with three heating steps from 65°F to 75°F and to 85°F; and the cooling exposure test used a cooling sequence with three cooling steps from 85°F to 75°F to 65°F (every session would test either the heating or the cooling exposure, however, it included both the *in-situ* and the IVE). After each temperature step change, the experimenter waits for ~5 min, so the air movement becomes still and the indoor temperature reaches the steady, so participants responses would be proper representative of the new temperature.

Each of the heating and cooling exposures were performed in two experimental conditions— *in-situ* and IVE, that is, 1) heating exposure in *in-situ*, 2) heating exposure in IVE, 3) cooling exposure in *in-situ*, 4) cooling exposure in IVE. Participants were assigned to each of the experimental sessions and sub-sessions in a random fashion to counterbalance and minimize the order effect. Half of the participants performed the heating sequence first, then cooling, while the other half did the cooling sequence first, then heating. Likewise, half of the participants completed the *in-situ* trial first, while the other half experienced the IVE for their first trial. Furthermore, since this study was concerned about the impact of the seasonal mismatch on the response variables of the study, the abovementioned sessions were repeated in a warmer outdoor condition (*i.e.*, April, May and June 2019).

All the physiological measurements were set to be collected continuously and be recorded at one second intervals. While the psychological votes on thermal comfort (*i.e.*, thermal sensation, thermal comfort, and thermal acceptability) were recorded only three times, at 65 °F, 75 °F, and 85 °F. The experimenter would read the questions and save the participants' responses over the online web-based questionnaire on an iPad.

As mentioned before, every session included two sub-sessions of *in-situ* and IVE (Figure 4.24 and 4.25), which included a ~10-15 min break in between. The sensors were detached from the participants' body after each of the sub-sessions, so participants could move outside the room, rest, and most importantly acclimatized to the comfort temperature (75 °F) of the observation area. In the meantime, the climate chamber temperature was set back to its starting state (65 °F for heating exposure and 85 °F for a cooling exposure) so it could be ready for the second sub-session. The duration in which the chamber temperature changed from one end to the other end, was about 30 minutes. The indoor relative humidity was maintained at about 50%, and the CO₂ level was controlled to be below 1000 ppm. With the assumption that the first sub-session was conducted in the *in-situ* condition, the second was in IVE, where participants were exposed to the virtual reality model of the chamber through the HMD. The same procedure for data collection was then repeated, and the only difference was the existence of the HMD on participant's face. Before each IVE trial, there was ~7-8 min familiarization step to calm down participants' excitement and possible anxiety, since literature has showed that participants could be excited once they were first exposed to the IVE scenes. This excitement can impact both their physiological and psychological responses (Jang et al. 2002; Wiederhold et al. 2002). Jang et al. (2002) revealed that after 7~8 min habituation, the physiological states return to the baseline.

At the end of every sub-session, participants were given a follow-up questionnaire in which several adaptive choices were offered so they could report how to overcome the produced possible discomfort. They were asked to pick their three most preferred choices to regain their thermal comfort. Besides, the IVE trial had an additional post-experiment questionnaire, measuring participants' sense of presence and the cybersickness while they were in the IVE.



Figure 4.24 *in-situ* Experimental Session



Figure 4.25 IVE Experimental Session

4.7 Data

4.7.1 Data Processing

The study collected data through the discussed experiments. To fully understand and interact with the data, it was necessary to organize it in a proper format beforehand. All the raw data was stored, structured, and manipulated in electronic spreadsheets, using Microsoft Excel. Since every piece of the data (*e.g.*, HR, HRV, T_{sk} , questionnaire data) was collected using a different sensor/platform, it was necessary to synchronize their time stamps. All the sensors were set to continuously measure and record data in one-second intervals; they were then averaged at different zones, *i.e.*, zone 1, 2, and 3 as shown in Figure 4.26. The exact starting time of each zone was defined when the indoor temperature was stabilized at the target temperature, while the ending of it was traced through the time of the recorded thermoception questionnaire. For instance, in a heating exposure session, the beginning of the experiment was when the indoor temperature was stabilized at 65 °F, in the case of thermostat overshoots, the stabilizing process would normally be longer, taking up to ~15 min. After stabilization process, participants were exposed to that temperature condition for ~5-7 min, and then the thermoception questionnaires was administered. Once the questions were responded, the indoor temperature set-point was then increased to the next step (75 °F). Similarly, if the system had overshoots, the experimenter would wait for the temperature to be stabilized and acclimatized the participant to the new temperature and then inquire about the thermoceptions. Figure 4.26 illustrates the data classification boundaries based on three different stabilized indoor temperature.

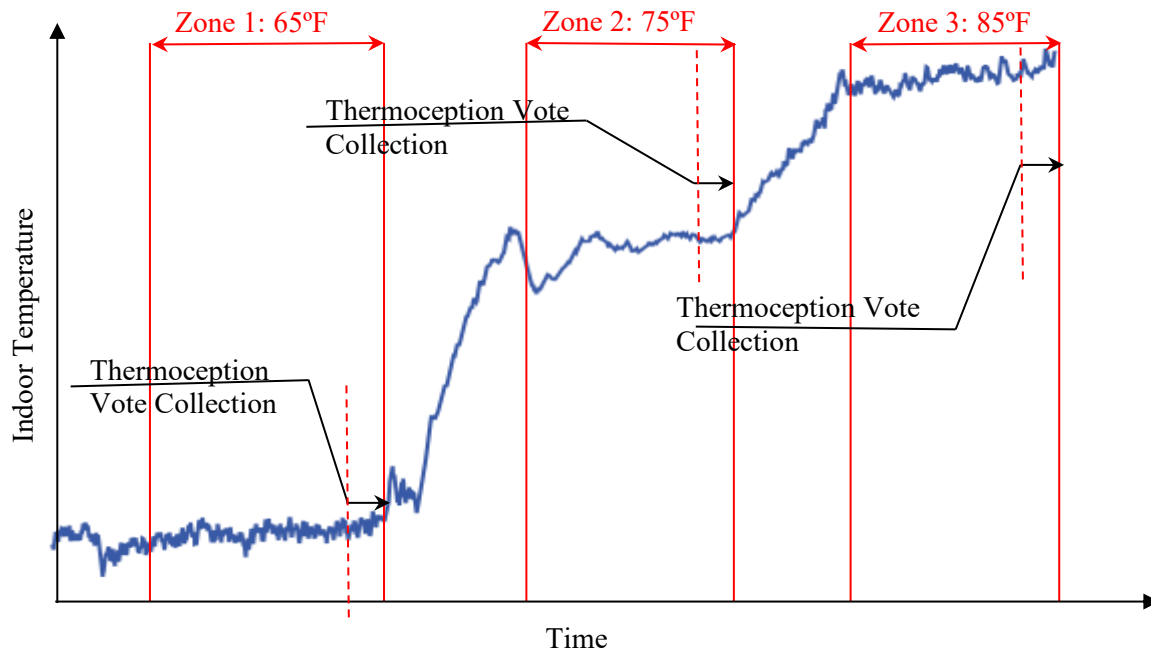


Figure 4.26 Data Collection Schematic Timeline

4.7.2 Data Cleaning

This step involved excluding the extreme values of the data, or the outliers. In particular, the actual indoor temperature was compared with the target temperature to ensure they were not significantly different. This process was critical to ensure that participants' thermoception votes and the physiological responses were accurate reflection of the aimed experimental condition. Since the air temperature often had a slight difference/fluctuation than the target indoor temperature, an acceptable range that could closely represent the target indoor temperature without compromising the accuracy of the responses was needed. In fact, the way that individuals detect the changes of their surrounding temperature, depends on factors, most of all, the rate of the temperature change. That is to say, if it changes at a rate of less than 0.5 °C (0.9 °F) per min, then a person can be unaware of a 4-5 °C (7.2-9 °F) temperature increment (Darian-Smith and Johnson 1977). In the climate chamber used in this study, changing 1°F temperature (anywhere between 65 °F -85 °F) often takes 1 min. With this rate, this study finds it safe to

assume that the participants had not been aware of at least ± 3 °F in ~10 min (10 min is the approximate duration to rise/drop 10 °F). Given that, the data points, which were ± 3 °F far from the target temperature, were removed from the analyses. Moreover, it is necessary to make sure that the average temperature in each pair of the experimental sessions (*e.g.*, period 1/cooling/zone 1 in-situ vs. period 1/cooling/zone 1 in IVE) was not significantly different from each other, defined herein as pairwise comparisons. This process was crucial to make sure that the experimental settings for performing pairwise comparisons are comparable and have ecological validity. Table 4.6 presents descriptive analysis of the indoor temperature in all of the pairs of experiments. Paired t-tests were performed to find statistical evidence for the comparability of the indoor temperature between the IVE and *in-situ* pairs— to determine whether the mean differences between the pairs were zero. Results of the tests revealed that except for the winter/cooling 65°F ($p < .0001$), the indoor temperature of all other sets of experiment were not statistically different ($p > 0.05$).

Table 4.6 Indoor temperature in All of the Pairs of the Experiment

Experimental Manipulators		Target Temperature	Actual indoor temperature in in-situ			Actual indoor temperature in IVE			DF	t	P-value
			N	Mean	St. Dev.	N	Mean	St. Dev.			
Period 2 (warmer)	Cooling	75	26	76.98	0.85	26	76.76	1.13	46.49	-0.77	0.44
		85	26	85.84	0.91	26	86.07	1.17	47.01	0.78	0.44
	Heating	65	25	66.03	1.13	25	66.09	1.54	44	0.18	0.86
		75	26	73.54	1.88	26	73.9	1.83	49.96	0.69	0.49
		85	26	82.47	1.32	26	82.11	1.27	49.92	-0.98	0.33
Period 1 (colder)	Cooling	65	9	67.47	0.85	9	69.52	0.75	15.76	5.42	<.0001*
		75	23	76.36	1.32	24	76.66	0.99	40.67	0.87	0.39
		85	26	85.28	1.11	27	85.04	1.58	46.72	-0.64	0.52
	Heating	65	27	65.71	1.04	28	66.05	1.24	52.03	1.12	0.27
		75	27	73.44	1.97	28	73.31	1.45	47.66	-0.27	0.79
		85	27	82.86	1.85	27	82.93	1.61	51.03	0.15	0.88

Additionally, further data trimming was necessary to more precisely locate each data point into the two contrasting seasons of the study (period 1 and 2). As a matter of fact, the subtropical climate of Louisiana (Köppen et al. 2011) allows two clearly distinguishable and non-overlapping hot vs. cold seasons. The air temperature in Baton Rouge typically varies from 43°F to 91°F. The hottest periods generally run from mid-June to mid-September, while December, January till mid-February are on average the coldest months in any year (<https://weatherspark.com/y/11336/Average-Weather-in-Baton-Rouge-Louisiana-United-States-Year-Round>). So, the data which was collected during December, January, and February, was considered colder outside condition (period 1), and data collected in April, May, June accounted for the warmer outside condition (period 2). However, it was necessary to ensure that each participant's period 1 and period 2 datasets were collected in two actually varying seasonal conditions; the challenge for specifying the threshold of two contrasting seasons was that “how far is far enough to be considered contrasting?” Given the limitations related to the seasonal variations and the short spans of the cold weather season in Louisiana, the study's assumption for specifying the two contrasting seasons was temperature difference variation of at least 20°F. Therefore, if the difference between the outside temperature of two equivalent tests was less than 20°F, that data line would be removed from the dataset. Table 4.7 and Figure 4.27, respectively, demonstrate the distribution and the descriptive statistics of the outside temperature in the format of period 1 (colder) and period 2 (warmer) divided into two cooling and heating exposures.

Table 4.7 Outside Temperature during the Experimental Sessions

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Period2/cooling	104	84.67	5.59	0.54	83.58	85.76
Period2/heating	140	84.29	5.79	0.48	83.32	85.26
Period1/cooling	120	62.64	7.59	0.69	61.26	64.0
Period1/heating	147	60.53	7.45	0.61	59.31	61.74

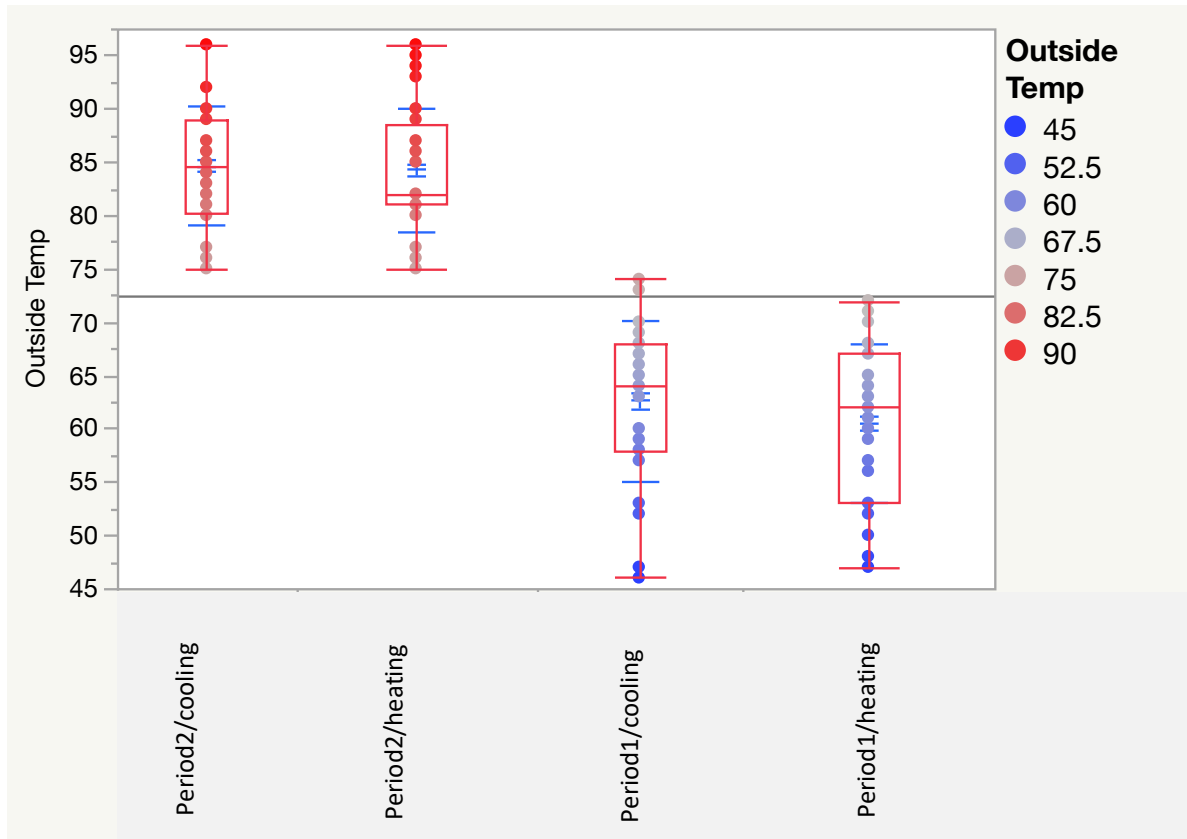


Figure 4.27 Outside Temperature during the Experimental Sessions

4.7.3 Data Organization

Once all the data was cleaned and trimmed, it was then structured and organized into a format that could be read and analyzed in Statistical Analysis Software 9.4 (SAS) and JMP 14. Table 4.8 represents one participant’s all experimental sub-sessions classified into order/season/experiment type/experimental setting. Order (1 or 2) indicates the order of the experimental setting. For instance, in “1/period1/cooling/in-situ” the first number 1 means that *in-situ* was the first sub-session in period 1/cooling experimental session—this is due to the fact that all *in-situ* and IVE sub-sessions were randomized between and within the participants and the experiment aimed at counting for the order effect, as well.

Table 4.8 Data Organization

#	Subject Code	Date	Order/Season/Experiment Type/Experimental Setting	Target Room Temperature	Outside Temp	Outside Humidity	Room Temperature (F)	Adaptive Behavior 1	Adaptive Behavior 2	Adaptive Behavior 3	# of the eco-friendly behaviors	Forehead Skin Temperature (F)	Neck Skin Temperature (F)
1	Anider	5/24/19 16:34	4/Period 2/Cooling/in-situ	75.00	81.00	60.00	75.76	Change post	Adjust clothi	Change activ	3.00	94.27	93.88
1	Anider	5/24/19 15:45	4/Period 2/Cooling/in-situ	85.00	81.00	60.00	83.48	Change post	Adjust clothi	Change activ	3.00	95.79	92.83
1	Anider	5/24/19 16:49	4/Period 2/Cooling/in-situ	65.00	92.00	42.00	65.46	Change post	Adjust clothi	Change activ	3.00	91.91	90.65
1	Anider	5/28/19 20:18	4/Period 2/Cooling/IVE	65.00	92.00	42.00	67.04	Blocking air c	Adjust clothi	Change post	2.00	98.01	94.42
1	Anider	5/28/19 20:06	4/Period 2/Cooling/IVE	75.00	92.00	42.00	74.92	Blocking air c	Adjust clothi	Change post	2.00	96.68	93.14
1	Anider	5/28/19 19:01	4/Period 2/Cooling/IVE	85.00	92.00	42.00	83.92	Blocking air c	Adjust clothi	Change post	2.00	96.35	93.43
1	Anider	4/24/19 17:19	3/Period 2/Heating/in-situ	65.00	81.00	60.00	64.08	Change post	No change re	No change re	1.00	92.86	93.74
1	Anider	4/24/19 17:29	3/Period 2/Heating/in-situ	75.00	81.00	60.00	70.42	Change post	No change re	No change re	1.00	93.04	93.39
1	Anider	4/24/19 17:39	3/Period 2/Heating/in-situ	85.00	81.00	60.00	80.70	Change post	No change re	No change re	1.00	95.39	93.63
1	Anider	4/24/19 16:36	3/Period 2/Heating/IVE	65.00	81.00	60.00	64.05	Change post	No change re	No change re	1.00	94.86	95.78
1	Anider	4/24/19 16:44	3/Period 2/Heating/IVE	75.00	81.00	60.00	70.23	Change post	No change re	No change re	1.00	96.20	96.06
1	Anider	4/24/19 16:53	3/Period 2/Heating/IVE	85.00	81.00	60.00	80.61	Change post	No change re	No change re	1.00	97.68	96.81
1	Anider	2/22/19 15:55	1/Period 1/Cooling/in-situ	65.00	81.00	69.00	67.73	Operating ot	Blocking air c	Turn on/off f	0.00	90.74	92.12
1	Anider	2/22/19 15:40	1/Period 1/Cooling/in-situ	75.00	81.00	69.00	76.88	Operating ot	Blocking air c	Turn on/off f	0.00	92.78	92.35
1	Anider	2/22/19 15:33	1/Period 1/Cooling/in-situ	85.00	81.00	69.00	84.20	Operating ot	Blocking air c	Turn on/off f	0.00	93.94	92.70
1	Anider	2/22/19 16:37	2/Period 1/Cooling/IVE	65.00	81.00	69.00	69.58	Operating ot	Turn on/off f	Blocking air c	0.00	98.50	94.30
1	Anider	2/22/19 16:25	2/Period 1/Cooling/IVE	75.00	81.00	69.00	76.56	Operating ot	Turn on/off f	Blocking air c	0.00	98.32	94.75
1	Anider	2/22/19 16:20	2/Period 1/Cooling/IVE	85.00	81.00	69.00	84.80	Operating ot	Turn on/off f	Blocking air c	0.00	95.79	94.09
1	Anider	2/1/19 16:16	2/Period 1/Heating/in-situ	65.00	64.00	90.00	66.96	Change post	Adjust clothi	Change activ	3.00	91.86	95.50
1	Anider	2/1/19 16:26	2/Period 1/Heating/in-situ	75.00	64.00	90.00	74.45	Change post	Adjust clothi	Change activ	3.00	93.46	95.53
1	Anider	2/1/19 16:34	2/Period 1/Heating/in-situ	85.00	64.00	90.00	80.62	Change post	Adjust clothi	Change activ	3.00	94.55	95.62
1	Anider	2/1/19 15:26	1/Period 1/Heating/IVE	65.00	64.00	90.00	65.47	Change post	Change activ	Move to a d	3.00	96.81	94.98
1	Anider	2/1/19 15:36	1/Period 1/Heating/IVE	75.00	64.00	90.00	70.09	Change post	Change activ	Move to a d	3.00	97.08	95.70
1	Anider	2/1/19 15:52	1/Period 1/Heating/IVE	85.00	64.00	90.00	77.12	Change post	Change activ	Move to a d	3.00		

All the thermoception and physiological measurements were investigated and compared across the corresponding pairs. The statistical test, which was applied to this part of the data was the Wilcoxon test for the categorical data (thermoception votes) and the paired-sample t-test for the continuous data (physiological measurements). The purpose of these tests was to figure out if the differences of the response variables across all the experimental settings (IVE vs. *in-situ*) were statistically significant or not. The results of the tests are presented in Appendix E and Appendix F. All the statistical analyses in this study were conducted at a level of 95% statistical significance.

4.7.3 Pre-experiment Questionnaire Results

4.7.3.1 Demographic and Background Information

This section presents the recorded demographic information of the participants in this study. The total number of the participants in this study was 28 (16 female and 12 male).

Participants were 32.14% (n=9) Caucasian American, 32.14% (n=9) Middle Eastern, 25% (n=7) Asian, 11% from other ethnicities, *i.e.*, Hispanic (n=2) and African American (n=1). The participants' age information is shown in Table 4.9.

Table 4.9 Participants' Age

N	Mean	Std Dev	Std Err Mean	Upper 95% Mean	Lower 95% Mean
28	26.6	6.34	1.198	29.06	24.14

The pre-experiment questionnaire also inquired about the participant's place of birth and the places where they have been living during the past five years. The results indicated that majority of the participants were born and have been recently living in warm climate locations.

Furthermore, the information related to the participants' highest education level and employment status were considered as a potential factor in thermally-driven behavioral intentions. The results are presented in Tables 4.10 and 4.11, respectively.

Table 4.10 Participants' *Highest Level of Education**

Level	Count	Prob
High school graduate	3	0.10
Some college	12	0.42
College graduate	6	0.21
Post graduate degree	7	0.25
Total	28	1.00

*Participants were asked to pick only one best option.

Table 4.11 Participants' Employment Status*

Level	Count	Prob
Employed full time (non-student)	7	0.25
Employed part time (<i>e.g.</i> , on campus or off campus part time job)	7	0.25
Unemployed (Student)	10	0.35
Unemployed looking for work	4	0.142
Total	28	1.00

*Participants were asked to pick only one best option.

Yet, due to the limited sample collected in this study, the levels of the above two variables did not have enough data that could allow the study draw solid conclusion about the pattern of the outcomes.

4.7.3.2 Immersive tendencies

The descriptive data related to participants' prior knowledge in computer and VR as well as their tendency to become immersed in virtual settings is given in Table 4.12. The variable prior knowledge in computer and VR was measured through inquiring the frequency of playing video-games, knowledge of 3D modeling creation and VR technology which (5-point scale, and 3 being as the intermediate level). On the other hand, immersive tendency measurements are broken down into four levels: focus, involvement, emotion, and entertainment (7-point scale). The responses were converted to percentage.

Table 4.12 Participants' Immersive Tendency

Statistics	Computer and VR knowledge	Immersive Tendency-Focus	Immersive Tendency-Involvement	Immersive Tendency-Emotion	Immersive Tendency-Entertainment
Mean	2.29	73.78	59.39	63.27	49.32
Std Dev	1.05	7.38	13.02	14.61	17.25
Std Err Mean	0.20	1.39	2.46	2.76	3.26
Upper 95% Mean	2.69	76.64	64.44	68.93	56.01
Lower 95% Mean	1.88	70.91	54.34	57.60	42.63
N	28	28	28	28	28

The individuals who participated in this study ranked lower than average in the frequency of playing video-games, knowledge of 3-D modeling creation and VR technology. However, the score of immersive tendency in this sample ranked average (tendency to entertain using media) and above average (ability to focus, get involved and excited in media).

4.7.3.3 Theory of Planned Behavior

The measurements about participants' pro-environmental behaviors are subdivided into behavioral attitudes, norms, control beliefs, intentions, awareness and the behavior. They are reported as in Table 4.13.

Table 4.13 Participants' Energy Saving Behavioral Values

Statistics	Attitudes about saving energy	Norms about saving energy	Controls about saving energy	Intentions about saving energy	Awareness about saving energy	Energy Saving Behaviors
Mean	92.86	75.95	76.07	81.43	85.00	51.57
Std Dev	9.27	15.00	12.12	13.25	13.47	13.52
Std Err Mean	1.75	2.83	2.29	2.50	2.55	2.56
Upper 95% Mean	96.45	81.77	80.77	86.57	90.22	56.82
Lower 95% Mean	89.26	70.14	71.37	76.29	79.78	46.33
N	28	28	28	28	28	28

The sample of this study reported to have high values for participants' attitudes, awareness, and intentions about saving energy. Their norms and control beliefs scored moderately high for performing energy saving behavior, while their actual pro-environmental behaviors ranked just average. This information would be useful to set a baseline for the experiment behavioral intention outcomes, also to figure to what extent IVEs could evoke participants realistic behaviors.

4.7.3.4 General Information

The general information which was likely to influence participants' thermal comfort states was used as a control factor and was qualitatively analyzed after the hypothesis testing. 1) The information related to the measurements of the body weight and height were obtained based on the participants' self-reports, and no significant difference was observed throughout the end of the data collection; 2) in order to limit the bias on the metabolic process across different sessions, participants were asked to schedule all of their experiments for some time either before or after a meal, so the conditions would not be as different, and the same rule applied to beverage and

cigarette consumption; 3) it was also requested not to do the experiment in the case of alcohol consumption and intense physical activity within the past 12 hours; 4) departure location (off-campus, on-campus, in building) and the mode of travel (walking, cycling, motorized means) was always asked and noted; 5) it was originally decided to make sure that the clothing thermal insulation is maintained consistent across different sessions of the experiments, so, they were asked to wear the same clothing each time they would report to the lab. Except one participant, the rest showed up for the experiments as requested— light long-sleeved athletic shirt and pants. Only one participant performed the experiments with short sleeve shirt and pants; 6) in order to avoid the variations that could happen due to the menstrual cycle in female participants, they were told not to participate during their periods.

4.7.4 Inferential Statistics (Hypothesis Testing)

The collected data was also analyzed through various statistical methods, including paired-sample t-tests, multivariate analysis, regression models, and a mixed effect model to gain useful insight about the applied IVE interventions and to be able to support/reject the hypothesis. The process and the results of the data analysis for each hypothesis testing are described below.

4.7.4.1 Hypothesis 1

H1: There is a similar pattern between temperature and thermal comfort in IVE and *in-situ* (thermal comfort in IVE is not statistically different from thermal comfort in in-situ).

This hypothesis assumes that the changes in indoor temperature have similar impact on participants' perception of the thermal environment, whether the IVE is involved or not. In other words, it is intended to find evidence that confirms the idea that IVE interventions do not alter individuals' thermoceptions. The hypothesis was examined from within-individual (paired-wise) variation perspectives, but in two different methods.

H1-a) indoor temperature variation at different thermoceptions levels (-2, ..., 2)

This hypothesis tested the indoor temperature variation at different thermal sensation level in IVE and *in-situ* experimental settings. In other words, it assessed whether the mean indoor temperature at certain reported thermal sensation (*e.g.*, -1) in *in-situ* was significantly different from the mean indoor temperature at its corresponding thermal sensation (*e.g.*, -1) in IVE. In fact, the indoor temperature was treated as a response (dependent) variable and the t-test analysis determined how its distribution differs across the levels of the variables: thermal sensation, thermal acceptability, and thermal comfort (Figure 4.28, Figure 4.29, and Figure 4.30). The Figures demonstrate the distribution of the indoor temperature across the levels of the thermoception variable separated by experiment type, and experimental setting. The pairs which are significantly different from each other are highlighted in yellow, and, the proceeding tables present detailed information on the statistical tests along with the results of the significance test (p-value). Paired t-test was used to determine whether the difference (measured in averages) between the two sets of indoor temperature at each level of thermoception is zero. In other words, the test declares if the differences between each pair are random or not.

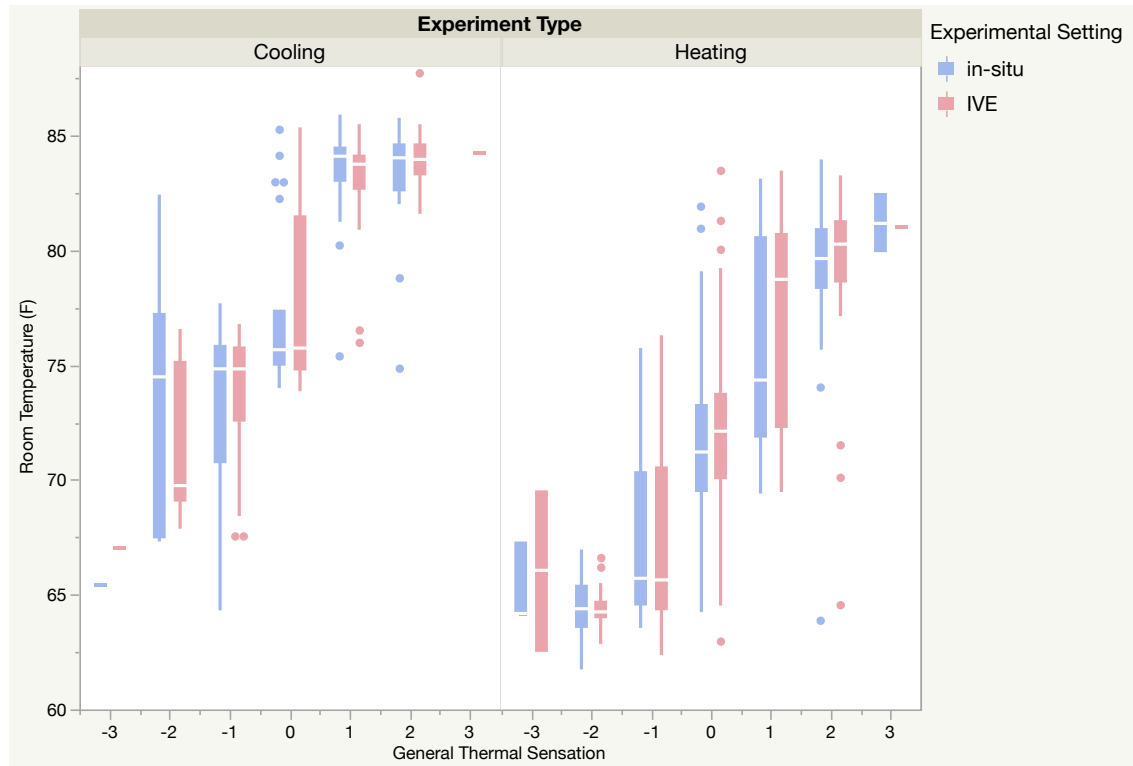


Figure 4.28 Indoor temperature vs. General Thermal Sensation Graph

Table 4.14 Indoor temperature vs. General Thermal Sensation Statistics

General Thermal Sensation Levels		Indoor temperature in in-situ			Indoor temperature in IVE			DF	t	P-value
		N	Mean	St.Dev	N	Mean	St.Dev			
Cooling	-2	9	72.88	5.62	13	71.85	3.25	11.73	-0.49	0.63
	-1	33	73.36	3.87	25	73.73	3.10	55.79	0.40	0.69
	0	23	77.20	3.54	31	77.72	3.97	50.17	0.50	0.69
	1	22	83.51	2.27	23	83.01	2.36	42.99	-0.72	0.47
	2	26	83.40	2.26	22	83.98	1.24	39.89	1.12	0.26
Heating	-2	26	64.43	1.27	23	64.40	0.88	47.71	-0.08	0.93
	-1	23	67.10	3.55	30	67.42	4.03	49.98	0.31	0.75
	0	39	71.78	4.22	38	72.40	4.48	74.45	0.63	0.53
	1	30	75.96	4.69	41	76.89	4.39	60.14	0.84	0.40
	2	35	79.17	3.41	24	79.01	4.41	41.03	-0.15	0.88

Figure 4.28 and Table 4.14 show that there is no discrepancy between the above in-situ/IVE pairs. That is, the indoor temperature at every level of perceived general thermal sensation was statistically comparable between the two IVE and *in-situ* experiments. Figure 4.29 and Table 4.15 demonstrate the thermal acceptability in a similar way as the thermal sensation.

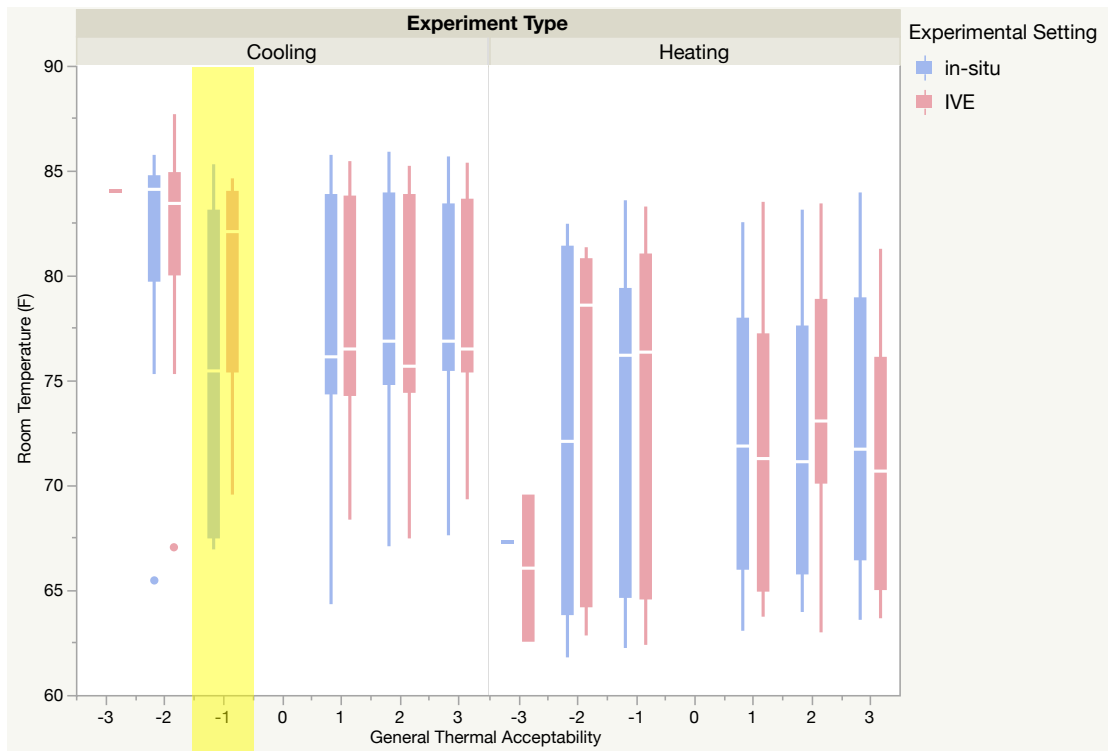


Figure 4.29 Indoor temperature vs. General Thermal Acceptability Graph

Table 4.15 Indoor temperature vs. General Thermal Acceptability Statistics

General Thermal Acceptability Levels		Indoor temperature in in-situ			Indoor temperature in IVE			DF	t	P-value
		N	Mean	St.Dev	N	Mean	St.Dev			
Cooling	-2	12	81.53	5.91	10	81.58	6.04	19.12	0.02	0.98
	-1	14	75.56	7.21	17	79.49	5.10	22.77	1.72	0.04*
	1	29	78.17	5.91	24	77.54	5.97	48.97	-0.38	0.70
	2	42	78.43	5.31	44	77.62	5.44	83.95	-0.70	0.48
Heating	-2	14	72.36	8.89	13	72.85	8.33	24.99	0.14	0.88
	-1	29	73.51	7.12	23	73.49	8.19	43.89	-0.01	0.99
	1	38	72.16	6.10	38	71.48	6.32	73.90	-0.47	0.63
	2	51	71.71	5.93	60	73.21	5.74	104.98	1.34	0.18

The only discrepancy that exists between the in-situ/IVE pairs of thermal acceptability, was in the indoor temperature level at which the -1 (slightly unacceptable) general thermal acceptability was reported. In the *in-situ* setting the temperature $75.56 \pm 7.21^{\circ}\text{F}$ was perceived as slightly unacceptable, while in the IVE setting the temperature $79.49 \pm 5.10^{\circ}\text{F}$ was perceived as slightly unacceptable. Even though that's a pretty wide range, since the means are above the

universal comfort level, it is more likely that the warmth was the origin of the unacceptability. Yet, the reason why “slightly unacceptable” (or -1) in IVE falls into a higher temperature range remains unknown. Nonetheless, to find a stronger support for this finding, a larger sample is required to confirm the p-value of 0.04 would decrease or stay below 0.05.

Figure 4.30 and Table 4.16 represent the distribution of the indoor temperature across the levels of the thermal comfort. The statistical tests reveal that the indoor temperature at every level of the perceived thermal comfort were not significantly different between the two IVE and *in-situ* experimental settings.

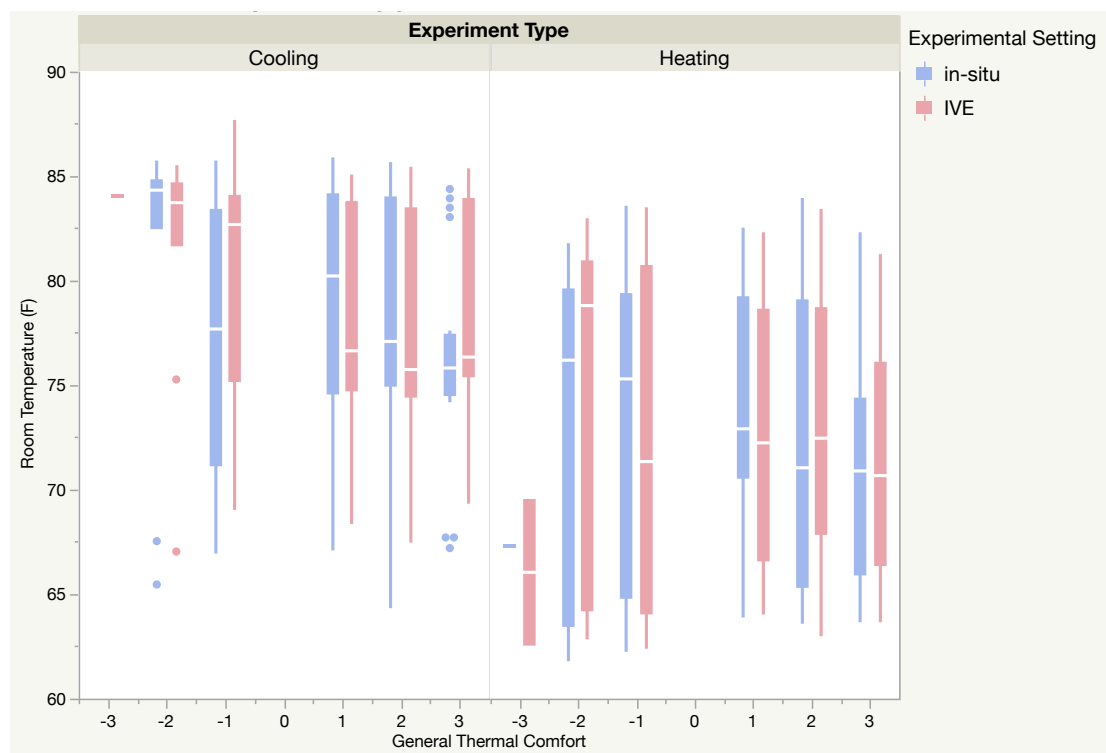


Figure 4.30 Indoor Temperature vs. General Thermal Comfort Graph

Table 4.16 Indoor Temperature vs. General Thermal Comfort Statistics

General Thermal Comfort Levels		Indoor temperature in in-situ			Indoor temperature in IVE			DF	t	P-value
		N	Mean	St.Dev	N	Mean	St.Dev			
Cooling	-2	11	81.06	7.29	11	81.65	5.60	18.76	0.21	0.83
	-1	17	77.23	6.7	16	79.59	6.05	30.92	1.05	0.29
	1	25	78.90	5.58	22	78.42	5.26	44.76	-0.31	0.76
	2	40	78.69	5.25	51	77.26	5.33	84.47	-1.28	0.20
Heating	-2	15	72.07	8.29	17	73.88	8.42	29.61	0.61	0.54
	-1	31	72.63	7.32	26	72.12	8.04	51.23	-0.24	0.81
	1	36	73.67	5.60	35	72.73	5.81	68.70	-0.69	0.49
	2	50	71.91	6.52	56	72.62	5.83	98.89	0.58	0.56

H1-b) thermoceptions at different indoor temperature levels (65 °F, 75 °F, 85 °F)

The other analysis was performed to compare two groups of the data from a different angle, verifying if the thermoceptions at each given nominal indoor temperature levels (*i.e.*, 65 °F, 75 °F, and 85 °F) have been reported similarly across the *in-situ* and IVE experimental settings or not. Wilcoxon signed-rank test was used to compare the responses on these measures. This test is a non-parametric statistical hypothesis test used to compare two matched samples or repeated measurements to examine whether their mean ranks differ. 18 pairs (e.g., thermal acceptability at 75° F in the *in-situ*/cooling vs. thermal acceptability at 75° F in the IVE/cooling) were compared to each other. Results of the Wilcoxon signed-rank tests revealed that no pair of the responses about the thermoceptions at any of the indoor temperature levels were statistically different. This finding suggests that IVE intervention did not cause an interference in perceiving thermal sensation, thermal acceptability, and thermal comfort at the temperatures of 65 °F, 75 °F, and 85 °F, in both cooling and heating exposures.

4.7.4.2 Hypothesis 2

H2: There is a similar pattern between the variables “physiological responses” and “indoor temperature” in the *in-situ* and IVE experimental settings (physiological responses in IVE is not statistically different from the physiological responses in *in-situ*).

This hypothesis assumes that the changes in indoor temperature have similar impacts on participants' physiological responses, be it in the *in-situ* or in the IVE. It is actually intended to find evidence that confirms or rejects the idea that IVE would interfere with individuals' physiological responses. This hypothesis was tested from within-individual (paired-wise) perspective to be able to address the impact of the experiment interventions (experimental setting, *in-situ* vs. IVE). The comparison of the groups of the data was performed using paired t-test. This parametric test is used to examine the difference in the mean values of the physiological measurements in all the experimental pairs (*e.g.*, HR at 65 °F in *in-situ* vs. HR at 65 °F in IVE). The mean value of the T_{sk} at 8 sites on the body, GSR, HR, and HRV (RMSSD, LF/HF, PNS, SNS), all at three levels of 65 °F, 75 °F, and 85, are examined and compared between the *in-situ* and IVE experimental settings. 84 pairs were compared and among them, only 8 pairs were statistically significant (see Table 4.17).

Table 4.17 Significantly Different Physiological Measures Between the *in-Situ* and IVE Pairs

Independent Variable		Response Variable	In-situ			IVE			DF	t	P-value
			N	Mean	St.Dev	N	Mean	St.Dev			
Cooling	75 °F	Forehead Skin Temperature (F)	49	95.02	0.90	49	96.73	0.99	95.16	8.92	<.0001 *
	85 °F	Forehead Skin Temperature (F)	52	95.48	1.29	52	96.38	1.00	95.87	3.97	0.0001 *
	85 °F	RMSSD	50	87.15	94.17	51	54.64	67.67	88.85	- 1.99	0.0498 *
	85 °F	PNS	50	0.32	2.69	51	-0.55	1.93	88.63	- 1.88	0.0317 *
Heating	65 °F	Forehead Skin Temperature (F)	52	93.03	1.55	51	94.50	1.46	100.8 3	4.94	<.0001 *
	65 °F	PNS	51	-0.16	1.89	53	-0.72	1.27	91.64	1.78	0.0390 *

(table cont'd.)

Independent Variable	Response Variable	In-situ			IVE			DF	t	P-value
		N	Mean	St.Dev	N	Mean	St.Dev			
75 °F	Forehead Skin Temperature (F)	53	93.91	1.64	52	95.52	1.58	102.95	5.11	<.0001*
85 °F	Forehead Skin Temperature (F)	53	95.2	1.41	50	96.8	0.99	93.37	6.58	<.0001*

The above table only shows the statistically different pairs. The significantly different local skin temperatures all occurred at the forehead, and this finding was indeed expected, due to the existence of the HMD over the participants' head. The other statistically different measurement between the IVE and the *in-situ* was related to the HRV – RMSSD at 85 °F cooling, and PNS at 65 °F.

4.7.4.3 Hypothesis 3

H3: There is a relationship between the thermoception differences and the variability of thermally-driven behavioral intentions across the *in-situ* and IVE.

Thermally-driven adaptive behaviors or adaptive behaviors were inquired with the participants at the end of the all experimental sessions. The survey presented 12 choices: adjust clothing; change posture; change activity; eat hot/cold foods; drink hot/cold beverages; move to a different location; open/close windows; open/close windows blinds; use handheld fan; turn on/off fans or heating; blocking air diffusers; operating other HVAC controls. The information gained from this questionnaire is classified by order/season/experiment type in the *in-situ* experimental setting, and is illustrated in two contingency tables, Figure 4.31, representing the *in-situ*, and Figure 4.32, representing the IVE.

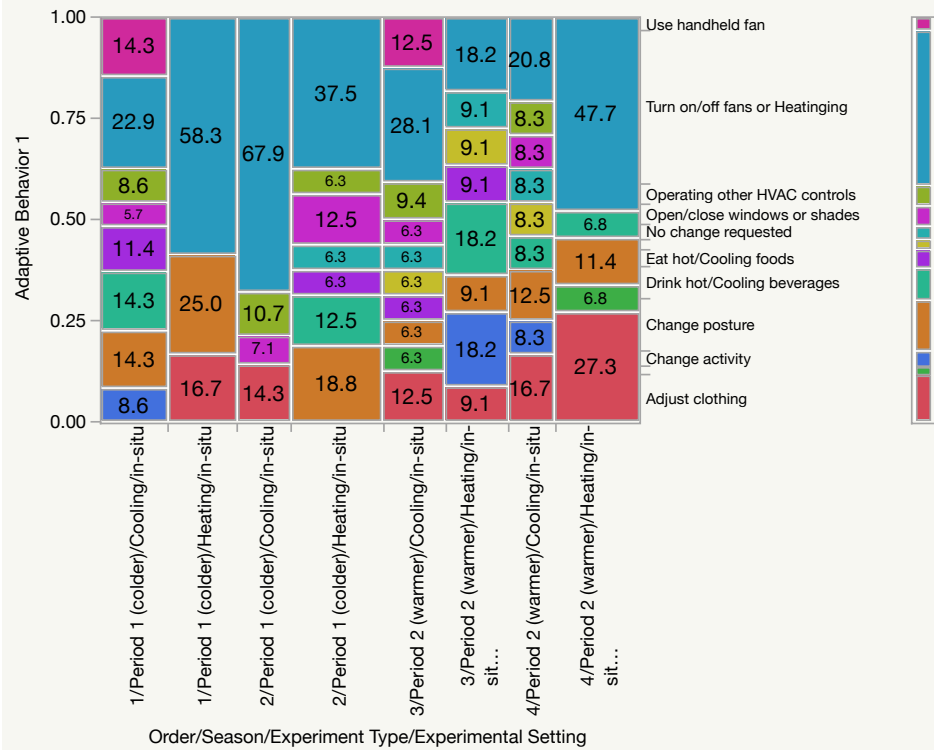


Figure 4.31 Adaptive Behavior 1 by Order/Season/Experiment Type in *in-situ*

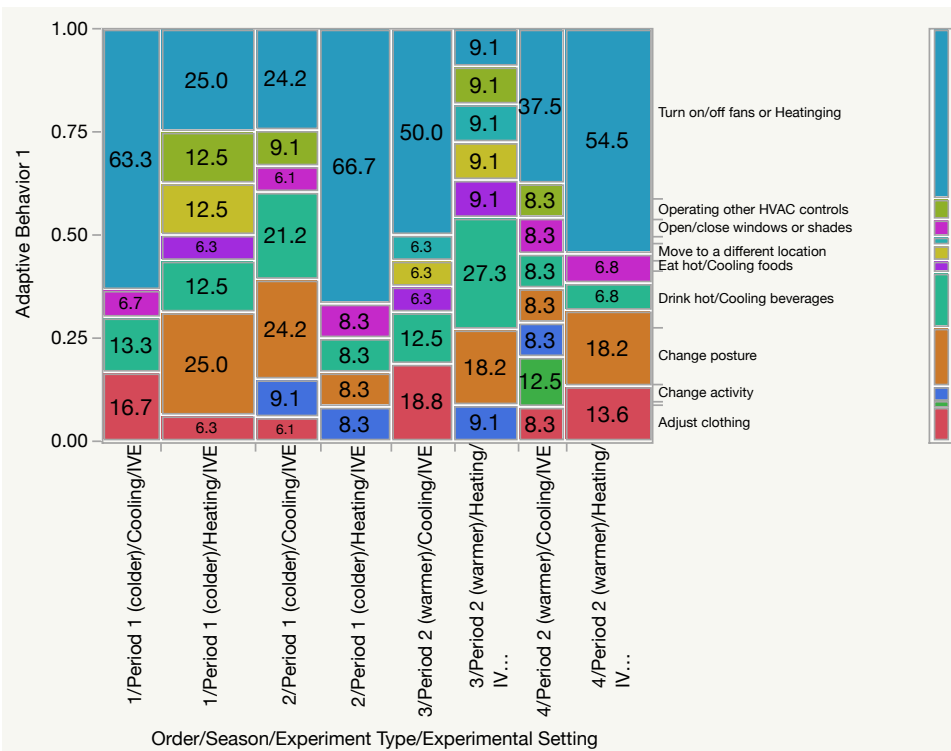


Figure 4.32 Adaptive Behavior 1 by Order/Season/Experiment Type in IVE

Furthermore, another way to look into the thermally-driven behavioral intentions in this study was considering the nature of the behavior; be it an eco-friendly or a non-eco-friendly behavioral choice. The choices that had no direct energy consumption consequences were considered as eco-friendly behaviors, and they include adjusting clothing, changing posture, changing activity, eating hot/cold foods, drinking hot/cold beverages, moving to a different location, opening/closing windows, opening/closing windows blinds, and using a handheld fan. The rest of the choices were not counted in this classification, and they include turning on/off fans or heating, blocking air diffusers, operating other HVAC controls.

Figure 4.33 and Figure 4.34 present the total number of the selected eco-friendly choices, again, classified by order/season/experiment type, in the *in-situ* and the IVE settings.

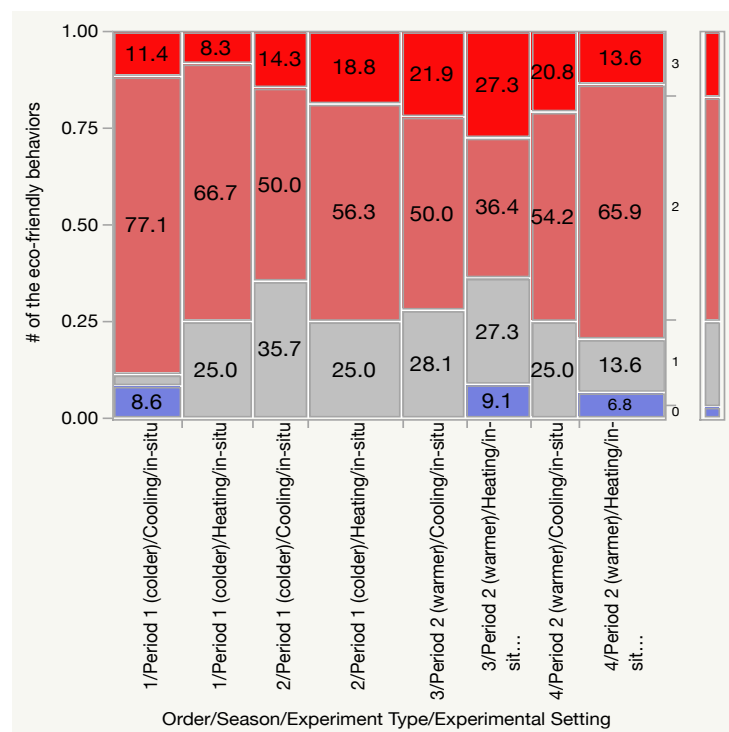


Figure 4.33 Total Number of the Eco-Friendly Behaviors by Order/Season/Experiment Type in *in-situ*

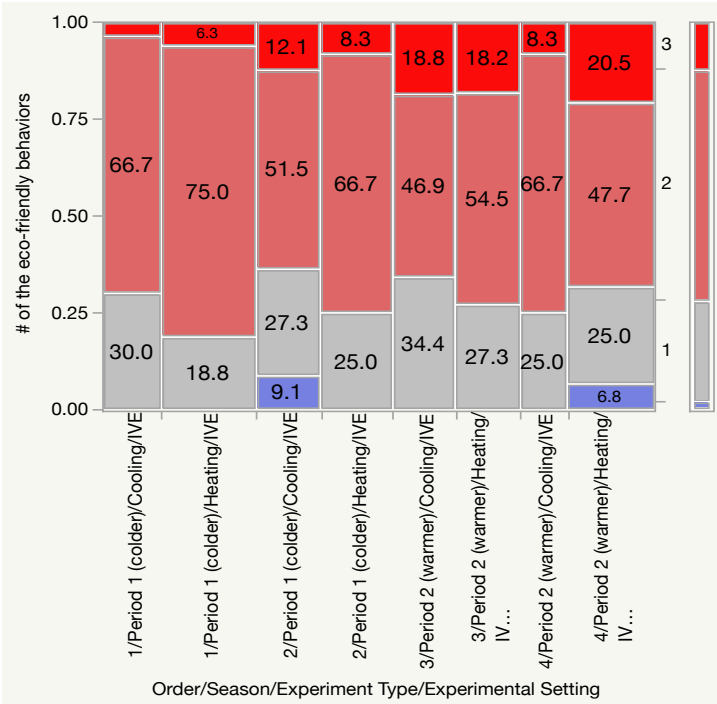


Figure 4.34 Total Number of the Eco-Friendly Behaviors by Order/Season/Experiment Type in IVE

To test the hypothesis 3, two variables of “thermoception differences” and “total number of listed common behaviors” were defined. The variable thermoception differences was defined as the variations in the general thermal sensation, general thermal acceptability and general thermal comfort that could occur between the two experimental settings (*e.g.*, Δ thermal sensation in cooling at 65 °F = |mean thermal sensation in cooling at 65 °F IVE - mean thermal sensation *in-situl*). To simplify the statistical analysis, the variable Δ was presented with only two levels (Different vs. Not different). If the Δ was 0 it was referred to as “Not different” and any Δ that was greater or equal to 1 it was presented as “Different.”

To perform this hypothesis testing only the last votes on the thermoceptions (at the end of the sessions, *e.g.*, heating exposure at 85 °F) were taken into account. This data was collected right before providing the participants with adaptive behavioral choices. Yet, because of the limited

numbers of the datapoints in the cooling exposure at 65 °F, this hypothesis testing was limited to examining the Δ thermoceptions in the heating exposure sessions.

The other variable, variability of the thermally-driven behavioral intentions was defined as the number of the common listed adaptive behavioral intentions. The data related to this variable was primarily collected by providing participants with a list of adaptive behaviors at the end of each session. Each participant's selected three most preferred choices were then compared between each corresponding *in-situ*/IVE pairs. Thus, three new variables of behavior match were produced, that each had two levels of 0 denoting the mismatch and 1 indicating the match of the selected choices. They were then summed up to the total number of the listed common behaviors which was used to be tested within the levels of Δ thermoceptions.

Mosaic plot (Figure 4.35, 4.36, and 4.37) and contingency table (Table 4.18, 4.19, and 4.20) are used to illustrate the proportion of the total number of the listed common behaviors within the levels of Δ thermoceptions (Different vs. Not different). Statistical dependence test (Fisher's exact test of independence) was then used to investigate possible association between the changes in the participant's reported thermoception votes, and the total number of the listed common behaviors.

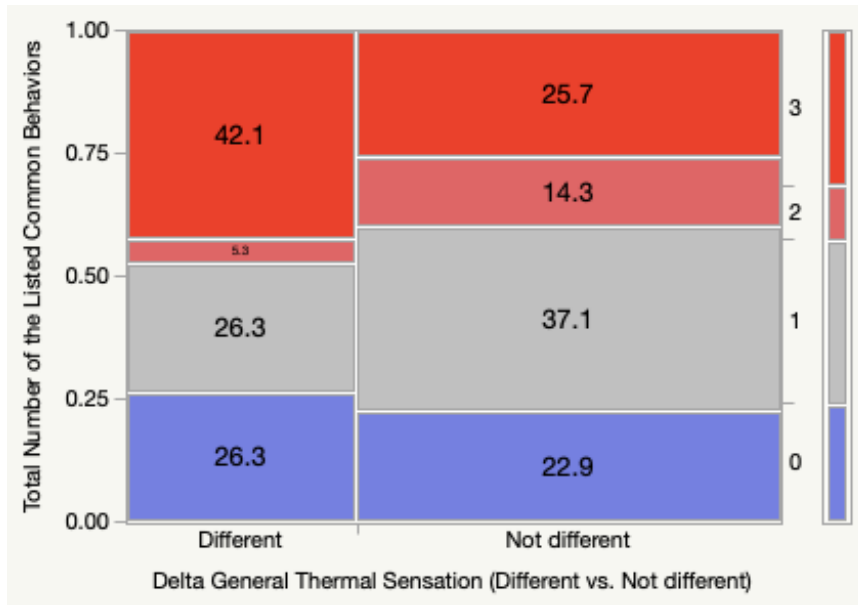


Figure 4.35 Total Number of the Listed Common Behaviors by Delta General Thermal Sensation (Different vs. Not different)

Table 4.18 Delta General Thermal Sensation (Different vs. Not different) by Total Number of the Listed Common Behaviors

Count Total %	0	1	2	3	Total
Different	5 9.26	5 9.26	1 1.85	8 14.81	19 35.19
Not different	8 14.81	13 24.07	5 9.26	9 16.67	35 64.81
Total	13 24.07	18 33.33	6 11.11	17 31.48	54

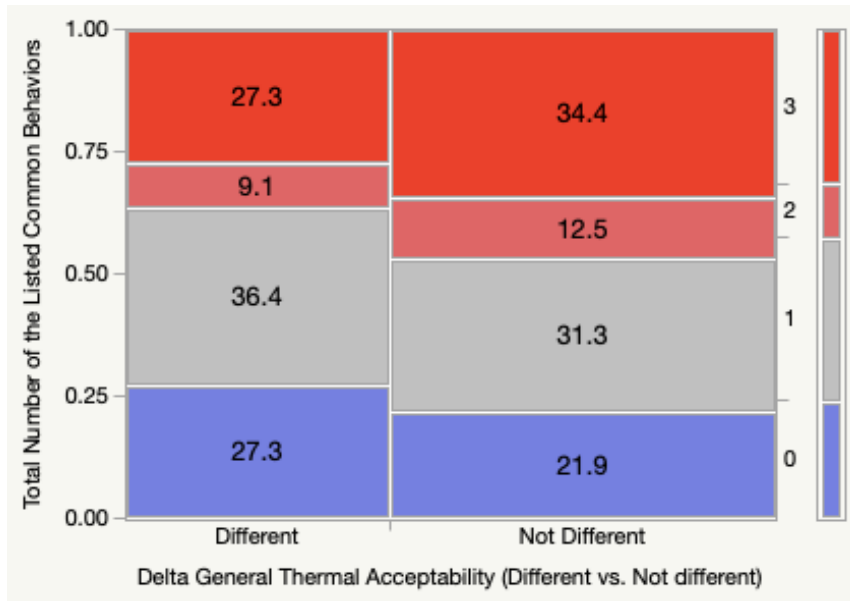


Figure 4.36 Total Number of the Listed Common Behaviors by Delta General Thermal Acceptability (Different vs. Not different)

Table 4.19 Delta General Thermal Acceptability (Different vs. Not different) by Total Number of the Listed Common Behaviors

Count Total %	0	1	2	3	Total
Different	6 11.11	8 14.81	2 3.70	6 11.11	22 40.74
Not Different	7 12.96	10 18.52	4 7.41	11 20.37	32 59.26
Total	13 24.07	18 33.33	6 11.11	17 31.48	54

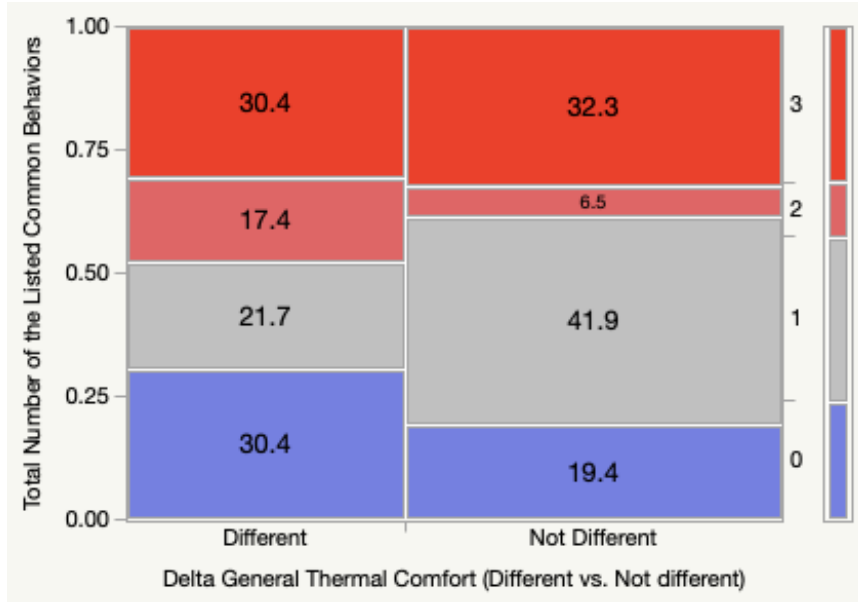


Figure 4.37 Analysis of Total Number of the Listed Common Behaviors by Delta General Thermal Comfort (Different vs. Not different)

Table 4.20 Delta General Thermal Comfort (Different vs. Not different) By Total Number of the Listed Common Behaviors

Count Total %	0	1	2	3	Total
Different	7 12.96	5 9.26	4 7.41	7 12.96	23 42.59
Not Different	6 11.11	13 24.07	2 3.70	10 18.52	31 57.41
Total	13 24.07	18 33.33	6 11.11	17 31.48	54

In addition to the graphical representation of the relationship between Δ thermoceptions and the number of the common behaviors, Fisher's exact test of independence was performed in order to examine the equivalence of the probability distributions of the two variables and , more specifically, to figure out if the number of the common behaviors across the *in-situ* and IVE settings has any non-random relationship with the Δ thermoceptions. The p-values associated with

this test (all greater than 0.05) indicate that there is no association between the two variables. In other words, if participants sense/perceive the thermal environment in a different way in IVE than in *in-situ*, the behavioral intentions do not necessarily follow a consistent pattern. Still, there has to be other factors that influence the Δ thermoceptions and Δ thermally-driven adaptive behaviors across the *in-situ* and IVE experimental settings, which hypothesis 4 explores.

4.7.4.4 Hypothesis 4

H4: Individual-related variables are related to the variability of thermally-driven adaptive behaviors across the *in-situ* and IVE experimental settings.

This hypothesis testing is an extension to H3 in that it tried to determine the relevant variables that are associated with selection of thermally-driven behavioral intentions in the IVE vs. in the *in-situ* experimental setting. The total number of the common thermally-driven behavioral intentions was measured by comparing each participant's three listed adaptive behaviors between the two corresponding *in-situ*/IVE pairs and then adding them together. Yet, unlike in H3, this calculation was performed cumulatively, incorporating both seasons and experiment types (cooling and heating). Next, the percentage of it was calculated.

The other response variable in this hypothesis was the total number of the eco-friendly adaptive behaviors which was simply calculated by adding the eco-friendly choices together. The choices that had no direct energy consumption consequences were considered as eco-friendly behaviors, and they include adjusting clothing, changing posture, changing activity, eating hot/cold foods, drinking hot/cold beverages, moving to a different location, opening/closing windows, opening/closing windows blinds, and using a handheld fan. The rest of the choices were not counted in this classification, and they include turning on/off fans or heating, blocking air diffusers,

operating other HVAC controls. The percentage of the total eco-friendly behaviors is calculated in the same way as the total percentage of the common thermally-driven behaviors.

As for the individual-related factors, both anecdotal evidence and previous literature were used to list the possible contributing factors in this regard; they include, demographic and background information (*i.e.*, age, gender, education, employment, place of origin, Immersive tendencies, knowledge of VR) as well as post-experiment information (*i.e.*, cybersickness, presence).

Figure 4.38 and Table 4.21 demonstrates the relationship between two variables percentage of the all listed common behaviors and age and using a linear regression model which shows that age has impact ($p\text{-value} < 0.05$) on the total percentage of the common behaviors between the *in-situ* and IVE. Older people have more tendency in performing similar behaviors across the two settings.

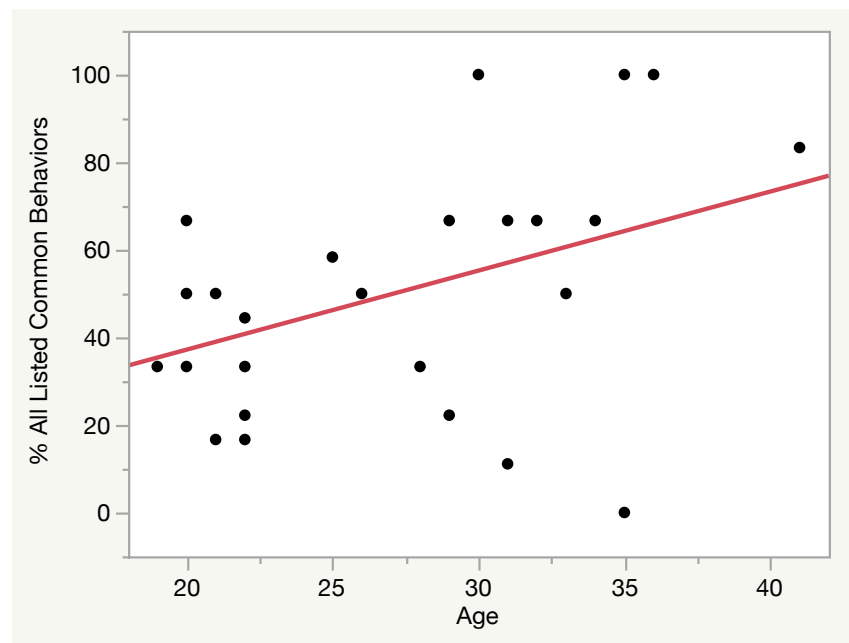


Figure 4.38 All Listed Common Behaviors by Age

Table 4.21 Summary Statistics of All Listed Common Behaviors by Age

	Value	Lower 95%	Upper 95%	Signif. Prob
Correlation	0.42306	0.059351	0.687609	0.0249*
Covariance	72.68151			
Count	28			

Next, the possible impact of gender on common behavioral intentions was examined, Figure 4.39 and Table 4.22 demonstrate the two-sample (independent) t-tests that compare the distribution of the total percentage of the common behaviors between male vs. females.

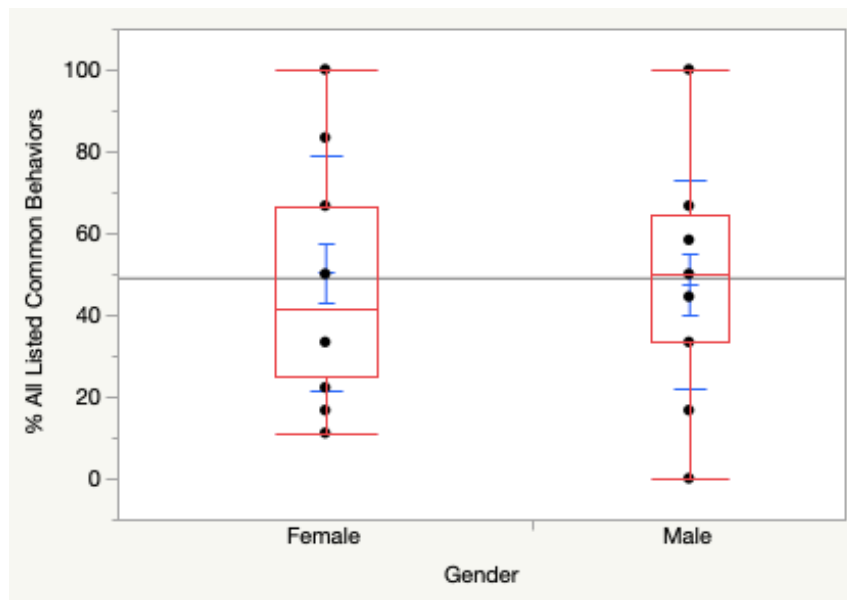


Figure 4.39 All Listed Common Behaviors by Gender

Table 4.22 Two sample t-test of All Listed Common Behaviors by Gender

Level	No	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	DF	t	P-value
Female	16	50.35	28.87	7.22	34.97	65.73	25.16	-0.27	0.78
Male	12	47.45	25.66	7.41	31.15	63.76			

The statistical evidence ($p\text{-value} > 0.05$) associated with this test indicates that the two (male vs. female) distribution of the responses (common behavioral intentions) are not significantly different. Therefore, gender does not play role in the total percentage of the common behavioral intentions across the IVE and *in-situ* experimental settings.

Next, the possibility that the variable place of origin could be a factor for changing the percentage of the total listed common behaviors across the IVE and the *in-situ* was examined; the mean of each group was compared with each other, using ANOVA. The p-value ($p>0.05$) of this statistical test casts off that idea that place of origin could have a significantly higher rank in the percentage of their common behavior (Figure 4.40 and Table 4.23). That is, place of origin did not have impact on the total percentage of the common behavioral intentions across the IVE and *in-situ* experimental settings.

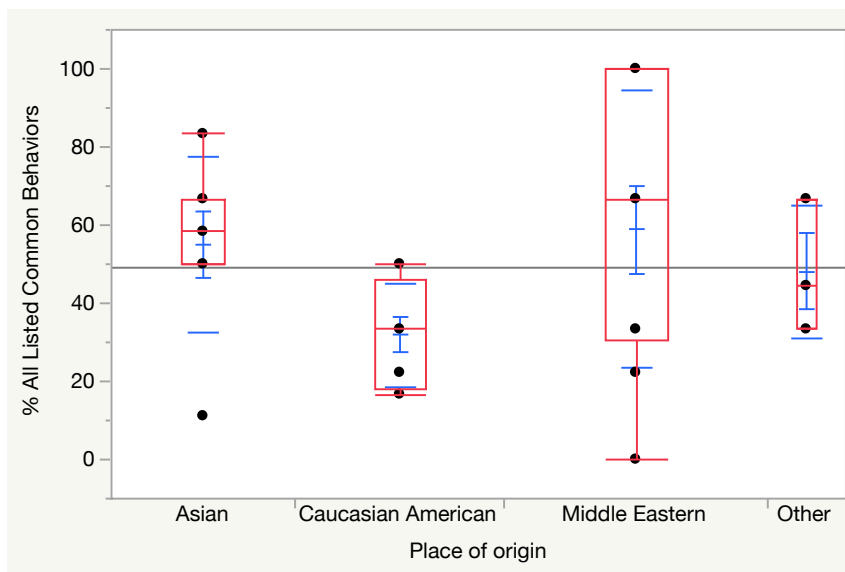


Figure 4.40 All Listed Common Behaviors by Place of Origin

Table 4.23 ANOVA test for Analysis of All Listed Common Behaviors by Place of Origin

Level	No	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	F Ratio	Prob > F
Asian	7	55.16	22.59	8.54	34.27	76.05	1.7611	0.1815
Middle Eastern	10	58.89	35.54	11.24	33.46	84.32		
Other	3	48.15	16.97	9.80	5.99	90.31		
Caucasian American	8	31.94	13.20	4.67	20.91	42.98		

A more detailed look into the behavioral choices was performed by analyzing the first selected behavior and plotting the frequency of each into the levels of the variable place of origin.

Figure 4.41 present the participants first reported adaptive behavior by their place of origin.

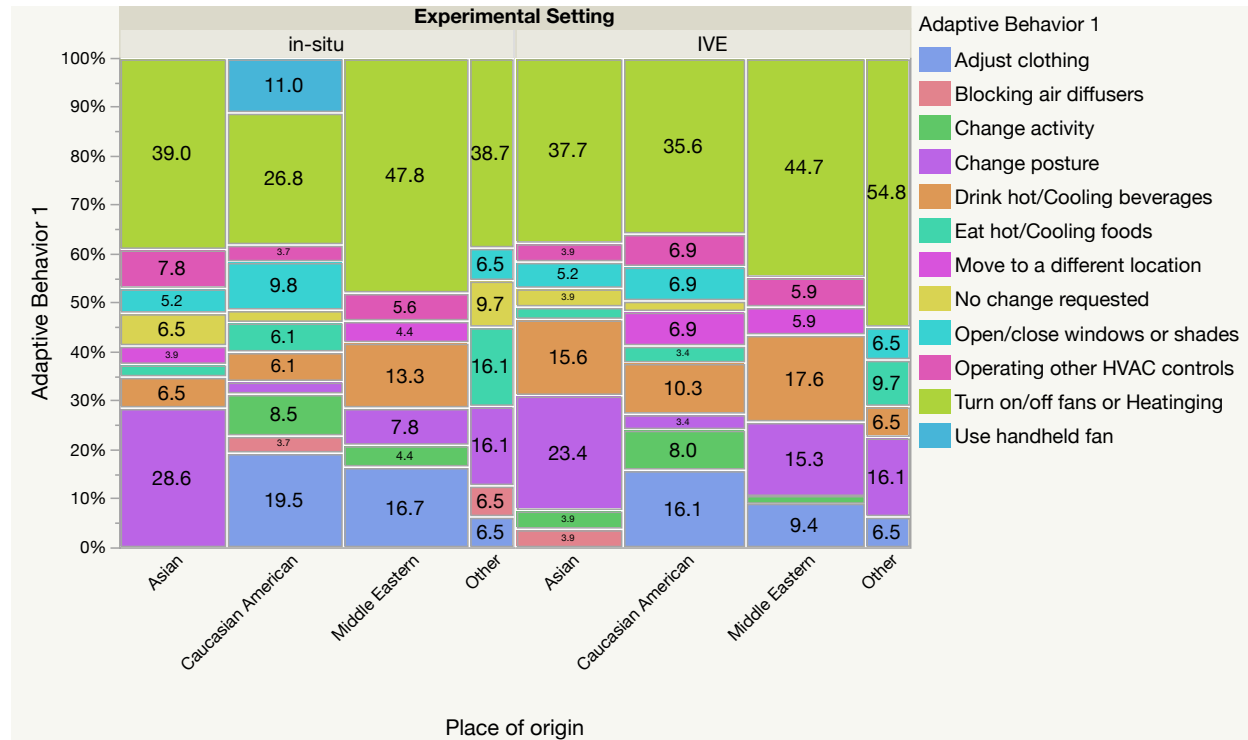


Figure 4.41 Adaptive Behavior 1 by Place of Origin

The statistics associated with Fisher's exact test of independence indicate that the first reported adaptive behavior is not related to the variable place of origin ($p\text{-value} > 0.05$).

The choice of the adaptive behaviors was also analyzed by looking into the nature of the behavioral choices—eco-friendly vs. non-eco-friendly (Figure 4.42). The statistics associated with Fisher's exact test indicate that the total number of the selected eco-friendly behaviors is not related to the variable place of origin ($p\text{-value} > 0.05$).

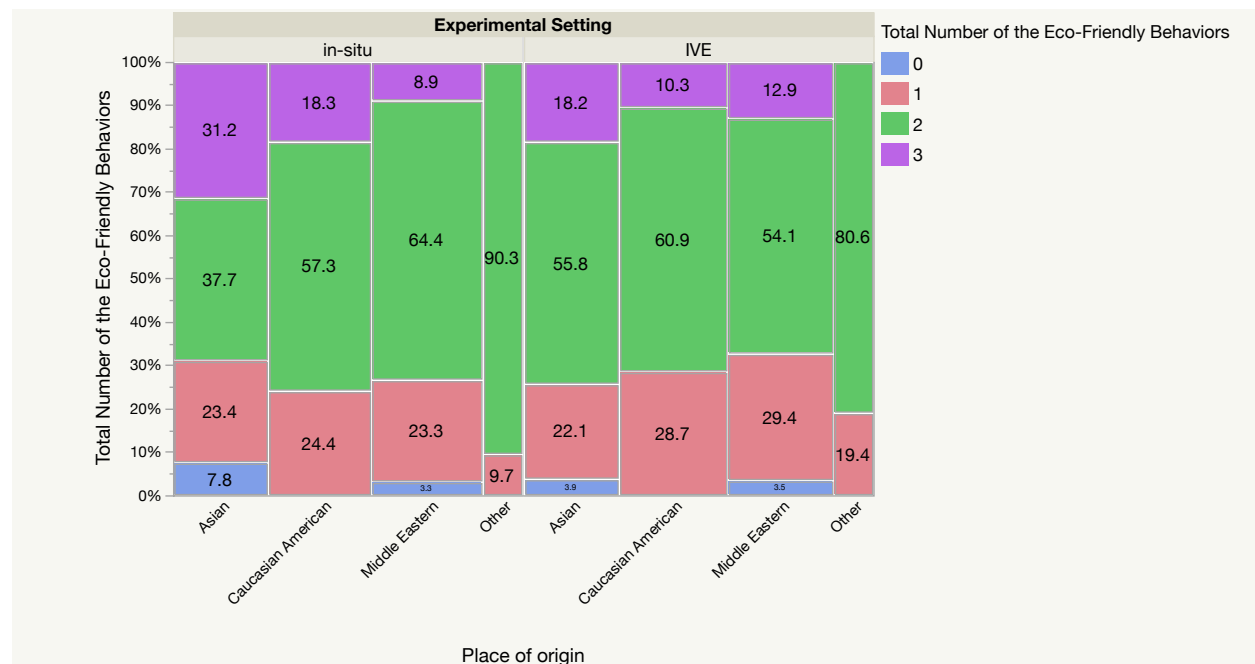


Figure 4.42 Total Number of Eco-Friendly Behavior 1 by Place of Origin

The next test was the total number of the common behaviors within the levels of “highest level of education.” Figure 4.43 depicts the graphical representation of the ANOVA test examining the variations between different education groups. Table 4.24 shows the statistics testing if there is a significant difference in the total number of the common behaviors among the education levels.

The statistics associated with the ANOVA test ($p\text{-value} > 0.05$) rejects the possibility that the variable education level could potentially impact the total percentage of the participants’ common behavior across the *in-situ* and IVE experimental settings. Yet, due to the lack of enough data in each group (*e.g.*, only 2 participants in the high-school graduate group), the results of this test, remain inconclusive.

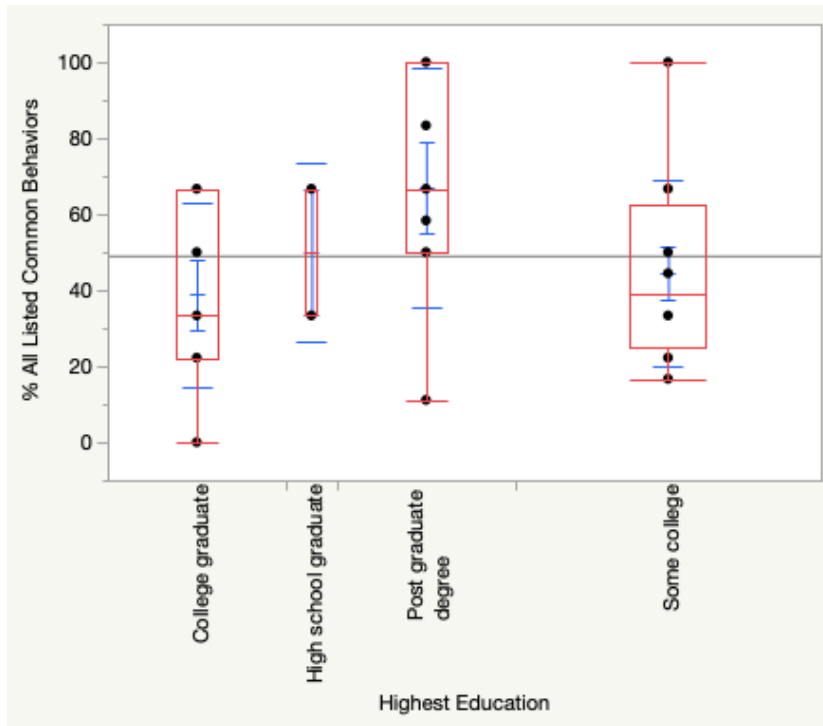


Figure 4.43 All Listed Common Behaviors by Highest Education

Table 4.24 ANOVA test for Analysis of All Listed Common Behaviors by Highest Education

Level	No	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	F Ratio	Prob > F
College graduate	7	38.89	24.22	9.15	16.49	61.29	1.571 2	0.22
High school graduate	2	50.00	23.57	16.67	-161.77	261.77		
Post graduate degree	7	67.06	31.44	11.88	37.98	96.14		
Some college	12	44.44	24.39	7.04	28.95	59.94		

The choice of the adaptive behaviors was also analyzed by looking into the nature of the behavioral choices—eco-friendly (Figure 4.44). The statistics associated with Fisher’s exact test of independence indicate that the total number of the selected eco-friendly behaviors is not potentially related to the variable education level ($p\text{-value} > 0.05$). Again, results from this test remain inconclusive, as the size of the sample in the study was not quite adequate.

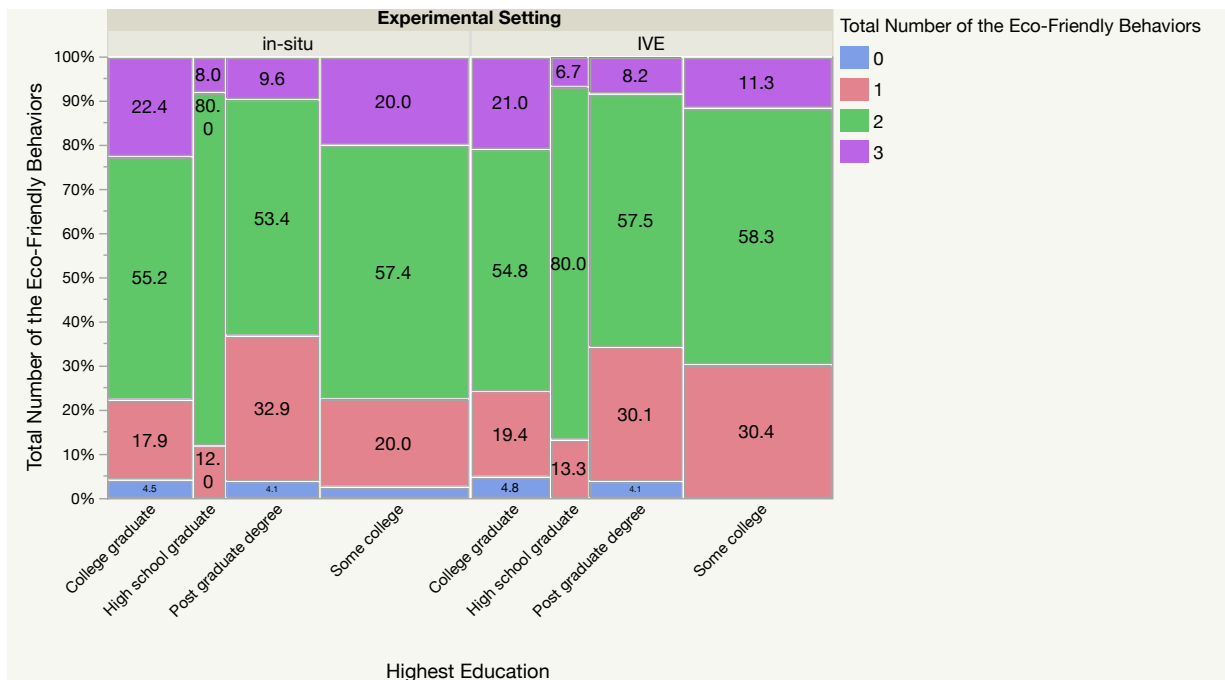


Figure 4.44 Total Number of Eco-friendly Behavior by Education

The last variable related to the participants' social and demographic information was employment status. Figure 4.45 and Table 4.25 demonstrates the distribution of the variable total number of common behaviors within the four levels of employment. The ANOVA test resulted in a p-value greater than 0.05, which indicates that average value of the dependent variable is not statistically different among the four groups of employment. Still, results from this test remain inconclusive since the sample size in the study was not adequately large.

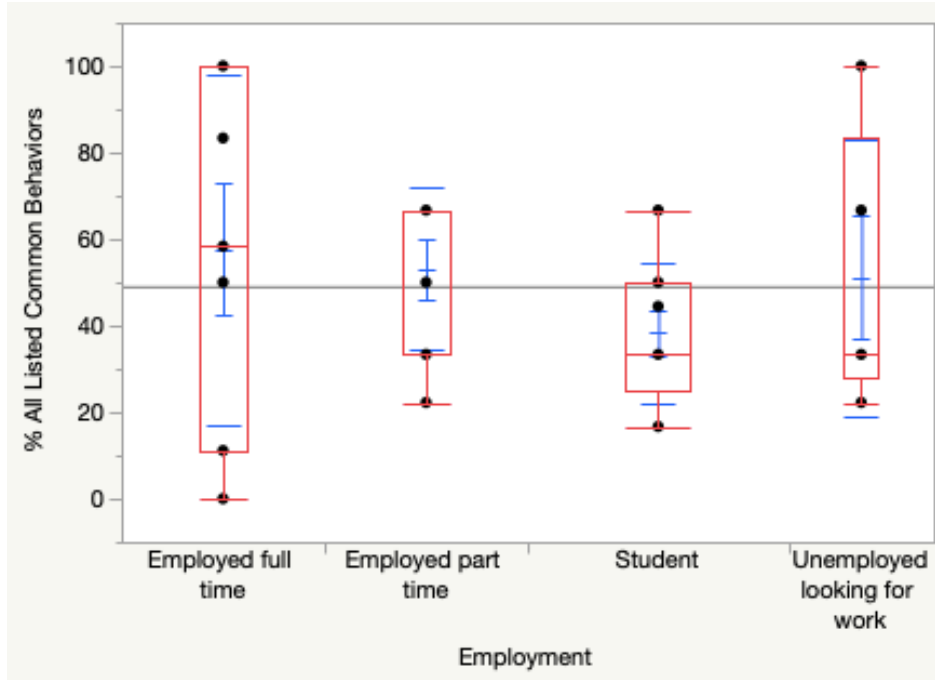


Figure 4.45 All Listed Common Behaviors by Employment

Table 4.25 ANOVA test for Analysis of All Listed Common Behaviors by Employment

Level	No	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	F Ratio	Prob > F
Employed full time	7	57.54	40.40	15.27	20.17	94.91	0.7467	0.5349
Employed part time	7	53.17	18.66	7.05	35.91	70.44		
Student	9	38.27	16.30	5.43	25.74	50.80		
Unemployed looking for work	5	51.11	32.01	14.32	11.36	90.86		

The choice of the adaptive behaviors was also analyzed by looking into the nature of the behavioral choices—eco-friendly (Figure 4.46). The statistics associated with Fisher's exact test of independence indicate that the total number of the selected eco-friendly behaviors is not related to the variable employment ($p\text{-value} > 0.05$). Again, results from this test remain inconclusive, as the size of the sample in the study was not quite adequate.

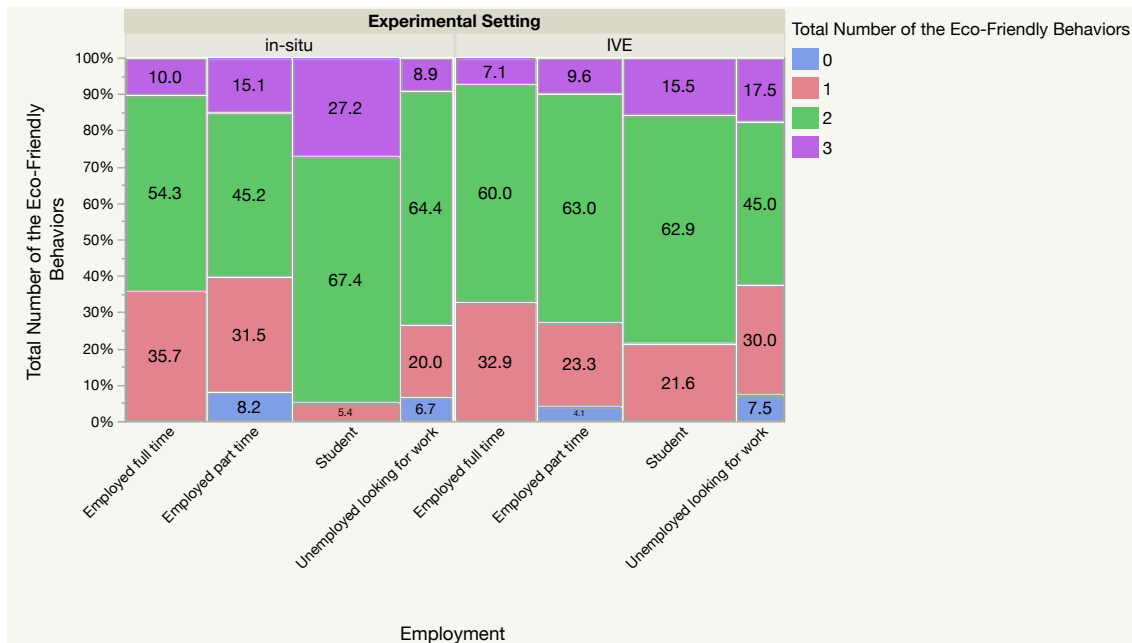


Figure 4.46 Total Number of Eco-friendly Behavior by Employment

Afterwards, the possible impact of the variable “computer skills and experience with VR” was investigated. The linear regression (Figure 4.47) model clearly indicate that participants with higher computer skills had higher rank in their common behaviors ($p\text{-value} < 0.05$).

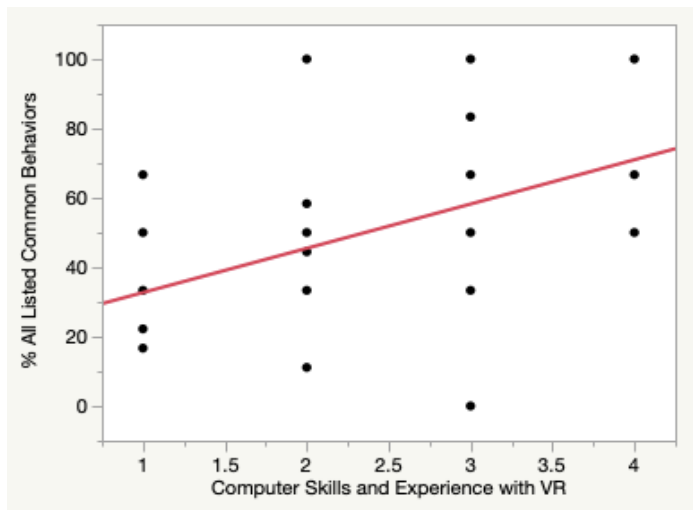


Figure 4.47 All Listed Common Behaviors by Computer Skills and Experience with VR

Table 4.26 Summary Statistics for All Listed Common Behaviors by Computer Skills and Experience with VR

	Value	Lower 95%	Upper 95%	Signif. Prob
Correlation	0.494584	0.149	0.732501	0.0075*
Covariance	14.05056			
Count	28			

Immersive tendency was another variable among the pre-experiment information that this study considered to examine. It was assumed that this variable has impact on the match of the adaptive behavior and the total number of the common behavior between IVE and *in-situ* settings. The linear regression (Figure 4.48) shows the significant correlation between the individuals' tendency to be entertained in the IVEs with the total number of the common behavior between IVE and *in-situ* settings (p-value<0.05).

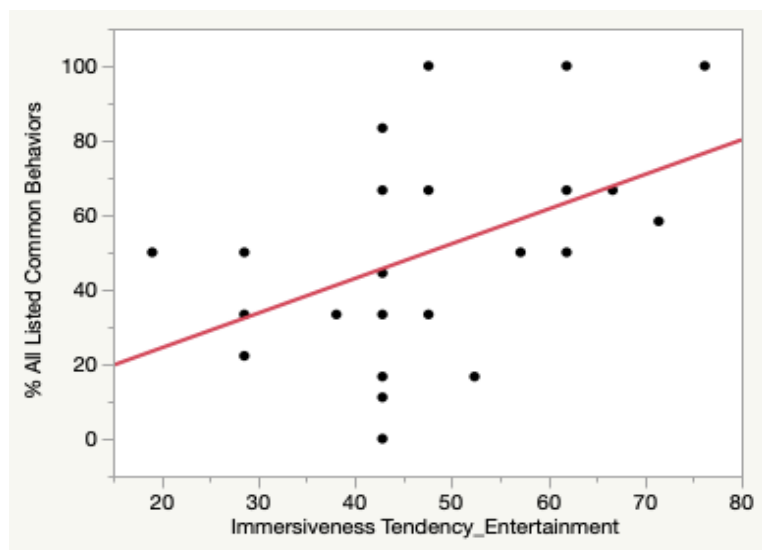


Figure 4.48 All Listed Common Behaviors by Immersive Tendencies

4.27 Summary Statistics for All Listed Common Behaviors by Immersive Tendencies

	Value	Lower 95%	Upper 95%	Signif. Prob
Correlation	0.50053	0.156717	0.736142	0.0067*
Covariance	197.4679			
Count	28			

Finally, the influence of the quality of the IVE experience which was measured through presence and cybersickness instruments was explored. The Figure 4.49 shows that there is a possibility that individuals with higher cybersickness (nausea) have lower levels of common behaviors across the IVE and *in-situ* settings (p-value is potentially significant). So, an IVE that offers higher levels of cybersickness could cause distortion in replicating behavioral intentions as in *in-situ*.

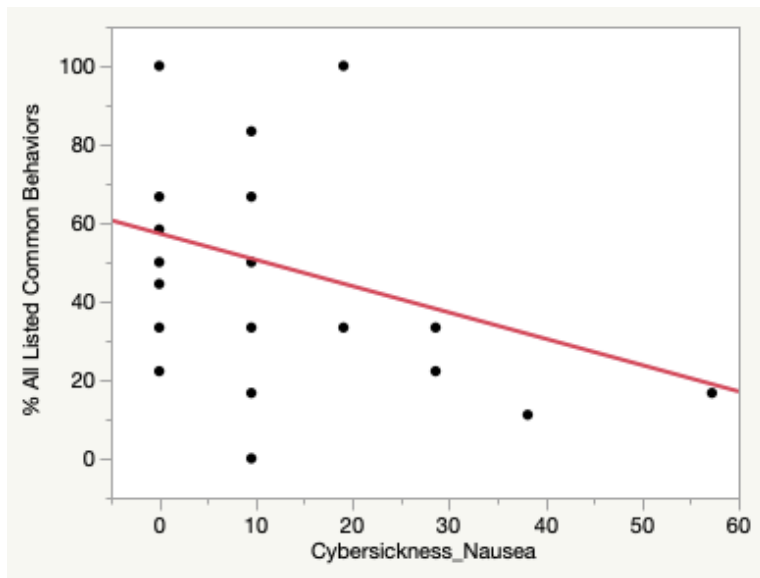


Figure 4.49 All Listed Common Behaviors by cybersickness

Table 4.28 Summary Statistics for All Listed Common Behaviors by Cybersickness

	Value	Lower 95%	Upper 95%	Signif. Prob
Correlation	-0.33966	-0.63258	0.038269	0.0770
Covariance	-126.05			
Count	28			

4.7.4.5 Hypothesis 5

H5: Seasonal mismatch will not significantly alter the thermoception and thermally-driven behaviors of participants compared to seasonally matched IVEs.

As explained before, to avoid unwanted variations in the data and to allow participants adjust to the lab condition, they were asked to sit in the waiting room outside the lab for 10-15

min. In order to make sure that the acclimatization of the participants before each experiment was done properly, a correlation test was performed between the variables “outside temperature” and “thermoception” separately for each season/experiment type category of data (Table 4.29).

Table 4.29 Pair-wise Comparisons of Outside Temperature and Thermoception

Independent Variables		Variable 1	Variable 2	Correlation	Count	Lower 95%	Upper 95%	Signif. Prob
Period 2 (warmer)	Cooling	Outside Temp	General Thermal Sensation	0.04	112	-0.14	0.23	0.64
		Outside Temp	General Thermal Acceptability	0.07	112	-0.11	0.25	0.46
		Outside Temp	General Thermal Comfort	0.08	112	-0.11	0.26	0.43
	Heating	Outside Temp	General Thermal Sensation	-0.09	154	-0.24	0.06	0.24
		Outside Temp	General Thermal Acceptability	-0.03	154	-0.19	0.13	0.69
		Outside Temp	General Thermal Comfort	-0.03	154	-0.18	0.13	0.69
Period 1 (colder)	Cooling	Outside Temp	General Thermal Sensation	-0.06	126	-0.24	0.11	0.44
		Outside Temp	General Thermal Acceptability	0.03	126	-0.14	0.21	0.73
		Outside Temp	General Thermal Comfort	0.10	126	-0.07	0.27	0.27
	Heating	Outside Temp	General Thermal Sensation	-0.09	167	-0.24	0.06	0.22
		Outside Temp	General Thermal Acceptability	0.04	167	-0.11	0.19	0.65
		Outside Temp	General Thermal Comfort	0.00	167	-0.14	0.15	0.97

The results of the Spearman-rank correlation coefficient test revealed that none of the thermoception responses were not related to the outside temperature in any of the tests (p-value>0.05).

With that knowledge in mind, the seasonal impact test was performed by comparing the thermoception votes across the levels of season/experiment type/experiment setting/target indoor temperature. For instance, the general thermal sensation in a period 1/heating exposure within an

in-situ setting at 65 °F was compared to its corresponding measure in the period 2 session. Given the categorical nature of the thermoception data, Wilcoxon test was used to analyze the means of each pair. The statistics associated with the Wilcoxon test revealed that the mean value of the thermoception measurements in all the corresponding mismatched vs. matched pairs (*e.g.*, period 1pe/cooling vs. period2/cooling) were not significantly different from one another (p-value>0.05) (see Appendix G).

The seasonal mismatch was also tested to figure if it would influence the thermally-driven behaviors. Another non-parametric statistical test, namely, Fisher's exact test of independence was used. The test tries to find evidence if there is any non-random association between the variables of the adaptive behavior and the seasons; that is, whether seasonally matched IVEs (simulation of snowing during Wintertime) produce similar data compared to seasonally unmatched (simulation of snowing during summertime) IVEs. The null hypothesis of this test is that there is no association between the two variables, such that the frequency of one behavior is not related to the setting in which the experiment is run. Participants' first selected adaptive behavior was tested over the variable of season/experiment/type/experiment setting. The mosaic plots (Figure 4.50 and Figure 4.51) present the proportion of the selected adaptive behaviors in each of the levels of season/experiment type/experiment settings.

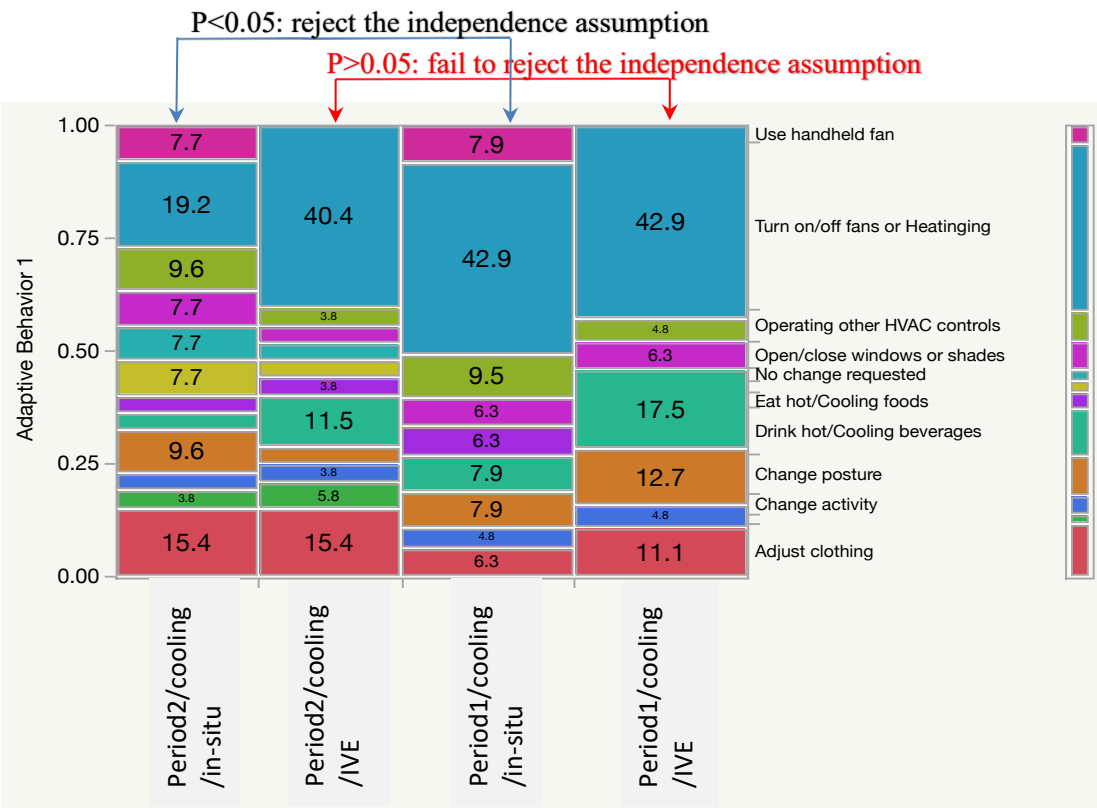


Figure 4.50 Adaptive Behavior by Season/Experiment Setting in Cooling Experiments

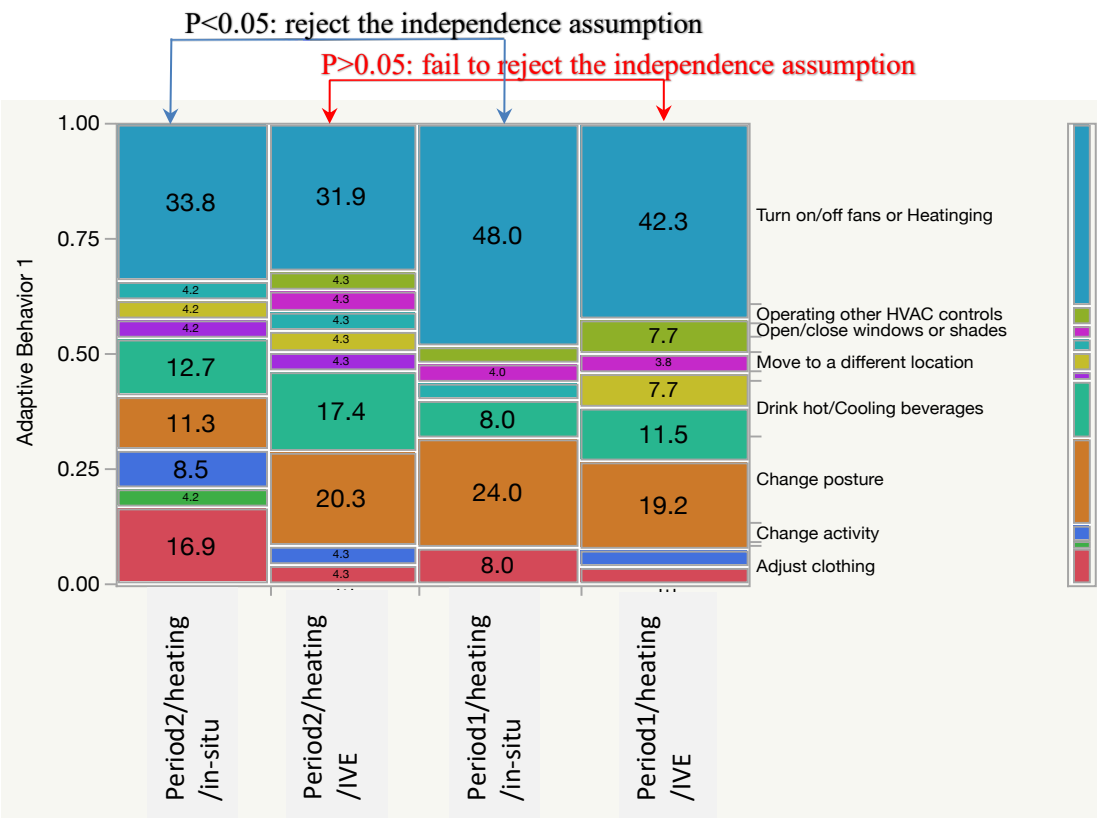


Figure 4.51 Adaptive Behavior by Season/Experiment Setting in Heating Experiments

The null hypothesis of Fisher's exact test of independence in the context of this hypothesis indicate that the relative proportions of variable "adaptive behavior 1" is independent of the levels of variable "experiment condition (period 1 and 2)." In other words, the two variables are not independent from one another and the proportions at the first variable are not statistically different within the levels of the second variable. The overall test for the *in-situ* experimental sessions in both the cooling and the heating exposures resulted in p-values smaller than 0.05 which rejects the assumption that the "adaptive behavior 1" and the "experiment condition (period 1 and 2)" are independent from each other; which means there is an association between the two variables, the proportions of the adaptive behavior 1 was statistically different in period 1 and period 2 in *in-situ* sessions. Yet, the statistics comparing the IVE/IVE pairs between the two different periods of data collection resulted in a p-value greater 0.05 which, fails to reject the assumption of independence, and suggests that, unlike the *in-situ* sessions, IVEs potentially generated similar thermally-driven behavioral intention in the two contrasting seasons. Thus, the IVE-based data of the sample of this study was independent of the differences of the outside experiment condition (period 1 and 2).

4.7.4.6 Mixed Effect Model

Experiments in this study were conducted as a split plot design with a randomized complete block design (RCBD) main plot. Specifically, a participant (subject) was treated as a block, and the main treatment was the seasonal impact (period 1 vs. period 2). The main plot was split three times, and sub-treatments included experimental setting (1st split, IVE vs. *in-situ*), indoor temperature change (2nd split, Heating vs. Cooling) and indoor temperature level (3rd split, 65°F vs. 75°F vs. 85°F). Data from this study was analyzed through a mixed model approach,

and statistics for the pre-knowledge collected from the pre-questionnaires were introduced to the model as covariates to remove systematic or non-systematic variations from the responses.

The conceptual model for this study is:

$$Y_{ijklm} = \mu + P_i + S_j + \varepsilon_{ps} + V_k + SV_{jk} + \varepsilon_{psv} + O_l + SO_{jl} + VO_{kl} + SVO_{jkl} + \varepsilon_{psvo} + T_m + ST_{jm} + VT_{km} + SVT_{jkm} + OT_{lm} + SOT_{jlm} + VOT_{klm} + SVOT_{jklm} + \varepsilon_{psvoT} + \beta_x \quad (\text{EQ.1})$$

$i = 1, 2, \dots, 25, j = 1, 2, k = 1, 2, l = 1, 2, m = 1, 2, 3.$

where Y_{ijklm} can be any individual response in the study, μ is the effect due to the overall mean, P_i is the block or the subject effect (random effect), S_j is the seasonal impact (fixed effect), ε_{ps} is an error term or an interaction for seasonal impact (random interaction), V_k is the experimental setting (fixed effect), SV_{jk} is the interaction between subject effect and experimental setting (fixed effect), ε_{psv} is an error term or an interaction for subjects, seasonal impact and experimental setting (random interaction), O_l is the indoor temperature change (fixed effect), SO_{jl} is the interaction between seasonal impact and indoor temperature change (fixed effect), VO_{kl} is the interaction between experimental setting and indoor temperature change (fixed effect), SVO_{jkl} is the interaction for seasonal impact, experimental setting and indoor temperature change (fixed effect), ε_{psvo} is an error term or an interaction for subjects, seasonal impact, experimental setting and indoor temperature change (random interaction), T_m is the indoor temperature level (fixed effect), ST_{jm} is the interaction between seasonal impact and indoor temperature level (fixed effect), VT_{km} is the interaction between experimental setting and indoor temperature level (fixed effect), SVT_{jkm} is the interaction for seasonal impact, experimental setting and indoor temperature level (fixed effect), OT_{lm} is the interaction between indoor temperature change and indoor temperature level (fixed effect), SOT_{jlm} is the interaction for seasonal impact, indoor temperature change and indoor temperature level (fixed effect), VOT_{klm} is the interaction for experimental

setting, indoor temperature change and indoor temperature level (fixed effect), $SVOT_{jklm}$ is the interaction for seasonal impact, experimental setting, indoor temperature change and indoor temperature level (fixed effect), ε_{psvoT} is an error term or an interaction for subjects, seasonal impact, experimental setting, indoor temperature change and indoor temperature level (random interaction), and β_x can be any covariate for the pre-knowledge including subjects' age, gender, place of origin, Immersive tendencies, cybersickness after IVE experiment, and presence. Figure 4.34 conceptualizes the design of this study in that participants play the role of a block and they each receive all the experiment treatments while each impose their specific personal attributes (covariates) into the results of the manipulations.

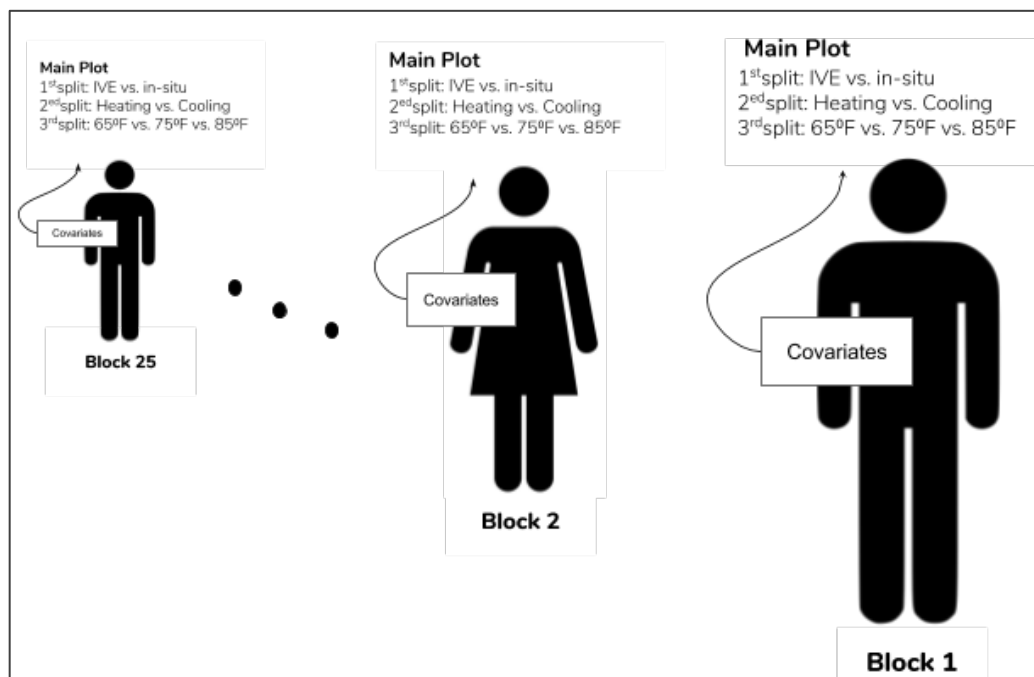


Figure 4.52 Customized split plot design with a randomized complete block design (RCBD) main plot

Table 4.30 presents the results of the mixed effect model using the p-values related to the significant tests for the effect of IVE on each responses variable of the study.

Table 4.30 Mixed Effect Model Results

Response Variables	Period 2 (warmer)						Period 1 (colder)					
	Cooling			Heating			Cooling			Heating		
	65	75	85	65	75	85	65	75	85	65	75	85
Forehead Skin Temperature (F)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00
Neck Skin Temperature (F)	0.84	0.96	0.70	0.81	0.97	0.79	0.14	0.99	0.99	0.44	0.26	0.04
Chest Skin Temperature (F)	0.94	0.76	0.61	0.72	0.68	0.66	0.90	0.72	0.81	0.05	0.18	0.18
Upper back Skin Temperature (F)	0.47	0.79	0.60	0.51	0.41	0.47	0.81	0.49	0.55	0.00	0.01	0.03
Forearm Skin Temperature (F)	0.64	0.20	0.71	0.97	0.75	0.48	0.06	0.95	0.32	0.47	0.85	0.59
Hand Skin Temperature (F)	0.81	0.28	0.81	0.76	0.91	0.99	0.13	0.26	0.34	0.02	0.39	0.83
Calf Skin Temperature (F)	0.80	0.39	0.85	0.04	0.10	0.13	0.88	0.87	0.87	0.69	0.81	0.79
Foot Skin Temperature (F)	0.23	0.62	0.23	0.25	0.47	0.57	0.65	0.83	0.73	0.48	0.44	0.60
GSR (5 μ S)	0.93	0.20	0.69	0.87	0.89	0.93	0.33	0.53	0.66	0.83	0.72	0.29
Heart Rate (bpm)	0.24	0.35	0.99	0.51	0.72	0.40	0.63	0.27	0.49	0.87	1.00	0.89
General Thermal Sensation	0.75	0.30	1.00	0.15	0.83	0.21	0.47	0.65	0.14	0.53	0.68	0.24
General Thermal Acceptability	0.63	0.91	0.52	0.92	1.00	0.34	0.86	0.69	0.67	0.92	1.00	0.79
General Thermal Comfort	0.83	0.59	0.29	0.72	0.83	0.59	0.88	0.45	0.59	0.53	0.83	0.86
Forehead Thermal Sensation	0.26	0.00	0.08	0.14	1.00	0.66	0.47	0.36	0.38	0.93	1.00	0.62
Forehead Thermal Acceptability	0.53	0.65	0.29	0.19	0.65	0.45	0.77	0.97	0.10	0.91	0.65	0.17
Neck Thermal Sensation	0.83	1.00	0.41	0.51	0.68	0.84	0.37	0.67	0.15	0.02	0.10	0.68
Neck Thermal Acceptability	0.38	0.57	0.20	0.83	0.47	0.67	0.76	0.65	0.04	0.30	0.67	1.00
Chest Thermal Sensation	0.40	0.83	0.66	0.45	1.00	0.13	0.50	0.14	0.66	0.64	0.83	0.43
Chest Thermal Acceptability	0.82	0.32	0.17	0.99	0.90	0.45	0.62	0.33	0.10	0.43	0.71	0.47
Upper back Thermal Sensation	0.28	0.70	0.08	0.72	0.85	0.18	0.66	0.63	0.44	0.30	0.18	0.22
Upper back Thermal Acceptability	0.47	0.53	0.10	0.78	0.90	0.45	0.26	0.71	0.06	0.99	0.71	0.39
Forearm Thermal Sensation	0.45	0.54	0.54	0.25	0.23	0.42	0.36	0.39	0.16	0.23	0.54	0.51
Forearm Thermal Acceptability	0.50	0.89	0.36	0.50	0.79	0.79	0.15	0.96	1.00	0.71	0.69	0.51
Hand Thermal Sensation	0.64	0.46	1.00	0.55	0.46	0.46	0.40	0.89	0.10	0.15	0.85	0.29
Hand Thermal Acceptability	0.24	1.00	0.64	0.25	0.64	0.81	0.35	0.71	0.48	0.84	0.48	0.80
Calf Thermal Sensation	0.56	0.67	0.40	0.24	0.53	0.29	0.53	0.05	0.00	0.14	0.83	0.64
Calf Thermal Acceptability	0.35	0.20	0.70	0.71	0.12	0.70	0.45	0.71	0.37	0.58	0.90	0.90
Foot Thermal Sensation	0.85	0.86	0.86	0.96	0.61	0.86	0.34	0.47	0.39	0.27	0.73	0.17
Foot Thermal Acceptability	0.87	0.58	0.32	0.79	0.74	0.82	0.46	0.88	0.74	0.69	0.82	0.90
Heart Rate Variability_RMSSD	0.72	0.18	0.29	0.07	0.99	0.45	0.50	0.25	0.03	0.57	0.94	0.97

(table cont'd.)

Response Variables	Period 2 (warmer)						Period 1 (colder)					
	Cooling			Heating			Cooling			Heating		
	65	75	85	65	75	85	65	75	85	65	75	85
Heart Rate Variability_LF/HF	0.16	0.10	0.16	0.56	0.55	0.58	0.37	0.21	0.82	0.87	0.36	0.28
Parasympathetic Nervous System (PNS)	0.29	0.09	0.27	0.04	0.82	0.40	0.36	0.35	0.05	0.53	0.81	0.83
Sympathetic Nervous System (SNS)	0.09	0.02	0.02	0.19	0.99	0.80	0.47	0.89	0.88	0.96	0.85	0.07

The highlighted cells are those with p-values smaller than 0.05, the likelihood of rejecting the null hypothesis, indicating that the measurements of the response variable of the study was significantly different between the IVE and in-situ experimental sessions. For example, for the response value for "Forehead Skin Temperature (F)", at "season=period 2 (warmer)", "experiment type=cooling" and "indoor temperature=65 °F", in IVE was significantly different from the same measure in the *in-situ* experiment (p-value<0.0001). Nonetheless, this study tends not to make conclusion based on marginally significant p-values. That is, it would not reject the null hypotheses only if there was very strong evidence against the null hypothesis in favor of the (e.g., p-value<0.001; less than one in a thousand chance of being wrong).

4.7.4.7 Post-experiment Questionnaire Results

Presence. The qualitative presence investigation was performed after every IVE experimental sessions. This scale, IPQ, consists of three major sub-measures of spatial presence, involvement, and the realness. The results of the questionnaires are shown in Table 4.31 are organized by the order of the IVE sessions, IVE-1 and IVE-2 refer to the first round of the data collection (Winter) and IVE-3 and IVE-4 are related to the second round (period 2, warmer). However, since the experiments were counterbalanced and randomized, each of the sessions include both the cooling and the heating exposures.

Table 4.31 Presence Questionnaire Results

Scale	Order	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	F Ratio	Prob>F
Spatial Presence	IVE-1	42	53.43	6.78	1.05	51.32	55.54	2.65	0.0490*
	IVE-2	29	56.00	8.62	1.60	52.72	59.28		
	IVE-3	101	51.96	11.93	1.19	49.61	54.31		
	IVE-4	108	50.48	10.05	0.97	48.56	52.40		
Presence_Involvement	IVE-1	42	65.83	7.32	1.13	63.55	68.11	1.63	0.18
	IVE-2	29	62.41	9.41	1.75	58.83	65.99		
	IVE-3	101	63.76	7.09	0.71	62.36	65.16		
	IVE-4	108	63.33	6.19	0.60	62.15	64.51		
Presence_Realness	IVE-1	42	59.88	8.66	1.34	57.18	62.58	2.91	0.0351*
	IVE-2	29	57.76	16.61	3.09	51.44	64.08		
	IVE-3	101	54.01	14.80	1.47	51.09	56.93		
	IVE-4	108	53.38	14.17	1.36	50.68	56.08		

Table 4.32 Physiological Measures Related to Presence

	Order	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	F Ratio	Prob>F
HR (bpm)	IVE-1	40	86.54	16.22	2.56	81.36	91.73	1.48	0.21
	IVE-2	23	80.90	9.52	1.98	76.79	85.02		
	IVE-3	98	81.00	13.05	1.32	78.39	83.62		
	IVE-4	108	80.58	19.01	1.83	76.95	84.20		
RMSSD	IVE-1	40	29.41	19.73	3.12	23.10	35.72	3.17	<.0246*
	IVE-2	26	62.27	77.15	15.13	31.10	93.43		
	IVE-3	101	62.27	63.29	6.30	49.77	74.76		
	IVE-4	108	60.83	64.60	6.22	48.51	73.15		
LF/HF	IVE-1	40	3.47	2.30	0.36	2.74	4.21	0.62	0.60
	IVE-2	26	2.97	3.01	0.59	1.75	4.18		
	IVE-3	101	3.11	3.53	0.35	2.42	3.81		
	IVE-4	108	2.75	2.78	0.27	2.22	3.28		
PNS	IVE-1	40	-1.51	1.11	0.18	-1.87	-1.16	6.23	0.0004*
	IVE-2	26	-0.03	2.41	0.47	-1.01	0.94		
	IVE-3	101	-0.18	1.91	0.19	-0.56	0.19		
	IVE-4	108	-0.18	1.80	0.17	-0.53	0.16		
SNS	IVE-1	40	2.74	2.79	0.44	1.85	3.64	9.14	<.0001*
	IVE-2	26	1.12	1.21	0.24	0.63	1.61		
	IVE-3	101	1.18	1.49	0.15	0.88	1.47		
	IVE-4	108	1.23	1.54	0.15	0.94	1.52		
GSR (5 μ)	IVE-1	42	1.16	0.80	0.12	0.92	1.41	4.64	0.0035*
	IVE-2	29	0.79	0.55	0.10	0.58	1.00		
	IVE-3	97	0.58	0.63	0.06	0.46	0.71		
	IVE-4	108	0.85	1.10	0.11	0.64	1.06		

Presence questionnaire revealed that IVE-1 and IVE-2 provided greater amount of spatial presence and realness for participants. Furthermore, HR, HRV and GSR data were used to provide support to the results of the presence questionnaire (Table 4.32). The study essentially expects that the physiological responses, which are hypothetically related to the concept of presence, match the results of the presence questionnaire. It revealed that in the first IVE sessions, HR, SNS, and GSR had their highest values among all 4 sessions. As discussed before, HR is strongly correlated with presence, and this confirms the results of the subjective measurements of the presence. Similarly, GSR reflects the intensity of human psychological arousal, and it suggests that participants felt more present while experiencing an IVE. On the other hand, the lowest RMSSD, and PNS were observed in the first session. According to the literature, RMSSD is correlated with HF power (Kleiger et al. 2005) and higher HF indicate a stronger influence of the PNS (A. Brogni, V. Vinayagamoorthy, A. Steed 2006; von Rosenberg et al. 2017). Lower HF power is correlated with stress, panic, anxiety, or worry (Shaffer and Ginsberg 2017). As discussed before, under mental stress conditions the LF component of the HRV increases and its HF component decreases. So, the lower value of RMSSD in the first IVE session can either suggest the absence of a strong PNS activity or availability of stress. Also, the first sessions of each season of the data collection (session IVE-1 and IVE-3) showed higher levels of the LF/HF (indicating anxiety or stress). Therefore, chances are that anxiety can still appear after a few months of IVE application.

Cybersickness. The qualitative cybersickness investigation was performed after every IVE experimental sessions. The data related to cybersickness is collected using SSQ standard, which is categorized into nausea, oculomotor, disorientation and total cybersickness (Table 4.33).

Table 4.33 Results of the Cybersickness Questionnaire

	Order	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	F Ratio	Prob>F
Cybersickne ss_ Nausea	IVE-1	42	14.99	12.84	1.98	10.99	18.99	5.39	<.0013*
	IVE-2	29	17.11	18.97	3.52	9.89	24.32		
	IVE-3	101	11.15	10.54	1.05	9.06	13.23		
	IVE-4	108	8.76	12.31	1.18	6.41	11.10		
Cybersickne ss_ Oculomotor	IVE-1	42	19.67	22.46	3.47	12.67	26.67	4.15	0.0067*
	IVE-2	29	20.39	24.40	4.53	11.11	29.67		
	IVE-3	101	15.24	15.22	1.51	12.23	18.24		
	IVE-4	108	11.86	13.56	1.31	9.27	14.45		
Cybersickne ss_ Disorientatio n	IVE-1	42	26.51	42.58	6.57	13.25	39.78	10.89	<.0001*
	IVE-2	29	29.76	33.43	6.21	17.05	42.47		
	IVE-3	101	11.03	17.75	1.77	7.52	14.53		
	IVE-4	108	10.58	12.75	1.23	8.14	13.01		
Total Cybersickne ss	IVE-1	42	22.71	25.84	3.99	14.66	30.76	7.65	<.0001*
	IVE-2	29	24.76	26.74	4.96	14.59	34.93		
	IVE-3	101	14.85	14.48	1.44	11.99	17.71		
	IVE-4	108	12.15	12.64	1.22	9.74	14.56		

This metrics can add useful insight to the experiment observations; e.g., they can offer explanations for possible discrepancies between the responses in IVEs comparing the baselines in *in-situ* to responses to the experimental stimuli. In this study, cybersickness, at all its levels, scored higher in IVE1 and IVE2 sessions, which confirms the results of the physiological data—producing the highest HR, SNS, LF, GSR and the lowest RMSSD, HF, PNS in the first session of the experiment. These all could indicate that stress or worry could have been potentially involved in IVE1 and IVE2 sessions.

4.8 Chapter Summary

This chapter was devoted to developing the theoretical framework of the study and the empirical evaluation of it. The main goal of the framework was to conceptualize the nature of the research and provide a structure in that the major components of the research could be presented and linked to each other. The framework also connected this research to the existing literature and

the pilot studies. Afterwards, several theoretical assumptions were articulated and possible associations between each of the variables were determined. With that, hypotheses were specifically formulated and were then evaluated through different statistical methods. Yet, each hypothesis presented a particular rationale for the research and investigated a certain dimension of the research problem. The hypotheses were all tested by empirical evaluation of the framework which was performed through proper experiment design and its execution. From each of the hypotheses testing, valuable findings were drawn which was followed by identifying the future directions. The hypothesis testing results are summarized as follows.

H1. The theoretical assumption on this test was that changing the indoor temperature between 65 °F to 85 °F has the same impact on participants' perception of the thermal environment in both IVE and *in-situ* settings. A deep look into the descriptive data on the indoor temperature and the statistical investigation of thermoception data together showed that under completely comparable experiment conditions, the overall pattern of the thermoceptions does not change. In all the IVE experimental sessions, the thermal sensation and the thermal comfort measurements showed a significantly similar pattern as in *in-situ*, however, the thermal acceptability in the cooling exposure, and more specifically at the level of -1 (slightly unacceptable), presented a significant difference. This can be linked to the inequivalent thermal condition of the indoor temperature across the two *in-situ* and IVE experimental settings in cooling exposures during the period 1 (colder) sessions. The physical constraints of the labs can usually cause discrepancies in observations, while performing repeated measured studies. Indeed, more research has to be done to determine the threshold of the indoor temperature variation in which thermoceptions would remain statistically consistent. Only after that, rigorous criteria can be defined in that respect.

H2. The theoretical assumption on this test was that changing the indoor temperature between 65 °F to 85 °F has the same impact on participants' T_{sk} , HR, HRV, and GSR in both IVE and *in-situ* settings. The significantly different local skin temperatures all occurred at the forehead, and this finding was, in fact, expected, due to the existence of the HMD over the participants' head. The other statistically different physiological measurements between the IVE and the *in-situ* were RMSSD at 85 °F (the cooling sequence), and PNS at 65 °F (the heating sequence) (both, i.e., RMSSD and PNS lower in IVE). It is worth noting that HRV metrics are non-invasive measures of ANS activities of the body (Sztajzel 2004), and given that RMSSD and PNS metrics are related to the HF. Since lower HF power is correlated with stress, panic, anxiety, or worry (Shaffer and Ginsberg 2017), it can be concluded that the lower values of RMSSD and PNS at 85 °F in the cooling exposure as well as at 65 °F in the heating exposure can refer to an increase in participants' stress during those segments of the experiments. Given the fact that both 85 °F of the cooling exposure and 65 °F of the heating exposure sessions were the beginning of the sessions, then this finding makes a logical sense, as the beginning of the IVE sessions could presumably alter individuals' psychological and mental states.

H3. This hypothesis was urged by the question of whether individuals' thermally-driven behavioral intentions would remain the same if the thermoception is different in IVE in comparison with the *in-situ*. The knowledge that is going to be gained from this hypothesis testing is specifically critical to the occupant behavior research and thermal comfort studies that aim to entirely replicate *in-situ* experiments with the IVEs. If this hypothesis fails, it suggests that thermally-driven behavioral intentions are not necessarily influenced by thermoceptions difference between IVE and *in-situ*, and under different perceptions of the thermal environments, one may or may not establish comparable behavioral patterns. Testing the variability of the participants'

thermally-driven behavioral intentions among the two levels of different vs. not different thermoceptions, resulted in finding no relationship between the two variables, meaning that, the behavioral intentions in IVEs vs. in *in-situ* are not necessarily equivalent/different if participants sense/perceive the thermal environment equivalently/differently. This observation was true for both the *in-situ* and IVE experiments, and it actually raised the need for finding the factors that contribute to the consistency of the thermally-driven behaviors.

H4. This hypothesis sought to explore the influence of the individual-related factors on the consistency of the thermally-driven behavioral intentions. So, both the frequency and the nature (be it eco-friendly/wasteful) of the behavioral intentions was examined. The factors that would possibly relate to the behavioral intentions were age, gender, education, employment, place of origin, immersive tendencies, computer skills and experience with VR) as well as post-experiment information (i.e., cybersickness, presence). The analyses of the collected sample of this study showed that the variables age, computer skills and experience with VR, and immersive tendency (entertainment) are positively correlated, and variable cybersickness (nausea) is negatively correlated with the total number of common thermally-driven behavioral intentions. The variables gender, education, employment, place of origin, and presence did not show any significant association with neither the nature nor the chance of consistency of the thermally-driven behavioral intentions between the *in-situ* and the IVE experimental settings.

H5. Pair-wise comparisons of thermoception measurements between the mismatched (*e.g.*, summer/cooling) and matched (*e.g.*, winter/cooling) seasonal sessions showed no significant difference among the groups of data. Thermally-driven behaviors in the IVE experiments showed significant independence from the seasons; in particular, the adaptive behavior 1 was selected for testing this assumption, and the proportion of it did not show it is significantly different between

the period 1 and period 2 sessions. However, this observation requires further investigation before making logical inferences about why the seasonal mismatches did not impact the thermally driven behaviors in the IVE, while it did in the in-situ.

The last discussed method for evaluating the sample of this study was fitting a mixed effect model to investigate both fixed and random effects alongside each other. The study came up with a design called randomized complete block design (RCBD), since the data was grouped, and the measurements were nested within the participants. The main goal was to keep the experimental error within each block as much as possible. In this method every block received a complete set of treatments, therefore differences among blocks are not due to treatments, and the variability among the participants can be estimated as a separate source of variation. Accounting for random effects are important since personal characteristics of the participants and their background could naturally be a source of creating discrepancies in the values of the responses. Majority of the findings from the mixed effect model, confirm the results of the previously discussed analysis; *e.g.*, discrepancy on forehead skin temperature across the IVE and in-situ as well as the imbalance readings of PNS, and SNS at the beginning of the experimental sessions. Yet, new information such as the impact of the IVE on upper back skin temperature was observed. To trace what variable exactly influenced this response variable, post-hoc tests would be required which will be a future study following this dissertation.

CHAPTER 5 CONCLUSIONS

5.1 General Discussions

This dissertation adopted a new strategy to incorporate human sensation and behavior in design to enhance building simulations. Despite the great advancements of multi-sensory IVEs in successfully replicating lifelike experiences in many domains, application of this technology to studying occupant behavior is still scarce. Although, there have been limited attempts examining sensations in IVEs, these efforts were not mature enough to replicate occupant energy behavior experiments. The pilot studies discussed in Chapter 3 of this dissertation provided several empirical observations about IVE applications in the field of studying occupant energy-use related behaviors. Each of the pilot studies provided an important piece of knowledge to take us one step closer to represent IVEs as replicas for conducting occupant behavior studies. They suggested important observations concerning the experiment design, procedure, and data processing to improve the validity of IVE-based data. Pilot study 1 explored how individuals experienced the lighting-related qualities of an indoor environment in an IVE. An experiment was designed and performed in participants' preferences for lighting as well as their visual comfort; visual stimulation and mood were compared across two similar IVE and *in-situ* indoor environments. The study discussed the issues regarding the likelihood of the visual sensory mismatches, the psychological implications, and the IVE-related sicknesses that could sabotage the realness of participants' synthetic experience in the IVE platform. Pilot study 2 and 3 evaluated another relevant area that contributes to how occupants perceive an indoor environment—thermoceptions and physiological responses. It was actually intended to discover whether the extrapolated findings from pilot study 1 could still be accurate with a different experimental stimulus—environment temperature. In other terms, could manipulating the thermal environment in IVEs produce

extensive evidence for the lighting study? Further, pilot study 4 opened up a new perspective in enabling IVEs for extended occupant behavior observations whilst accounting for the contextual-related necessities of the testing platform. Evidently, building occupant related information is context-sensitive and ideally experimenting with occupant behavior during the design phase should reflect different aspects of context. Literature has firmly declared that choices of occupant behavior in indoor environments can be influenced by variables such as the time, season and the indoor physical and functional qualities. The findings of pilot study 4 revealed that the design of the events as well as the associated cues (representing spatial, temporal, seasonal features of the indoor environment of the IVE) play important roles in the choices of occupant lighting-related behavioral intentions. There were cases that the IVE design or the associated cues could not properly characterize the events (*e.g., intermediate (short) leaves and returns from/to the office* in pilot study 4). Hence, careful design is required in order for an IVE to be able to present an intended scene and elicit realistic human-building interactions, accordingly. A well-grounded basis for developing a theoretical framework for this research was made possible by linking the observed findings and the procedures of the four pilot studies. Figure 5.1 shows the results of testing the hypothesis of the dissertation theoretical framework's empirical evaluation. Results of H1 and H2 tests revealed that changing the indoor temperature between 65 °F and 85 °F has the same impact on participants' thermoception, T_{sk} , HR, HRV, and GSR in both IVE and *in-situ* settings (exception cases exist which are discussed in the summary section of chapter 4). Testing H3 showed that individuals' thermoception differences between the IVE and the *in-situ* do not necessarily change their thermally-driven behavioral intentions. This finding suggests that even under different perceptions of the thermal environments, individuals may still select comparable thermally-driven behaviors.

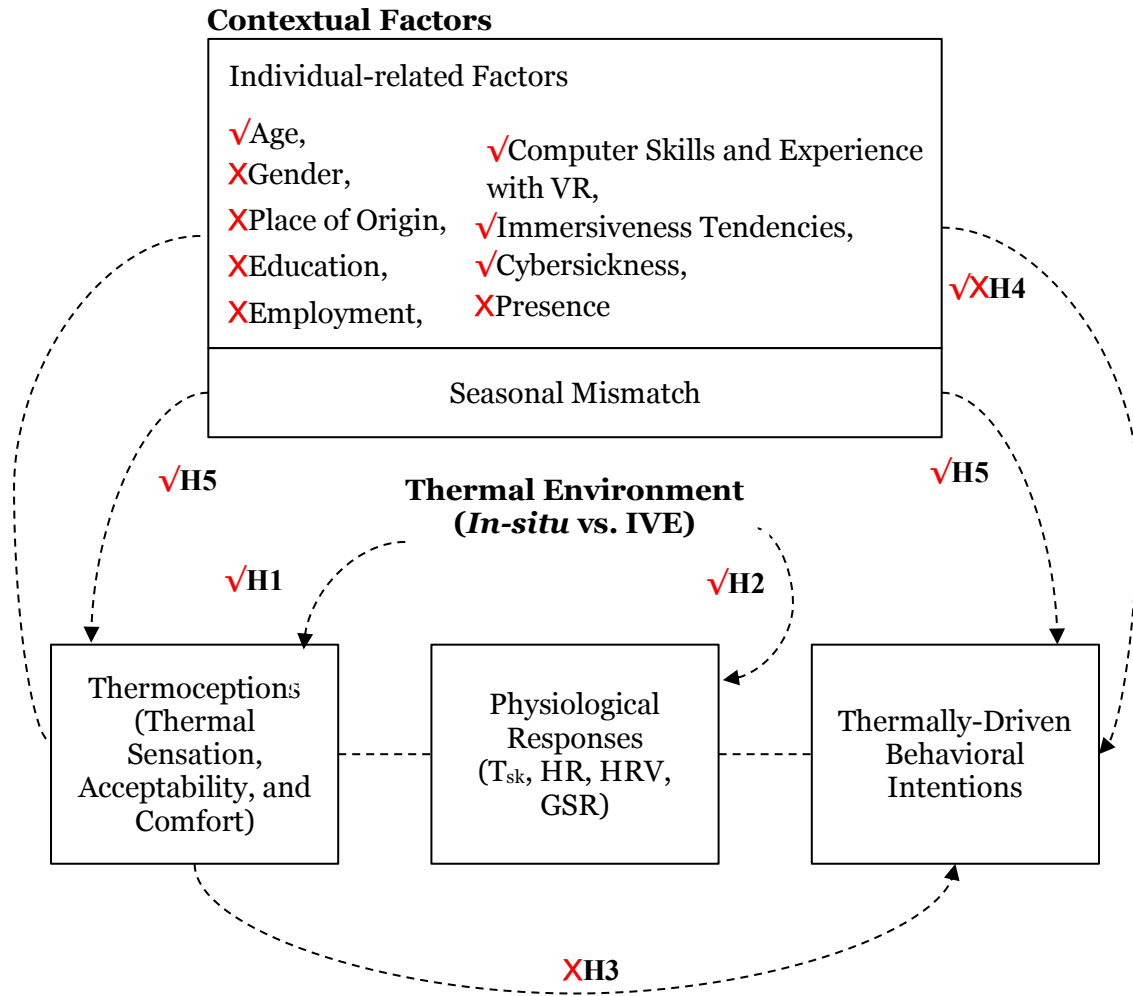


Figure 5.1 Hypotheses Testing Results

The findings of the H4 test are that age, computer skills and experience with VR, and immersive tendency (entertainment) are positively correlated, and cybersickness (nausea) is negatively correlated with the consistency of the thermally-driven behavioral intentions. The rest of the individual-related variables (*i.e.*, gender, highest level of education, employment, place of origin, presence) did not show a strong relationship with the thermally-driven behaviors. These findings help future experiments in more purposefully selecting participants. Lastly, H5 test results show that thermoceptions and thermally-driven behaviors in the IVE experiments are independent of the seasonal impacts, meaning that using simulated IVEs of one season (such as winter) to

collect thermal state and behavior data, while the actual season is different (such as summer), will not be a problem. Lastly, the results of the mixed effect model confirmed the majority of the hypothesis testing findings, where IVE intervention could cause interference in the response variables of the study and where it could completely replicate the *in-situ* experimenting condition.

5.2 Contributions

Several theoretical and practical implications can be carried from the findings of this dissertation. The most prominent theoretical achievement of this dissertation include adding a new insight about using immersive virtual environment for studying thermoceptions in predesign stages of buildings' life cycle. That is, the application of multi-sensory IVEs can provide future building occupants with thermal-experience of a non-physically-existent environment. In other words, this novel data collection approach can incorporate human thermoception in design, which is not possible with conventional data collection approaches. With that said, during the design stages of buildings occupant thermally-related feedback inputs can be captured and stored. This input can be analyzed, and the insight gained from the analysis is useful for improving building performance simulations.

The practical contribution of this dissertation is combining the state-of-the-art IVE with a climate chamber as a research/data collection tool. This dissertation answered fundamental questions regarding multi-sensory IVEs, *i.e.*, testing whether multi-sensory IVEs are capable of inducing the responses of individuals in the same way as *in-situ*. The pilot studies and the empirical evaluation of the proposed theoretical framework of the dissertation provide evidence in favor of the ecological validity of the IVE-based data. The pair-wise comparisons of the response variables of the studies across the two IVE and *in-situ* experimental settings indicated that multi-sensory IVEs are able to produce data comparable to the *in-situ* setting. The major value of using this tool

for data collection is that future building occupants are no longer passive viewers of the building design; they instead become a part of the design process, being fully immersive within multi-sensory IVEs. In other words, the occupants experience a non-physically existent environment first-hand, where their sensations and behaviors are incorporated into a synthetic experimental platform. This experience introduces many potentials that provides better insight about future occupants' interaction with the environment which could eventually reduce the performance gaps of new and retrofitting buildings.

Moreover, this dissertation investigated the potential of the multi-sensory IVEs for extended observations. In fact, pilot study 4 presented the idea of collecting longitudinal data to further extend the existing capabilities of multi-sensory IVEs for occupant behavior modeling. This possibility was examined using an event-driven modeling technique that could provide balanced coverage of observations, through repeated measures over various salient events. The concept was more extensively explored in hypothesis 5 of the dissertation where the temporal/seasonal aspects of the data were introduced; while, the *in-situ* sessions resulted in two statistically different sets of thermally-driven behavioral intentions, IVE sessions generated potentially similar thermally-driven behavioral intentions between the two contrasting seasons of the data collection. This finding raised the question of whether IVEs obfuscate some of the environmental factors that naturally impact individuals' behavioral intentions. It is critical to find more vivid evidence on the possible implications that IVEs could have on individuals' behavioral intentions so the event-driven modeling could be more confidently used. This dissertation makes another contribution in posing the above question to in order to maintain multi-sensory IVEs cognizant of the significance of context; *e.g.*, connecting space conditions and time, which are both critical to designing experiments for longitudinal data collection in built environments.

5.3 Practical Limitations and Future Directions

This dissertation showed promising potential for utilizing multi-sensory IVEs in the area of occupant energy behavior studies and provided the groundwork for future research. Nevertheless, given the exploratory nature of this dissertation, the conclusions of this research are dependent upon the conditions that this research is subject to. Here, in order to complement the ultimate goal of the dissertation, the limitations of this research and the future research directions are discussed below:

- 1) Although results from the current research and the pilot tests provided evidence for the ecological validity of the IVE-based occupant behavior studies, future investigation on the data is necessary to perform some other forms of validity and reliability analysis. The criterion-related validity can actually be extracted from the findings of hypothesis 1, 2, 3, and 5; the similarity/dissimilarity between the behavioral patterns between the two IVE and *in-situ* settings can be an indicator in testing the threats to this type of validity. Construct validity can also make possible to determine if the IVE simulations serve its purpose; it is necessary to add some other different categories of participants (*e.g.*, participants residing in cold climate) to see if the simulation and the treatment can differentiate between the groups. Providing evidence to support the external validity of the experiments and generalizing the findings of them also requires a more diverse sample (*e.g.*, more diverse participants in terms of age, education, computer proficiency). Face and content validity in this study can be simply established since the study used questionnaires, which have been widely used and tested previously. Last but not least, internal validity which is regarded as another important aspect of human-related experiments to answer if different experimental interventions or treatments (IVE and the *in-situ*) on participants is able to produce comparable cause and effect relation. To address the internal validity of the

application of the multi-sensory IVE for occupant behavior studies, design and data analysis for specific experiments are needed in future studies. Testing the reliability of the IVE-based data and the findings would involve repeating the studies with same method, using the same instruments and equipment. Experiments in this dissertation are in fact designed to be replicable.

2) As discussed in the literature review, human perception and experience is a complex phenomenon and it largely depends on the information obtained through different sensory modalities. In real buildings, occupant behavior is a response to various overlaying sensory influences, which occur simultaneously. To enable IVEs to provide a plausible experience of buildings, more advances around the VR technology are required in order to supply multi-sensory IVEs with more than simply the visual and thermal features of the environment, but to be able to replicate a more comprehensive list of sensory stimuli such as audio, touch, olfactory and so forth. The present dissertation provided a fair amount of presence; however, increasing the fidelity and the realism of the simulation can lead to better replicas of real-world experiences. As a matter of fact, more complicated IVE-based experiences must involve a closer examination of human-computer interactions and the psycho-physiological implications of them. Future study should explore all those possibilities offered by the current and future IVE technologies.

3) As the pilot studies showed, the design of IVE cues are important to correctly evoke participants' behavioral intentions. It seemed that IVEs are sensitive to the salient incidents more strongly. This study revealed that critical moments during the data collection may cause a change in the patterns of the data. Currently, IVE designs are mostly ad-hoc and vary case-by-case. Best practices or design principles addressing virtual experiences are needed to further advance the field.

4) This study originally intended to have a precise control on the ambient temperature and humidity around the participant, at 12 spots (4 corners around the participant, and at 3 levels of 4", 24, and 43"). However, due to technical issues in the readings, this data was not used in the analysis. Therefore, only the readings from one surface temperature probe which was placed near the participants' measurement spot (set at the level of 24" of the floor) was selected to present the ambient indoor temperature. Future studies should take a closer look into the temperature variations at different spots/levels surrounding participant, in the testing environment.

5) Lack of automation in processing of the dataset, which was a combination of various sensor readings as well as questionnaires, posed limitations in terms of time and iterations of data processing. For instance, it is beneficial to dig into different time intervals of the measurements of the physiological data and collect additional in-depth knowledge. Due to the manual processing of the data, this study was limited to merely analyzing the average data within specific time periods (*e.g.*, HR at 65 °F). Future research with automated data processing system should be able to reorganize the data representing different timeframes to gain deeper insight about the interventions at different periods of the data collection.

6) For generating effective analytical models about occupant behavior, it is required to apply more sophisticated mathematical models to find the best fit for the IVE-based data. This study applied a mixed effect model that could merely find the response variables that were influenced by being exposed to the IVE. To fully explore the major elements that caused this effect, more statistical testing and post-hoc examinations are necessary.

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APPENDIX A IMMERSIVE TENDENCIES QUESTIONNAIRE (ITQ)

Indicate your preferred answer by marking an "X" in the appropriate box of the seven point scale. Please consider the entire scale when making your responses, as the intermediate levels may apply. For example, if your response is once or twice, the second box from the left should be marked. If your response is many times but not extremely often, then the sixth (or second box from the right) should be marked.

1. Do you easily become deeply involved in movies or tv dramas?

NEVER			OCCASIONALLY			OFTEN

2. Do you ever become so involved in a television program or book that people have problems getting your attention?

NEVER			OCCASIONALLY			OFTEN

3. How mentally alert do you feel at the present time?

NOT ALERT			MODERATELY			FULLY ALERT

4. Do you ever become so involved in a movie that you are not aware of things happening around you?

NEVER			OCCASIONALLY			OFTEN

5. How frequently do you find yourself closely identifying with the characters in a story line?

NEVER			OCCASIONALLY			OFTEN

6. Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?

NEVER			OCCASIONALLY			OFTEN

7. How physically fit do you feel today?

NOT FIT			MODERATELY FIT			EXTREMELY FIT

8. How good are you at blocking out external distractions when you are involved in something?

NOT VERY GOOD			SOMEWHAT GOOD			VERY GOOD

9. When watching sports, do you ever become so involved in the game that you react as if you were one of the players?

NEVER			OCCASIONALLY			OFTEN

10. Do you ever become so involved in a daydream that you are not aware of things happening around you?

NEVER			OCCASIONALLY			OFTEN

11. Do you ever have dreams that are so real that you feel disoriented when you awake?

NEVER			OCCASIONALLY			OFTEN

12. When playing sports, do you become so involved in the game that you lose track of time?

NEVER			OCCASIONALLY			OFTEN

13. How well do you concentrate on enjoyable activities?

NOT AT ALL			MODERATELY WELL			VERY WELL

14. How often do you play arcade or video games? (OFTEN should be taken to mean every day or every two days, on average.)

| | | | |
NEVER OCCASIONALLY OFTEN

15. Have you ever gotten excited during a chase or fight scene on TV or in the movies?

| | | | |
NEVER OCCASIONALLY OFTEN

16. Have you ever gotten scared by something happening on a TV show or in a movie?

| | | | |
NEVER OCCASIONALLY OFTEN

17. Have you ever remained apprehensive or fearful long after watching a scary movie?

| | | | |
NEVER OCCASIONALLY OFTEN

18. Do you ever become so involved in doing something that you lose all track of time?

| | | | |
NEVER OCCASIONALLY OFTEN

APPENDIX B THEORY OF PLANNED BEHAVIOR (TPB) IN PREDICTING PRO-ENVIRONMENTAL BEHAVIOUR

Attitude measurements

- I believe it is adequate to conserve energy.
- I believe it is wise to conserve energy.
- I believe it is useful to conserve energy.
- I like to think that people should conserve energy.

Subjective norms measurements

- Most people who are important to me support my effort to conserve energy for environmental reasons
- Most people who are important to me think I should conserve energy for environmental reasons
- Most people who are important to me take steps to conserve energy for environmental reasons

Perceived behavioral control measurements

- I have enough environmental knowledge for discerning between responsible and harmful behaviour.
- I have the necessary will and wisdom to reduce energy consumption for environmental reasons.
- I have enough time and resources to use alternative means of ecological transport.
- I believe I am responsible for the environment we're living in.

Intention to behave in a pro-environmental manner measurements

- I want to conserve energy for environmental reasons.
- I intend to conserve energy for environmental reasons.
- I intend to use natural resources in a responsible manner (e.g. water, electricity, gas).
- I will try to reduce my carbon footprint in the forthcoming month.

Pro-environmental behavior measurements

- I leave the lights on when I leave a room*
- I leave the water running while brushing my teeth*
- I leave my computer on or asleep at night (not fully turned off)*
- I replace incandescent light bulbs with energy efficient alternatives
- I don't drive unless it's necessary and I try to use public transportation or the bicycle.

APPENDIX C IGROUP PRESENCE QUESTIONNAIRE (IPQ)

Number	PQ/II Nr. (internal)	IPQ item name	shortcut	loading on ...	English question	English anchors	Copyright (item source)
1	s62	G1	sense of being there	PRES	In the computer generated world I had a sense of "being there"	not at all--very much	Slater & Usoh (1994)
2	s44	SP1	sense of VE behind	SP	Somehow I felt that the virtual world surrounded me.	fully disagree-- fully agree	IPQ
3	s30	SP2	only pictures	SP	I felt like I was just perceiving pictures.	fully disagree-- fully agree	IPQ
4	s28	SP3	not sense of being in v. space	SP	I did not feel present in the virtual space.	did not feel--felt present	???
5	s31	SP4	sense of acting in VE	SP	I had a sense of acting in the virtual space, rather than operating something from outside.	fully disagree-- fully agree	IPQ
6	s33	SP5	sense of being present in VE	SP	I felt present in the virtual space.	fully disagree-- fully agree	IPQ
7	s64	INV1	awareness of real env.	INV	How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?	extremely aware-- moderately aware-not aware at all	Witmer & Singer (1994)
8	s37	INV2	not aware of real env.	INV	I was not aware of my real environment.	fully disagree-- fully agree	IPQ
9	s40	INV3	no attention to real env.	INV	I still paid attention to the real environment.	fully disagree-- fully agree	IPQ
10	s38	INV4	attention captivated by VE	INV	I was completely captivated by the virtual world.	fully disagree-- fully agree	IPQ
11	s48	REAL1	VE real (real/not real)	REAL	How real did the virtual world seem to you?	completely real-- not real at all	Hendrix (1994)
12	s7	REAL2	experience similar to real env.	REAL	How much did your experience in the virtual environment seem consistent with your real world experience ?	not consistent-- moderately consistent-very consistent	Witmer & Singer (1994)
13	s59	REAL3	VE real (imagined/real)	REAL	How real did the virtual world seem to you?	about as real as an imagined world-- indistinguishable from the real world	Carlin, Hoffman, & Weghorst (1997)
14	s47	REAL4	VE wirklich	REAL	The virtual world seemed more realistic than the real world.	fully disagree-- fully agree	IPQ

APPENDIX D SIMULATOR SICKNESS QUESTIONNAIRE (SSQ)

Instructions : Circle how much each symptom below is affecting you right now.

1. General discomfort	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
2. Fatigue	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
3. Headache	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
4. Eye strain	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
5. Difficulty focusing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
6. Salivation increasing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
7. Sweating	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
8. Nausea	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
9. Difficulty concentrating	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
10. « Fullness of the Head »	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
11. Blurred vision	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
12. Dizziness with eyes open	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
13. Dizziness with eyes closed	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
14. *Vertigo	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
15. **Stomach awareness	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
16. Burping	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version : March 2013

***Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3(3), 203-220.

APPENDIX E THERMOCEPTIONS BETWEEN ALL THE PAIRS OF IN-SITU AND IVE EXPERIMENTAL SETTINGS

Table E.1 General Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.17	1.38	0.23	-0.30	0.65	ns, P > 0.05
1/Winter/Cooling/IVE	30	-0.13	1.25	0.23	-0.60	0.33	
1/Winter/Heating/in-situ	36	0.39	1.50	0.25	-0.12	0.90	ns, P > 0.05
1/Winter/Heating/IVE	47	0.26	1.47	0.21	-0.18	0.69	
2/Winter/Cooling/in-situ	28	-0.07	1.44	0.27	-0.63	0.49	ns, P > 0.05
2/Winter/Cooling/IVE	33	0.03	1.33	0.23	-0.44	0.50	
2/Winter/Heating/in-situ	48	0.19	1.45	0.21	-0.23	0.61	ns, P > 0.05
2/Winter/Heating/IVE	36	-0.14	1.29	0.22	-0.58	0.30	
3/Summer/Cooling/in-situ	32	0.28	1.25	0.22	-0.17	0.73	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.38	1.29	0.23	-0.09	0.84	
3/Summer/Heating/in-situ	33	-0.06	1.46	0.25	-0.58	0.46	ns, P > 0.05
3/Summer/Heating/IVE	33	0.03	1.26	0.22	-0.42	0.48	
4/Summer/Cooling/in-situ	24	0.29	1.43	0.29	-0.31	0.90	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.29	1.40	0.29	-0.30	0.88	
4/Summer/Heating/in-situ	44	0.05	1.48	0.22	-0.40	0.49	ns, P > 0.05
4/Summer/Heating/IVE	44	-0.02	1.39	0.21	-0.45	0.40	

Table E.2 General Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.97	1.60	0.27	0.42	1.52	ns, P > 0.05
1/Winter/Cooling/IVE	30	1.47	1.36	0.25	0.96	1.97	
1/Winter/Heating/in-situ	36	1.42	1.54	0.26	0.90	1.94	ns, P > 0.05
1/Winter/Heating/IVE	47	1.17	1.52	0.22	0.72	1.62	
2/Winter/Cooling/in-situ	28	1.07	1.46	0.28	0.50	1.64	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.12	1.67	0.29	0.53	1.71	
2/Winter/Heating/in-situ	48	0.96	1.61	0.23	0.49	1.43	ns, P > 0.05
2/Winter/Heating/IVE	36	1.36	1.57	0.26	0.83	1.89	
3/Summer/Cooling/in-situ	32	1.13	1.66	0.29	0.53	1.72	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.91	1.80	0.32	0.26	1.56	
3/Summer/Heating/in-situ	33	0.94	1.56	0.27	0.39	1.49	ns, P > 0.05
3/Summer/Heating/IVE	33	1.09	1.55	0.27	0.54	1.64	
4/Summer/Cooling/in-situ	24	1.13	1.57	0.32	0.46	1.79	ns, P > 0.05
4/Summer/Cooling/IVE	24	1.17	1.46	0.30	0.55	1.79	
4/Summer/Heating/in-situ	44	0.73	1.66	0.25	0.22	1.23	ns, P > 0.05
4/Summer/Heating/IVE	44	0.80	1.66	0.25	0.29	1.30	

Table E.3 General Thermal Comfort

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.06	1.63	0.27	0.50	1.62	ns, P > 0.05
1/Winter/Cooling/IVE	30	1.57	1.22	0.22	1.11	2.02	
1/Winter/Heating/in-situ	36	1.42	1.52	0.25	0.90	1.93	ns, P > 0.05
1/Winter/Heating/IVE	47	1.15	1.57	0.23	0.69	1.61	
2/Winter/Cooling/in-situ	28	1.14	1.58	0.30	0.53	1.76	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.12	1.54	0.27	0.58	1.67	
2/Winter/Heating/in-situ	48	1.04	1.64	0.24	0.57	1.52	ns, P > 0.05
2/Winter/Heating/IVE	36	1.00	1.67	0.28	0.43	1.57	
3/Summer/Cooling/in-situ	32	1.09	1.65	0.29	0.50	1.69	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.84	1.85	0.33	0.18	1.51	
3/Summer/Heating/in-situ	33	0.82	1.55	0.27	0.27	1.37	ns, P > 0.05
3/Summer/Heating/IVE	33	0.97	1.69	0.29	0.37	1.57	
4/Summer/Cooling/in-situ	24	1.17	1.58	0.32	0.50	1.83	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.96	1.57	0.32	0.29	1.62	
4/Summer/Heating/in-situ	44	0.59	1.76	0.26	0.06	1.12	ns, P > 0.05
4/Summer/Heating/IVE	44	0.70	1.76	0.27	0.17	1.24	

Table E.4 Forehead Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.40	0.95	0.16	0.08	0.72	ns, P > 0.05
1/Winter/Cooling/IVE	30	0.60	0.77	0.14	0.31	0.89	
1/Winter/Heating/in-situ	36	0.83	0.85	0.14	0.55	1.12	P < 0.05*
1/Winter/Heating/IVE	47	0.36	0.79	0.12	0.13	0.59	
2/Winter/Cooling/in-situ	28	0.32	0.98	0.19	-0.06	0.70	P < 0.05*
2/Winter/Cooling/IVE	33	0.45	0.71	0.12	0.20	0.71	
2/Winter/Heating/in-situ	48	0.35	0.84	0.12	0.11	0.60	ns, P > 0.05
2/Winter/Heating/IVE	36	0.58	0.91	0.15	0.28	0.89	
3/Summer/Cooling/in-situ	32	0.34	1.07	0.19	-0.04	0.73	P < 0.05*
3/Summer/Cooling/IVE	32	0.94	0.98	0.17	0.58	1.29	
3/Summer/Heating/in-situ	33	0.73	1.01	0.18	0.37	1.08	P < 0.05*
3/Summer/Heating/IVE	33	0.97	0.88	0.15	0.66	1.28	
4/Summer/Cooling/in-situ	24	0.63	0.92	0.19	0.23	1.02	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.88	0.99	0.20	0.46	1.29	
4/Summer/Heating/in-situ	44	0.30	0.93	0.14	0.01	0.58	ns, P > 0.05
4/Summer/Heating/IVE	44	0.30	0.82	0.12	0.05	0.55	

Table E.5 Forehead Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.46	1.24	0.21	1.03	1.88	P < 0.05*
1/Winter/Cooling/IVE	30	1.97	1.13	0.21	1.55	2.39	
1/Winter/Heating/in-situ	36	1.67	1.24	0.21	1.25	2.09	P < 0.05*
1/Winter/Heating/IVE	47	1.83	1.15	0.17	1.49	2.17	
2/Winter/Cooling/in-situ	28	1.39	1.45	0.27	0.83	1.95	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.70	0.92	0.16	1.37	2.02	
2/Winter/Heating/in-situ	48	1.65	1.04	0.15	1.34	1.95	ns, P > 0.05
2/Winter/Heating/IVE	36	1.86	1.20	0.20	1.46	2.27	
3/Summer/Cooling/in-situ	32	1.09	1.51	0.27	0.55	1.64	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.91	1.78	0.32	0.26	1.55	
3/Summer/Heating/in-situ	33	1.73	1.15	0.20	1.32	2.14	ns, P > 0.05
3/Summer/Heating/IVE	33	1.67	1.24	0.22	1.23	2.11	
4/Summer/Cooling/in-situ	24	1.50	1.06	0.22	1.05	1.95	ns, P > 0.05
4/Summer/Cooling/IVE	24	1.42	1.44	0.29	0.81	2.03	
4/Summer/Heating/in-situ	44	1.30	1.30	0.20	0.90	1.69	ns, P > 0.05
4/Summer/Heating/IVE	44	1.43	1.26	0.19	1.05	1.82	

Table E.6 Neck Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.26	0.89	0.15	-0.05	0.56	P < 0.05*
1/Winter/Cooling/IVE	30	-0.10	0.76	0.14	-0.38	0.18	
1/Winter/Heating/in-situ	36	0.83	0.85	0.14	0.55	1.12	P < 0.05*
1/Winter/Heating/IVE	47	0.30	1.06	0.15	-0.01	0.61	
2/Winter/Cooling/in-situ	28	0.21	0.79	0.15	-0.09	0.52	P < 0.05*
2/Winter/Cooling/IVE	33	0.09	0.72	0.13	-0.17	0.35	
2/Winter/Heating/in-situ	48	0.29	0.82	0.12	0.05	0.53	ns, P > 0.05
2/Winter/Heating/IVE	36	0.06	0.86	0.14	-0.24	0.35	
3/Summer/Cooling/in-situ	32	0.31	0.93	0.16	-0.02	0.65	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.47	0.98	0.17	0.11	0.82	
3/Summer/Heating/in-situ	33	0.36	0.93	0.16	0.03	0.69	ns, P > 0.05
3/Summer/Heating/IVE	33	0.42	0.87	0.15	0.12	0.73	
4/Summer/Cooling/in-situ	24	0.50	0.78	0.16	0.17	0.83	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.42	1.02	0.21	-0.01	0.85	
4/Summer/Heating/in-situ	44	0.23	0.86	0.13	-0.03	0.49	ns, P > 0.05
4/Summer/Heating/IVE	44	0.09	1.05	0.16	-0.23	0.41	

Table E.7 Neck Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.51	1.20	0.20	1.10	1.93	ns, P > 0.05
1/Winter/Cooling/IVE	30	1.87	0.97	0.18	1.50	2.23	
1/Winter/Heating/in-situ	36	1.92	0.91	0.15	1.61	2.22	ns, P > 0.05
1/Winter/Heating/IVE	47	1.53	1.35	0.20	1.14	1.93	
2/Winter/Cooling/in-situ	28	1.75	1.14	0.22	1.31	2.19	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.79	0.82	0.14	1.50	2.08	
2/Winter/Heating/in-situ	48	1.56	1.11	0.16	1.24	1.88	ns, P > 0.05
2/Winter/Heating/IVE	36	1.89	1.19	0.20	1.49	2.29	
3/Summer/Cooling/in-situ	32	1.28	1.46	0.26	0.75	1.81	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.91	1.71	0.30	0.29	1.52	
3/Summer/Heating/in-situ	33	1.73	1.15	0.20	1.32	2.14	ns, P > 0.05
3/Summer/Heating/IVE	33	1.85	0.94	0.16	1.52	2.18	
4/Summer/Cooling/in-situ	24	1.42	1.32	0.27	0.86	1.97	ns, P > 0.05
4/Summer/Cooling/IVE	24	1.42	1.25	0.25	0.89	1.94	
4/Summer/Heating/in-situ	44	1.39	1.22	0.18	1.01	1.76	ns, P > 0.05
4/Summer/Heating/IVE	44	1.27	1.44	0.22	0.84	1.71	

Table E.8 Chest Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.63	1.03	0.17	0.27	0.98	ns, P > 0.05
1/Winter/Cooling/IVE	30	0.37	0.81	0.15	0.06	0.67	
1/Winter/Heating/in-situ	36	1.03	1.06	0.18	0.67	1.38	ns, P > 0.05
1/Winter/Heating/IVE	47	0.70	0.91	0.13	0.44	0.97	
2/Winter/Cooling/in-situ	28	0.46	0.92	0.17	0.11	0.82	ns, P > 0.05
2/Winter/Cooling/IVE	33	0.39	0.83	0.14	0.10	0.69	
2/Winter/Heating/in-situ	48	0.54	0.87	0.13	0.29	0.80	ns, P > 0.05
2/Winter/Heating/IVE	36	0.47	0.91	0.15	0.16	0.78	
3/Summer/Cooling/in-situ	32	0.56	0.88	0.16	0.25	0.88	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.63	1.07	0.19	0.24	1.01	
3/Summer/Heating/in-situ	33	0.79	0.99	0.17	0.44	1.14	ns, P > 0.05
3/Summer/Heating/IVE	33	0.67	0.96	0.17	0.33	1.01	
4/Summer/Cooling/in-situ	24	0.83	0.87	0.18	0.47	1.20	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.83	1.09	0.22	0.37	1.29	
4/Summer/Heating/in-situ	44	0.50	0.95	0.14	0.21	0.79	ns, P > 0.05
4/Summer/Heating/IVE	44	0.34	0.96	0.15	0.05	0.63	

Table E.9 Chest Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.20	1.41	0.24	0.72	1.68	P < 0.05*
1/Winter/Cooling/IVE	30	1.87	1.11	0.20	1.45	2.28	
1/Winter/Heating/in-situ	36	1.53	1.42	0.24	1.05	2.01	ns, P > 0.05
1/Winter/Heating/IVE	47	1.64	1.36	0.20	1.24	2.04	
2/Winter/Cooling/in-situ	28	1.71	1.05	0.20	1.31	2.12	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.61	1.14	0.20	1.20	2.01	
2/Winter/Heating/in-situ	48	1.35	1.31	0.19	0.97	1.74	ns, P > 0.05
2/Winter/Heating/IVE	36	1.78	1.15	0.19	1.39	2.17	
3/Summer/Cooling/in-situ	32	1.38	1.24	0.22	0.93	1.82	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.94	1.79	0.32	0.29	1.58	
3/Summer/Heating/in-situ	33	1.55	1.25	0.22	1.10	1.99	ns, P > 0.05
3/Summer/Heating/IVE	33	1.64	1.50	0.26	1.11	2.17	
4/Summer/Cooling/in-situ	24	1.54	1.14	0.23	1.06	2.02	ns, P > 0.05
4/Summer/Cooling/IVE	24	1.33	1.52	0.31	0.69	1.98	
4/Summer/Heating/in-situ	44	1.09	1.57	0.24	0.61	1.57	ns, P > 0.05
4/Summer/Heating/IVE	44	1.11	1.63	0.25	0.62	1.61	

Table E.10 Upper back Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.31	0.96	0.16	-0.02	0.65	ns, P > 0.05
1/Winter/Cooling/IVE	30	0.10	0.61	0.11	-0.13	0.33	
1/Winter/Heating/in-situ	36	0.75	0.84	0.14	0.47	1.03	P < 0.05*
1/Winter/Heating/IVE	47	0.34	0.96	0.14	0.06	0.62	
2/Winter/Cooling/in-situ	28	0.21	0.74	0.14	-0.07	0.50	ns, P > 0.05
2/Winter/Cooling/IVE	33	0.24	0.87	0.15	-0.07	0.55	
2/Winter/Heating/in-situ	48	0.35	0.89	0.13	0.10	0.61	ns, P > 0.05
2/Winter/Heating/IVE	36	0.17	0.70	0.12	-0.07	0.40	
3/Summer/Cooling/in-situ	32	0.34	0.94	0.17	0.01	0.68	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.59	1.24	0.22	0.15	1.04	
3/Summer/Heating/in-situ	33	0.30	1.02	0.18	-0.06	0.66	ns, P > 0.05
3/Summer/Heating/IVE	33	0.48	0.94	0.16	0.15	0.82	
4/Summer/Cooling/in-situ	24	0.71	0.86	0.18	0.35	1.07	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.58	1.14	0.23	0.10	1.06	
4/Summer/Heating/in-situ	44	0.11	1.06	0.16	-0.21	0.44	ns, P > 0.05
4/Summer/Heating/IVE	44	0.20	1.05	0.16	-0.11	0.52	

Table E.11 Upper back Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.26	1.36	0.23	0.79	1.72	P < 0.05*
1/Winter/Cooling/IVE	30	2.00	0.87	0.16	1.67	2.33	
1/Winter/Heating/in-situ	36	1.58	1.34	0.22	1.13	2.04	ns, P > 0.05
1/Winter/Heating/IVE	47	1.70	1.21	0.18	1.35	2.06	
2/Winter/Cooling/in-situ	28	1.68	1.16	0.22	1.23	2.13	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.55	1.15	0.20	1.14	1.95	
2/Winter/Heating/in-situ	48	1.54	1.03	0.15	1.24	1.84	ns, P > 0.05
2/Winter/Heating/IVE	36	1.69	1.17	0.19	1.30	2.09	
3/Summer/Cooling/in-situ	32	1.28	1.40	0.25	0.78	1.78	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.94	1.93	0.34	0.24	1.63	
3/Summer/Heating/in-situ	33	1.73	1.15	0.20	1.32	2.14	ns, P > 0.05
3/Summer/Heating/IVE	33	1.67	1.24	0.22	1.23	2.11	
4/Summer/Cooling/in-situ	24	1.46	1.35	0.28	0.89	2.03	ns, P > 0.05
4/Summer/Cooling/IVE	24	1.21	1.47	0.30	0.59	1.83	
4/Summer/Heating/in-situ	44	1.18	1.57	0.24	0.70	1.66	ns, P > 0.05
4/Summer/Heating/IVE	44	1.25	1.45	0.22	0.81	1.69	

Table E.12 Forearm Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.14	1.00	0.17	-0.20	0.49	ns, P > 0.05
1/Winter/Cooling/IVE	30	0.07	0.87	0.16	-0.26	0.39	
1/Winter/Heating/in-situ	36	0.42	1.05	0.18	0.06	0.77	ns, P > 0.05
1/Winter/Heating/IVE	47	0.09	1.23	0.18	-0.28	0.45	
2/Winter/Cooling/in-situ	28	0.11	0.96	0.18	-0.26	0.48	ns, P > 0.05
2/Winter/Cooling/IVE	33	-0.12	0.78	0.14	-0.40	0.16	
2/Winter/Heating/in-situ	48	-0.02	0.91	0.13	-0.29	0.24	ns, P > 0.05
2/Winter/Heating/IVE	36	0.11	0.95	0.16	-0.21	0.43	
3/Summer/Cooling/in-situ	32	0.03	1.03	0.18	-0.34	0.40	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.22	1.16	0.20	-0.20	0.64	
3/Summer/Heating/in-situ	33	0.12	1.17	0.20	-0.29	0.53	ns, P > 0.05
3/Summer/Heating/IVE	33	0.12	0.96	0.17	-0.22	0.46	
4/Summer/Cooling/in-situ	24	0.29	0.91	0.19	-0.09	0.68	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.25	1.15	0.24	-0.24	0.74	
4/Summer/Heating/in-situ	44	-0.02	1.05	0.16	-0.34	0.30	ns, P > 0.05
4/Summer/Heating/IVE	44	-0.20	1.09	0.16	-0.54	0.13	

Table E.13 Forearm Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.51	1.25	0.21	1.09	1.94	ns, P > 0.05
1/Winter/Cooling/IVE	30	1.87	0.94	0.17	1.52	2.22	
1/Winter/Heating/in-situ	36	1.86	1.02	0.17	1.52	2.21	ns, P > 0.05
1/Winter/Heating/IVE	47	1.60	1.26	0.18	1.23	1.97	
2/Winter/Cooling/in-situ	28	1.64	1.22	0.23	1.17	2.12	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.67	0.96	0.17	1.33	2.01	
2/Winter/Heating/in-situ	48	1.52	1.07	0.15	1.21	1.83	ns, P > 0.05
2/Winter/Heating/IVE	36	1.67	1.22	0.20	1.25	2.08	
3/Summer/Cooling/in-situ	32	1.28	1.44	0.25	0.76	1.80	ns, P > 0.05
3/Summer/Cooling/IVE	32	1.13	1.74	0.31	0.50	1.75	
3/Summer/Heating/in-situ	33	1.79	0.93	0.16	1.46	2.12	ns, P > 0.05
3/Summer/Heating/IVE	33	1.82	0.98	0.17	1.47	2.17	
4/Summer/Cooling/in-situ	24	1.46	1.10	0.23	0.99	1.92	ns, P > 0.05
4/Summer/Cooling/IVE	24	1.42	1.21	0.25	0.90	1.93	
4/Summer/Heating/in-situ	44	1.32	1.34	0.20	0.91	1.73	ns, P > 0.05
4/Summer/Heating/IVE	44	1.18	1.43	0.22	0.75	1.62	

Table E.14 Hand Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.49	1.22	0.21	0.07	0.91	ns, P > 0.05
1/Winter/Cooling/IVE	30	0.57	0.97	0.18	0.20	0.93	
1/Winter/Heating/in-situ	36	0.36	1.29	0.22	-0.08	0.80	ns, P > 0.05
1/Winter/Heating/IVE	47	0.26	1.48	0.22	-0.18	0.69	
2/Winter/Cooling/in-situ	28	0.43	1.20	0.23	-0.04	0.89	ns, P > 0.05
2/Winter/Cooling/IVE	33	0.18	1.07	0.19	-0.20	0.56	
2/Winter/Heating/in-situ	48	0.23	1.17	0.17	-0.11	0.57	ns, P > 0.05
2/Winter/Heating/IVE	36	0.25	1.25	0.21	-0.17	0.67	
3/Summer/Cooling/in-situ	32	0.22	1.21	0.21	-0.22	0.66	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.25	1.22	0.22	-0.19	0.69	
3/Summer/Heating/in-situ	33	0.42	1.09	0.19	0.04	0.81	ns, P > 0.05
3/Summer/Heating/IVE	33	0.52	1.18	0.20	0.10	0.93	
4/Summer/Cooling/in-situ	24	0.71	1.27	0.26	0.17	1.24	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.79	1.32	0.27	0.24	1.35	
4/Summer/Heating/in-situ	44	-0.23	1.27	0.19	-0.61	0.16	ns, P > 0.05
4/Summer/Heating/IVE	44	-0.16	1.20	0.18	-0.52	0.21	

Table E.15 Hand Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.20	1.53	0.26	0.67	1.73	P < 0.05*
1/Winter/Cooling/IVE	30	1.83	1.05	0.19	1.44	2.23	
1/Winter/Heating/in-situ	36	1.67	1.20	0.20	1.26	2.07	ns, P > 0.05
1/Winter/Heating/IVE	47	1.36	1.42	0.21	0.94	1.78	
2/Winter/Cooling/in-situ	28	1.46	1.17	0.22	1.01	1.92	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.45	1.23	0.21	1.02	1.89	
2/Winter/Heating/in-situ	48	1.31	1.43	0.21	0.90	1.73	ns, P > 0.05
2/Winter/Heating/IVE	36	1.50	1.25	0.21	1.08	1.92	
3/Summer/Cooling/in-situ	32	1.13	1.45	0.26	0.60	1.65	ns, P > 0.05
3/Summer/Cooling/IVE	32	1.19	1.49	0.26	0.65	1.72	
3/Summer/Heating/in-situ	33	1.52	1.00	0.17	1.16	1.87	ns, P > 0.05
3/Summer/Heating/IVE	33	1.45	1.30	0.23	0.99	1.92	
4/Summer/Cooling/in-situ	24	1.04	1.52	0.31	0.40	1.68	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.92	1.56	0.32	0.26	1.57	
4/Summer/Heating/in-situ	44	1.20	1.42	0.21	0.77	1.64	ns, P > 0.05
4/Summer/Heating/IVE	44	0.98	1.49	0.22	0.53	1.43	

Table E.16 Calf Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	-0.17	1.04	0.18	-0.53	0.19	ns, P > 0.05
1/Winter/Cooling/IVE	30	-0.40	0.77	0.14	-0.69	-0.11	
1/Winter/Heating/in-situ	36	0.03	1.11	0.18	-0.35	0.40	ns, P > 0.05
1/Winter/Heating/IVE	47	-0.26	0.92	0.13	-0.53	0.01	
2/Winter/Cooling/in-situ	28	-0.32	1.09	0.21	-0.74	0.10	ns, P > 0.05
2/Winter/Cooling/IVE	33	-0.61	0.83	0.14	-0.90	-0.31	
2/Winter/Heating/in-situ	48	-0.33	0.78	0.11	-0.56	-0.11	ns, P > 0.05
2/Winter/Heating/IVE	36	-0.42	1.05	0.18	-0.77	-0.06	
3/Summer/Cooling/in-situ	32	-0.09	1.06	0.19	-0.48	0.29	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.00	1.14	0.20	-0.41	0.41	
3/Summer/Heating/in-situ	33	-0.30	1.10	0.19	-0.69	0.09	ns, P > 0.05
3/Summer/Heating/IVE	33	-0.27	0.88	0.15	-0.58	0.04	
4/Summer/Cooling/in-situ	24	0.13	0.99	0.20	-0.29	0.54	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.08	0.97	0.20	-0.33	0.49	
4/Summer/Heating/in-situ	44	-0.30	1.11	0.17	-0.63	0.04	ns, P > 0.05
4/Summer/Heating/IVE	44	-0.36	1.04	0.16	-0.68	-0.05	

Table E.17 Calf Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.49	1.12	0.19	1.10	1.87	ns, P > 0.05
1/Winter/Cooling/IVE	30	1.53	1.38	0.25	1.02	2.05	
1/Winter/Heating/in-situ	36	1.78	1.24	0.21	1.36	2.20	ns, P > 0.05
1/Winter/Heating/IVE	47	1.55	1.25	0.18	1.19	1.92	
2/Winter/Cooling/in-situ	28	1.46	1.32	0.25	0.95	1.98	ns, P > 0.05
2/Winter/Cooling/IVE	33	1.73	1.07	0.19	1.35	2.11	
2/Winter/Heating/in-situ	48	1.42	1.20	0.17	1.07	1.77	ns, P > 0.05
2/Winter/Heating/IVE	36	1.39	1.48	0.25	0.89	1.89	
3/Summer/Cooling/in-situ	32	1.13	1.60	0.28	0.55	1.70	ns, P > 0.05
3/Summer/Cooling/IVE	32	1.41	1.50	0.27	0.87	1.95	
3/Summer/Heating/in-situ	33	1.52	1.15	0.20	1.11	1.92	ns, P > 0.05
3/Summer/Heating/IVE	33	1.39	1.30	0.23	0.93	1.85	
4/Summer/Cooling/in-situ	24	1.46	1.25	0.26	0.93	1.99	ns, P > 0.05
4/Summer/Cooling/IVE	24	1.46	1.22	0.25	0.95	1.97	
4/Summer/Heating/in-situ	44	1.25	1.51	0.23	0.79	1.71	ns, P > 0.05
4/Summer/Heating/IVE	44	1.07	1.50	0.23	0.61	1.52	

Table E.18 Foot Thermal Sensation

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.03	1.15	0.19	-0.37	0.42	ns, P > 0.05
1/Winter/Cooling/IVE	30	-0.13	1.14	0.21	-0.56	0.29	
1/Winter/Heating/in-situ	36	-0.11	1.37	0.23	-0.57	0.35	ns, P > 0.05
1/Winter/Heating/IVE	47	-0.62	1.17	0.17	-0.96	-0.27	
2/Winter/Cooling/in-situ	28	-0.54	1.17	0.22	-0.99	-0.08	ns, P > 0.05
2/Winter/Cooling/IVE	33	-0.36	1.14	0.20	-0.77	0.04	
2/Winter/Heating/in-situ	48	-0.81	1.08	0.16	-1.13	-0.50	ns, P > 0.05
2/Winter/Heating/IVE	36	-0.72	1.45	0.24	-1.21	-0.23	
3/Summer/Cooling/in-situ	32	-0.09	1.33	0.23	-0.57	0.39	ns, P > 0.05
3/Summer/Cooling/IVE	32	-0.09	1.35	0.24	-0.58	0.39	
3/Summer/Heating/in-situ	33	-0.61	1.43	0.25	-1.11	-0.10	ns, P > 0.05
3/Summer/Heating/IVE	33	-0.48	1.44	0.25	-1.00	0.03	
4/Summer/Cooling/in-situ	24	0.17	1.37	0.28	-0.41	0.75	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.13	1.26	0.26	-0.41	0.66	
4/Summer/Heating/in-situ	44	-0.70	1.29	0.19	-1.10	-0.31	ns, P > 0.05
4/Summer/Heating/IVE	44	-0.70	1.25	0.19	-1.08	-0.32	

Table E.19 Foot Thermal Acceptability

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.34	1.33	0.22	0.89	1.80	ns, $P > 0.05$
1/Winter/Cooling/IVE	30	1.50	1.38	0.25	0.98	2.02	
1/Winter/Heating/in-situ	36	1.36	1.44	0.24	0.87	1.85	ns, $P > 0.05$
1/Winter/Heating/IVE	47	1.19	1.50	0.22	0.75	1.63	
2/Winter/Cooling/in-situ	28	1.25	1.38	0.26	0.72	1.78	ns, $P > 0.05$
2/Winter/Cooling/IVE	33	1.52	1.46	0.25	1.00	2.03	
2/Winter/Heating/in-situ	48	0.94	1.76	0.25	0.43	1.45	ns, $P > 0.05$
2/Winter/Heating/IVE	36	0.97	1.68	0.28	0.40	1.54	
3/Summer/Cooling/in-situ	32	0.97	1.73	0.31	0.34	1.59	ns, $P > 0.05$
3/Summer/Cooling/IVE	32	0.88	1.76	0.31	0.24	1.51	
3/Summer/Heating/in-situ	33	1.00	1.41	0.25	0.50	1.50	ns, $P > 0.05$
3/Summer/Heating/IVE	33	0.85	1.64	0.29	0.27	1.43	
4/Summer/Cooling/in-situ	24	1.25	1.59	0.33	0.58	1.92	ns, $P > 0.05$
4/Summer/Cooling/IVE	24	1.21	1.47	0.30	0.59	1.83	
4/Summer/Heating/in-situ	44	0.61	1.73	0.26	0.09	1.14	ns, $P > 0.05$
4/Summer/Heating/IVE	44	0.68	1.70	0.26	0.17	1.20	

APPENDIX F PHYSIOLOGICAL RESPONSES BETWEEN ALL THE PAIRS OF IN-SITU AND IVE EXPERIMENTAL SETTINGS

Table F.1 Forehead Skin Temperature (F)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	94.85	1.23	0.21	94.43	95.27	P < 0.05*
1/Winter/Cooling/IVE	23	96.01	1.11	0.23	95.53	96.50	
1/Winter/Heating/in-situ	33	93.41	1.82	0.32	92.76	94.06	P < 0.05*
1/Winter/Heating/IVE	43	95.57	1.53	0.23	95.09	96.04	
2/Winter/Cooling/in-situ	23	95.37	1.33	0.28	94.80	95.95	P < 0.05*
2/Winter/Cooling/IVE	30	96.66	0.83	0.15	96.35	96.97	
2/Winter/Heating/in-situ	48	94.26	1.87	0.27	93.72	94.80	P < 0.05*
2/Winter/Heating/IVE	36	95.66	1.66	0.28	95.10	96.22	
3/Summer/Cooling/in-situ	32	95.22	1.10	0.20	94.83	95.62	P < 0.05*
3/Summer/Cooling/IVE	30	96.76	1.14	0.21	96.33	97.18	
3/Summer/Heating/in-situ	33	94.20	1.31	0.23	93.74	94.67	P < 0.05*
3/Summer/Heating/IVE	33	95.49	1.59	0.28	94.93	96.05	
4/Summer/Cooling/in-situ	24	94.88	1.48	0.30	94.25	95.50	P < 0.05*
4/Summer/Cooling/IVE	23	96.89	0.72	0.15	96.58	97.20	
4/Summer/Heating/in-situ	44	94.25	1.90	0.29	93.67	94.83	P < 0.05*
4/Summer/Heating/IVE	41	95.69	1.88	0.29	95.10	96.28	

Table F.2 Neck Skin Temperature (F)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	93.93	1.78	0.30	93.31	94.54	ns, P > 0.05
1/Winter/Cooling/IVE	23	94.10	2.30	0.48	93.10	95.09	
1/Winter/Heating/in-situ	33	92.27	2.79	0.48	91.28	93.26	P < 0.05*
1/Winter/Heating/IVE	43	90.95	2.86	0.44	90.07	91.83	
2/Winter/Cooling/in-situ	23	93.40	2.23	0.46	92.44	94.37	P < 0.05*
2/Winter/Cooling/IVE	30	93.77	1.52	0.28	93.21	94.34	
2/Winter/Heating/in-situ	48	91.75	3.00	0.43	90.87	92.62	ns, P > 0.05
2/Winter/Heating/IVE	36	91.66	3.30	0.55	90.54	92.78	
3/Summer/Cooling/in-situ	32	93.87	1.80	0.32	93.22	94.52	ns, P > 0.05
3/Summer/Cooling/IVE	30	93.97	1.91	0.35	93.26	94.69	
3/Summer/Heating/in-situ	33	92.84	2.05	0.36	92.11	93.56	ns, P > 0.05
3/Summer/Heating/IVE	33	93.08	2.24	0.39	92.28	93.87	
4/Summer/Cooling/in-situ	24	94.40	2.42	0.49	93.37	95.42	ns, P > 0.05
4/Summer/Cooling/IVE	23	94.91	1.88	0.39	94.09	95.72	
4/Summer/Heating/in-situ	44	92.53	2.37	0.36	91.81	93.25	ns, P > 0.05
4/Summer/Heating/IVE	44	92.28	2.56	0.39	91.50	93.06	

Table F.3 Chest Skin Temperature (F)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	94.12	1.28	0.22	93.68	94.56	ns, P > 0.05
1/Winter/Cooling/IVE	23	94.61	1.78	0.37	93.84	95.38	
1/Winter/Heating/in-situ	33	93.31	1.95	0.34	92.62	94.01	P < 0.05*
1/Winter/Heating/IVE	43	92.21	2.60	0.40	91.41	93.01	
2/Winter/Cooling/in-situ	22	94.83	1.79	0.38	94.04	95.63	ns, P > 0.05
2/Winter/Cooling/IVE	30	94.50	2.28	0.42	93.65	95.35	
2/Winter/Heating/in-situ	48	92.97	2.65	0.38	92.20	93.74	ns, P > 0.05
2/Winter/Heating/IVE	36	93.44	2.09	0.35	92.74	94.15	
3/Summer/Cooling/in-situ	30	94.45	2.13	0.39	93.65	95.24	ns, P > 0.05
3/Summer/Cooling/IVE	29	94.13	2.69	0.50	93.11	95.15	
3/Summer/Heating/in-situ	30	93.24	1.80	0.33	92.57	93.91	ns, P > 0.05
3/Summer/Heating/IVE	30	92.81	2.03	0.37	92.05	93.57	
4/Summer/Cooling/in-situ	24	93.92	2.22	0.45	92.99	94.86	ns, P > 0.05
4/Summer/Cooling/IVE	23	94.62	1.74	0.36	93.87	95.37	
4/Summer/Heating/in-situ	44	93.15	2.46	0.37	92.40	93.89	ns, P > 0.05
4/Summer/Heating/IVE	43	92.80	2.19	0.33	92.13	93.47	

Table F.4 Upperback Skin Temperature (F)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	93.47	1.80	0.30	92.85	94.09	ns, P > 0.05
1/Winter/Cooling/IVE	23	93.87	1.99	0.42	93.01	94.74	
1/Winter/Heating/in-situ	33	93.35	1.69	0.29	92.75	93.95	P < 0.05*
1/Winter/Heating/IVE	40	91.47	2.73	0.43	90.60	92.34	
2/Winter/Cooling/in-situ	23	93.42	1.40	0.29	92.82	94.03	ns, P > 0.05
2/Winter/Cooling/IVE	30	93.49	1.93	0.35	92.77	94.21	
2/Winter/Heating/in-situ	48	92.05	2.39	0.34	91.36	92.74	ns, P > 0.05
2/Winter/Heating/IVE	36	92.37	1.94	0.32	91.71	93.02	
3/Summer/Cooling/in-situ	32	93.83	2.00	0.35	93.11	94.55	ns, P > 0.05
3/Summer/Cooling/IVE	30	93.84	1.91	0.35	93.13	94.56	
3/Summer/Heating/in-situ	33	92.25	1.83	0.32	91.60	92.90	ns, P > 0.05
3/Summer/Heating/IVE	33	92.90	1.58	0.27	92.35	93.46	
4/Summer/Cooling/in-situ	24	93.66	2.17	0.44	92.75	94.58	ns, P > 0.05
4/Summer/Cooling/IVE	23	94.10	2.15	0.45	93.17	95.03	
4/Summer/Heating/in-situ	44	91.87	1.92	0.29	91.28	92.45	ns, P > 0.05
4/Summer/Heating/IVE	44	92.43	1.95	0.29	91.84	93.03	

Table F.5 Forearm Skin Temperature (F)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	91.59	2.62	0.44	90.69	92.49	ns, P > 0.05
1/Winter/Cooling/IVE	23	91.80	1.73	0.36	91.05	92.55	
1/Winter/Heating/in-situ	33	88.63	2.07	0.36	87.89	89.36	ns, P > 0.05
1/Winter/Heating/IVE	43	88.45	2.03	0.31	87.82	89.07	
2/Winter/Cooling/in-situ	23	91.22	1.88	0.39	90.41	92.03	ns, P > 0.05
2/Winter/Cooling/IVE	30	91.16	2.27	0.41	90.32	92.01	
2/Winter/Heating/in-situ	48	87.94	1.72	0.25	87.44	88.44	ns, P > 0.05
2/Winter/Heating/IVE	36	88.04	2.03	0.34	87.36	88.73	
3/Summer/Cooling/in-situ	32	92.17	1.38	0.24	91.67	92.66	ns, P > 0.05
3/Summer/Cooling/IVE	30	91.93	2.08	0.38	91.16	92.71	
3/Summer/Heating/in-situ	33	87.93	1.88	0.33	87.27	88.60	ns, P > 0.05
3/Summer/Heating/IVE	33	87.73	1.41	0.25	87.23	88.23	
4/Summer/Cooling/in-situ	24	91.88	1.80	0.37	91.12	92.64	ns, P > 0.05
4/Summer/Cooling/IVE	22	92.40	1.52	0.32	91.73	93.08	
4/Summer/Heating/in-situ	44	89.19	2.12	0.32	88.54	89.83	ns, P > 0.05
4/Summer/Heating/IVE	44	88.89	2.31	0.35	88.19	89.59	

Table F.6 Hand Skin Temperature (F)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	91.74	3.02	0.51	90.71	92.78	P < 0.05*
1/Winter/Cooling/IVE	23	93.25	2.03	0.42	92.37	94.13	
1/Winter/Heating/in-situ	33	90.24	2.99	0.52	89.18	91.30	P < 0.05*
1/Winter/Heating/IVE	43	88.70	4.04	0.62	87.46	89.95	
2/Winter/Cooling/in-situ	23	92.55	1.97	0.41	91.70	93.40	ns, P > 0.05
2/Winter/Cooling/IVE	30	92.37	2.22	0.41	91.54	93.20	
2/Winter/Heating/in-situ	48	89.49	2.51	0.36	88.76	90.22	ns, P > 0.05
2/Winter/Heating/IVE	36	89.76	2.53	0.42	88.90	90.62	
3/Summer/Cooling/in-situ	32	93.44	1.95	0.35	92.74	94.15	ns, P > 0.05
3/Summer/Cooling/IVE	30	93.35	2.49	0.45	92.42	94.28	
3/Summer/Heating/in-situ	30	89.84	3.01	0.55	88.72	90.97	ns, P > 0.05
3/Summer/Heating/IVE	32	90.11	2.18	0.39	89.32	90.90	
4/Summer/Cooling/in-situ	24	93.38	3.20	0.65	92.02	94.73	ns, P > 0.05
4/Summer/Cooling/IVE	23	93.57	3.22	0.67	92.18	94.96	
4/Summer/Heating/in-situ	41	89.14	3.54	0.55	88.02	90.26	ns, P > 0.05
4/Summer/Heating/IVE	41	89.40	3.41	0.53	88.32	90.47	

Table F.7 Calf Skin Temperature (F)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	88.94	2.76	0.47	87.99	89.89	ns, P > 0.05
1/Winter/Cooling/IVE	23	89.94	2.86	0.60	88.70	91.18	
1/Winter/Heating/in-situ	33	86.10	3.04	0.53	85.02	87.17	ns, P > 0.05
1/Winter/Heating/IVE	43	85.97	1.90	0.29	85.39	86.56	
2/Winter/Cooling/in-situ	23	87.58	1.93	0.40	86.74	88.41	ns, P > 0.05
2/Winter/Cooling/IVE	30	87.83	1.93	0.35	87.10	88.55	
2/Winter/Heating/in-situ	48	84.78	2.03	0.29	84.19	85.37	ns, P > 0.05
2/Winter/Heating/IVE	36	85.23	2.66	0.44	84.33	86.13	
3/Summer/Cooling/in-situ	32	88.39	2.49	0.44	87.50	89.29	ns, P > 0.05
3/Summer/Cooling/IVE	30	88.26	2.16	0.39	87.45	89.07	
3/Summer/Heating/in-situ	33	84.10	2.22	0.39	83.31	84.88	ns, P > 0.05
3/Summer/Heating/IVE	33	84.07	2.20	0.38	83.29	84.85	
4/Summer/Cooling/in-situ	24	88.88	2.56	0.52	87.80	89.96	ns, P > 0.05
4/Summer/Cooling/IVE	23	88.76	2.58	0.54	87.65	89.88	
4/Summer/Heating/in-situ	44	85.67	3.20	0.48	84.69	86.64	P < 0.05*
4/Summer/Heating/IVE	44	84.49	2.74	0.41	83.66	85.32	

Table 4.8 Foot Skin Temperature (F)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	88.87	3.35	0.57	87.72	90.02	ns, P > 0.05
1/Winter/Cooling/IVE	23	89.62	2.23	0.47	88.66	90.59	
1/Winter/Heating/in-situ	33	87.40	2.66	0.46	86.46	88.35	P < 0.05*
1/Winter/Heating/IVE	43	85.43	3.45	0.53	84.37	86.50	
2/Winter/Cooling/in-situ	23	86.69	2.60	0.54	85.57	87.81	ns, P > 0.05
2/Winter/Cooling/IVE	30	87.44	3.49	0.64	86.14	88.75	
2/Winter/Heating/in-situ	48	85.41	3.87	0.56	84.29	86.53	ns, P > 0.05
2/Winter/Heating/IVE	36	85.53	2.92	0.49	84.54	86.52	
3/Summer/Cooling/in-situ	32	90.10	3.05	0.54	89.01	91.20	ns, P > 0.05
3/Summer/Cooling/IVE	30	90.76	2.28	0.42	89.90	91.61	
3/Summer/Heating/in-situ	33	85.81	3.07	0.53	84.72	86.90	ns, P > 0.05
3/Summer/Heating/IVE	33	85.66	3.59	0.63	84.38	86.93	
4/Summer/Cooling/in-situ	24	91.01	2.76	0.56	89.84	92.17	ns, P > 0.05
4/Summer/Cooling/IVE	23	90.38	3.52	0.73	88.86	91.91	
4/Summer/Heating/in-situ	44	85.02	3.48	0.52	83.96	86.08	ns, P > 0.05
4/Summer/Heating/IVE	44	84.63	3.67	0.55	83.51	85.74	

Table F.9 GSR (5 μ S)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.51	1.33	0.22	1.05	1.96	P < 0.05*
1/Winter/Cooling/IVE	27	0.87	0.62	0.12	0.62	1.11	
1/Winter/Heating/in-situ	33	0.68	0.58	0.10	0.47	0.88	P < 0.05*
1/Winter/Heating/IVE	47	1.11	0.99	0.14	0.82	1.40	
2/Winter/Cooling/in-situ	23	0.67	0.49	0.10	0.46	0.89	P < 0.05*
2/Winter/Cooling/IVE	33	1.55	1.65	0.29	0.96	2.13	
2/Winter/Heating/in-situ	48	1.11	1.09	0.16	0.79	1.43	P < 0.05*
2/Winter/Heating/IVE	36	0.62	0.59	0.10	0.42	0.82	
3/Summer/Cooling/in-situ	32	0.68	0.57	0.10	0.48	0.89	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.52	0.37	0.06	0.39	0.66	
3/Summer/Heating/in-situ	33	0.48	0.36	0.06	0.36	0.61	ns, P > 0.05
3/Summer/Heating/IVE	33	0.39	0.27	0.05	0.30	0.49	
4/Summer/Cooling/in-situ	24	0.81	0.87	0.18	0.45	1.18	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.49	0.50	0.10	0.28	0.70	
4/Summer/Heating/in-situ	44	0.65	0.52	0.08	0.50	0.81	ns, P > 0.05
4/Summer/Heating/IVE	44	0.67	0.50	0.08	0.52	0.82	

Table F.10 Heart Rate (bpm)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	81.79	13.61	2.30	77.12	86.47	ns, P > 0.05
1/Winter/Cooling/IVE	25	82.03	8.08	1.62	78.70	85.37	
1/Winter/Heating/in-situ	32	80.51	8.55	1.51	77.42	83.59	ns, P > 0.05
1/Winter/Heating/IVE	48	82.94	16.16	2.33	78.24	87.63	
2/Winter/Cooling/in-situ	22	80.85	8.51	1.81	77.08	84.63	ns, P > 0.05
2/Winter/Cooling/IVE	30	78.64	9.81	1.79	74.97	82.30	
2/Winter/Heating/in-situ	47	81.59	16.82	2.45	76.65	86.53	ns, P > 0.05
2/Winter/Heating/IVE	33	79.37	10.11	1.76	75.79	82.96	
3/Summer/Cooling/in-situ	32	83.52	16.93	2.99	77.41	89.62	ns, P > 0.05
3/Summer/Cooling/IVE	32	81.33	15.56	2.75	75.72	86.94	
3/Summer/Heating/in-situ	33	81.07	13.44	2.34	76.30	85.83	ns, P > 0.05
3/Summer/Heating/IVE	33	83.81	13.92	2.42	78.87	88.74	
4/Summer/Cooling/in-situ	24	90.82	19.40	3.96	82.63	99.01	ns, P > 0.05
4/Summer/Cooling/IVE	24	91.93	26.14	5.34	80.90	102.97	
4/Summer/Heating/in-situ	44	76.56	12.39	1.87	72.79	80.32	ns, P > 0.05
4/Summer/Heating/IVE	44	76.78	18.68	2.82	71.10	82.46	

Table F.11 Heart Rate Variability_RMSSD

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	87.70	104.13	17.60	51.93	123.47	P < 0.05*
1/Winter/Cooling/IVE	28	40.32	25.13	4.75	30.57	50.06	
1/Winter/Heating/in-situ	30	43.17	45.62	8.33	26.13	60.20	ns, P > 0.05
1/Winter/Heating/IVE	48	35.71	24.16	3.49	28.69	42.72	
2/Winter/Cooling/in-situ	21	44.99	61.91	13.51	16.80	73.17	ns, P > 0.05
2/Winter/Cooling/IVE	30	33.17	14.68	2.68	27.69	38.66	
2/Winter/Heating/in-situ	48	37.61	23.99	3.46	30.64	44.57	ns, P > 0.05
2/Winter/Heating/IVE	36	51.42	67.29	11.21	28.65	74.19	
3/Summer/Cooling/in-situ	32	98.59	94.73	16.75	64.43	132.74	ns, P > 0.05
3/Summer/Cooling/IVE	32	69.41	88.41	15.63	37.54	101.29	
3/Summer/Heating/in-situ	33	67.57	53.36	9.29	48.65	86.49	ns, P > 0.05
3/Summer/Heating/IVE	33	72.76	61.12	10.64	51.09	94.43	
4/Summer/Cooling/in-situ	24	101.93	82.22	16.78	67.21	136.65	ns, P > 0.05
4/Summer/Cooling/IVE	24	86.04	77.74	15.87	53.21	118.86	
4/Summer/Heating/in-situ	44	58.33	46.71	7.04	44.13	72.53	ns, P > 0.05
4/Summer/Heating/IVE	44	74.49	75.03	11.31	51.68	97.30	

Table F.12 Heart Rate Variability_LF/HF

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	3.54	3.05	0.52	2.49	4.59	ns, P > 0.05
1/Winter/Cooling/IVE	28	4.06	4.18	0.79	2.43	5.68	
1/Winter/Heating/in-situ	30	3.61	2.60	0.47	2.64	4.58	ns, P > 0.05
1/Winter/Heating/IVE	48	3.47	2.37	0.34	2.78	4.15	
2/Winter/Cooling/in-situ	21	3.70	4.30	0.94	1.75	5.66	ns, P > 0.05
2/Winter/Cooling/IVE	30	2.96	2.61	0.48	1.99	3.94	
2/Winter/Heating/in-situ	48	4.10	3.62	0.52	3.05	5.15	ns, P > 0.05
2/Winter/Heating/IVE	36	3.05	2.94	0.49	2.06	4.05	
3/Summer/Cooling/in-situ	32	2.28	2.53	0.45	1.36	3.19	ns, P > 0.05
3/Summer/Cooling/IVE	32	3.20	3.95	0.70	1.78	4.63	
3/Summer/Heating/in-situ	33	2.23	2.03	0.35	1.51	2.95	ns, P > 0.05
3/Summer/Heating/IVE	33	2.15	2.33	0.41	1.33	2.98	
4/Summer/Cooling/in-situ	24	2.16	2.39	0.49	1.15	3.17	ns, P > 0.05
4/Summer/Cooling/IVE	24	2.72	2.65	0.54	1.60	3.84	
4/Summer/Heating/in-situ	44	2.64	1.84	0.28	2.08	3.20	ns, P > 0.05
4/Summer/Heating/IVE	44	2.49	2.99	0.45	1.58	3.40	

Table F.13 Parasympathetic Nervous System (PNS)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	0.34	2.94	0.50	-0.67	1.36	P < 0.05*
1/Winter/Cooling/IVE	28	-1.02	1.21	0.23	-1.49	-0.55	
1/Winter/Heating/in-situ	30	-1.02	1.56	0.28	-1.61	-0.44	ns, P > 0.05
1/Winter/Heating/IVE	48	-1.17	1.34	0.19	-1.56	-0.78	
2/Winter/Cooling/in-situ	21	-0.79	1.90	0.41	-1.65	0.07	ns, P > 0.05
2/Winter/Cooling/IVE	30	-0.94	0.89	0.16	-1.27	-0.61	
2/Winter/Heating/in-situ	48	-1.10	1.25	0.18	-1.46	-0.74	P < 0.05*
2/Winter/Heating/IVE	36	-0.45	2.12	0.35	-1.16	0.27	
3/Summer/Cooling/in-situ	32	0.83	2.71	0.48	-0.15	1.81	ns, P > 0.05
3/Summer/Cooling/IVE	32	0.06	2.55	0.45	-0.86	0.98	
3/Summer/Heating/in-situ	33	-0.04	1.45	0.25	-0.56	0.47	ns, P > 0.05
3/Summer/Heating/IVE	33	0.09	1.64	0.29	-0.49	0.67	
4/Summer/Cooling/in-situ	24	0.72	2.29	0.47	-0.25	1.69	ns, P > 0.05
4/Summer/Cooling/IVE	24	0.19	1.90	0.39	-0.61	0.99	
4/Summer/Heating/in-situ	44	-0.17	1.63	0.25	-0.67	0.32	ns, P > 0.05
4/Summer/Heating/IVE	44	0.42	2.11	0.32	-0.22	1.06	

Table F.14 Sympathetic Nervous System (SNS)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Significance test
1/Winter/Cooling/in-situ	35	1.10	1.16	0.20	0.70	1.50	P < 0.05*
1/Winter/Cooling/IVE	28	1.62	1.27	0.24	1.13	2.12	
1/Winter/Heating/in-situ	30	1.69	1.07	0.20	1.29	2.09	ns, P > 0.05
1/Winter/Heating/IVE	48	2.21	2.79	0.40	1.40	3.02	
2/Winter/Cooling/in-situ	21	1.70	1.37	0.30	1.08	2.33	ns, P > 0.05
2/Winter/Cooling/IVE	30	1.61	1.43	0.26	1.07	2.14	
2/Winter/Heating/in-situ	48	2.09	2.76	0.40	1.29	2.89	P < 0.05*
2/Winter/Heating/IVE	36	1.29	1.24	0.21	0.87	1.71	
3/Summer/Cooling/in-situ	32	0.86	1.49	0.26	0.32	1.39	ns, P > 0.05
3/Summer/Cooling/IVE	32	1.28	2.03	0.36	0.55	2.01	
3/Summer/Heating/in-situ	33	0.97	0.82	0.14	0.68	1.26	ns, P > 0.05
3/Summer/Heating/IVE	33	1.09	0.94	0.16	0.76	1.42	
4/Summer/Cooling/in-situ	24	1.09	1.13	0.23	0.61	1.56	ns, P > 0.05
4/Summer/Cooling/IVE	24	1.49	1.09	0.22	1.03	1.95	
4/Summer/Heating/in-situ	44	0.89	1.53	0.23	0.42	1.36	ns, P > 0.05
4/Summer/Heating/IVE	44	0.72	1.75	0.26	0.18	1.25	

APPENDIX G THERMOCEPTIONS BETWEEN ALL THE PAIRS OF IN-SITU AND IVE EXPERIMENTAL SETTINGS (AT DIFFERENT TEMPERATURE LEVELS)

Table G.1 Oneway Analysis of General Thermal Sensation by Season/Experiment Type/Experiment Setting Target Room Temp=65.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Upper CL
Winter/Heating/in-situ	Summer/Heating/in-situ	6.68	3.73	1.79	0.63	0	1
Winter/Heating/IVE	Summer/Heating/in-situ	5.33	3.78	1.41	0.85	0	1
Winter/Cooling/in-situ	Summer/Heating/in-situ	4.81	3.37	1.42	0.85	-1	2
Winter/Heating/in-situ	Summer/Heating/IVE	3.67	3.68	1.00	0.97	-1	1
Winter/Heating/in-situ	Summer/Cooling/IVE	3.48	4.25	0.82	0.99	-1	5
Winter/Heating/in-situ	Winter/Cooling/IVE	2.94	3.50	0.84	0.99	-1	1
Winter/Cooling/in-situ	Summer/Heating/IVE	2.76	3.27	0.85	0.99	-1	1
Summer/Heating/IVE	Summer/Heating/in-situ	2.76	3.56	0.77	0.99	-1	1
Winter/Heating/IVE	Summer/Cooling/IVE	2.74	4.37	0.63	1.00	-2	3
Winter/Heating/IVE	Summer/Heating/IVE	2.27	3.73	0.61	1.00	-1	1
Winter/Cooling/IVE	Summer/Heating/in-situ	2.08	3.31	0.63	1.00	-1	1
Winter/Heating/IVE	Winter/Cooling/IVE	1.87	3.58	0.52	1.00	-1	1
Winter/Cooling/in-situ	Summer/Cooling/IVE	1.58	2.26	0.70	1.00	.	.
Summer/Heating/IVE	Summer/Cooling/IVE	1.18	3.82	0.31	1.00	.	.
Winter/Cooling/IVE	Summer/Cooling/IVE	0.53	2.26	0.23	1.00	.	.
Winter/Heating/in-situ	Summer/Cooling/in-situ	0.44	4.24	0.10	1.00	-1	5
Summer/Heating/in-situ	Summer/Cooling/IVE	0.00	3.99	0.00	1.00	-2	3
Winter/Cooling/in-situ	Summer/Cooling/in-situ	0.00	2.20	0.00	1.00	.	.
Winter/Cooling/IVE	Summer/Heating/IVE	0.00	3.20	0.00	1.00	-1	1
Winter/Heating/in-situ	Winter/Cooling/in-situ	-0.14	3.52	-0.04	1.00	-1	1
Winter/Heating/IVE	Summer/Cooling/in-situ	-0.14	4.36	-0.03	1.00	-2	3
Summer/Cooling/IVE	Summer/Cooling/in-situ	-0.50	1.50	-0.33	1.00	.	.
Winter/Cooling/IVE	Summer/Cooling/in-situ	-0.70	2.28	-0.31	1.00	.	.
Summer/Heating/IVE	Summer/Cooling/in-situ	-1.18	3.86	-0.31	1.00	.	.
Winter/Heating/IVE	Winter/Cooling/in-situ	-1.25	3.59	-0.35	1.00	-1	1
Winter/Heating/IVE	Winter/Heating/in-situ	-1.61	3.84	-0.42	1.00	-1	1
Winter/Cooling/IVE	Winter/Cooling/in-situ	-1.80	2.39	-0.75	1.00	-3	1
Summer/Heating/in-situ	Summer/Cooling/in-situ	-2.64	4.02	-0.66	1.00	-2	3

Table G.2 Oneway Analysis of General Thermal Acceptability by Season/Experiment Type/Experiment Setting Target Room Temp=65.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Upper CL
Winter/Heating/IVE	Winter/Cooling/in-situ	6.65	3.82	1.74	0.66	-1	3
Winter/Heating/in-situ	Winter/Cooling/in-situ	5.95	3.74	1.59	0.76	-1	3
Winter/Heating/IVE	Summer/Heating/IVE	5.75	3.96	1.45	0.83	-1	3
Winter/Heating/IVE	Summer/Heating/in-situ	5.61	3.98	1.41	0.85	-1	2
Winter/Heating/in-situ	Summer/Heating/IVE	5.51	3.93	1.40	0.86	-1	3
Winter/Heating/in-situ	Summer/Heating/in-situ	5.34	3.95	1.35	0.88	-1	2
Winter/Cooling/IVE	Winter/Cooling/in-situ	4.50	2.54	1.77	0.64	-1	3
Winter/Cooling/IVE	Summer/Heating/IVE	4.22	3.48	1.21	0.93	-1	3
Winter/Cooling/IVE	Summer/Heating/in-situ	4.16	3.53	1.18	0.94	-1	3
Winter/Heating/in-situ	Summer/Cooling/in-situ	1.89	4.49	0.42	1.00	-5	5
Winter/Heating/in-situ	Summer/Cooling/IVE	1.89	4.48	0.42	1.00	-4	5
Winter/Heating/IVE	Summer/Cooling/in-situ	1.88	4.62	0.41	1.00	-5	5
Winter/Heating/IVE	Summer/Cooling/IVE	1.88	4.59	0.41	1.00	-4	5
Winter/Cooling/IVE	Summer/Cooling/in-situ	0.88	2.40	0.36	1.00	.	.
Winter/Cooling/IVE	Summer/Cooling/IVE	0.70	2.35	0.30	1.00	.	.
Summer/Cooling/IVE	Summer/Cooling/in-situ	0.00	1.68	0.00	1.00	.	.
Winter/Heating/IVE	Winter/Heating/in-situ	0.00	4.07	0.00	1.00	-1	1
Winter/Heating/IVE	Winter/Cooling/IVE	-0.07	3.80	-0.02	1.00	-2	2
Winter/Heating/in-situ	Winter/Cooling/IVE	-0.14	3.74	-0.04	1.00	-2	2
Winter/Cooling/in-situ	Summer/Cooling/in-situ	-0.35	2.36	-0.15	1.00	.	.
Summer/Heating/IVE	Summer/Heating/in-situ	-0.49	3.81	-0.13	1.00	-2	2
Winter/Cooling/in-situ	Summer/Heating/IVE	-0.87	3.48	-0.25	1.00	-3	2
Summer/Heating/in-situ	Summer/Cooling/in-situ	-0.88	4.18	-0.21	1.00	-6	5
Summer/Heating/in-situ	Summer/Cooling/IVE	-1.03	4.15	-0.25	1.00	-5	5
Summer/Heating/IVE	Summer/Cooling/in-situ	-1.03	4.07	-0.25	1.00	.	.
Summer/Heating/IVE	Summer/Cooling/IVE	-1.18	4.05	-0.29	1.00	.	.
Winter/Cooling/in-situ	Summer/Cooling/IVE	-1.40	2.36	-0.59	1.00	.	.
Winter/Cooling/in-situ	Summer/Heating/in-situ	-1.65	3.53	-0.47	1.00	-3	2

Table G.3 Oneway Analysis of General Thermal Comfort by Season/Experiment Type/Experiment Setting Target Room Temp=65.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Upper CL
Winter/Heating/in-situ	Summer/Heating/in-situ	9.47	3.93	2.41	0.24	0	3
Winter/Heating/in-situ	Summer/Heating/IVE	7.61	3.91	1.94	0.52	-1	3
Winter/Heating/IVE	Summer/Heating/in-situ	6.76	3.97	1.70	0.69	-1	3
Winter/Cooling/IVE	Summer/Heating/in-situ	6.46	3.48	1.86	0.58	-1	4
Winter/Heating/IVE	Summer/Heating/IVE	5.12	3.96	1.29	0.90	-1	3
Winter/Cooling/IVE	Summer/Heating/IVE	4.95	3.45	1.44	0.84	-1	4
Winter/Heating/in-situ	Winter/Cooling/in-situ	4.55	3.74	1.22	0.93	-2	3
Winter/Heating/in-situ	Summer/Cooling/IVE	3.63	4.45	0.82	0.99	-4	5
Winter/Heating/in-situ	Summer/Cooling/in-situ	3.05	4.45	0.68	1.00	-5	5
Winter/Cooling/IVE	Winter/Cooling/in-situ	2.80	2.55	1.10	0.96	-2	4
Winter/Heating/IVE	Winter/Cooling/in-situ	2.70	3.83	0.70	1.00	-2	3
Winter/Cooling/in-situ	Summer/Heating/in-situ	2.15	3.56	0.60	1.00	-3	3
Winter/Cooling/IVE	Summer/Cooling/IVE	1.75	2.23	0.79	0.99	.	.
Winter/Heating/IVE	Summer/Cooling/IVE	1.73	4.60	0.38	1.00	-4	5
Winter/Heating/IVE	Summer/Cooling/in-situ	1.59	4.61	0.34	1.00	-5	5
Winter/Cooling/in-situ	Summer/Heating/IVE	1.38	3.50	0.39	1.00	-3	3
Winter/Cooling/IVE	Summer/Cooling/in-situ	1.05	2.30	0.46	1.00	.	.
Summer/Heating/IVE	Summer/Heating/in-situ	1.02	3.80	0.27	1.00	-2	2
Winter/Heating/in-situ	Winter/Cooling/IVE	0.63	3.67	0.17	1.00	-2	2
Summer/Cooling/IVE	Summer/Cooling/in-situ	0.00	1.68	0.00	1.00	.	.
Winter/Cooling/in-situ	Summer/Cooling/in-situ	0.00	2.42	0.00	1.00	.	.
Winter/Cooling/in-situ	Summer/Cooling/IVE	-0.18	2.42	⁻ 0.07	1.00	.	.
Summer/Heating/IVE	Summer/Cooling/IVE	-0.74	4.05	⁻ 0.18	1.00	.	.
Summer/Heating/IVE	Summer/Cooling/in-situ	-0.89	4.05	⁻ 0.22	1.00	.	.
Summer/Heating/in-situ	Summer/Cooling/in-situ	-1.61	4.15	⁻ 0.39	1.00	-6	5
Summer/Heating/in-situ	Summer/Cooling/IVE	-1.61	4.14	⁻ 0.39	1.00	-5	5
Winter/Heating/IVE	Winter/Cooling/IVE	-2.01	3.77	⁻ 0.53	1.00	-3	1
Winter/Heating/IVE	Winter/Heating/in-situ	-3.18	4.05	⁻ 0.78	0.99	-2	1

Table G.4 Oneway Analysis of General Thermal Sensation by Season/Experiment Type/Experiment Setting Target Room Temp=75.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Lower CL
Winter/Heating/in-situ	Winter/Cooling/IVE	17.28	3.87	4.47	0.0002*	0	2
Winter/Heating/IVE	Winter/Cooling/IVE	17.10	3.94	4.35	0.0004*	0	2
Winter/Heating/in-situ	Summer/Cooling/in-situ	15.60	3.82	4.08	0.0012*	0	2
Winter/Heating/in-situ	Winter/Cooling/in-situ	15.44	3.88	3.98	0.0018*	0	2
Winter/Heating/IVE	Summer/Cooling/in-situ	15.34	3.88	3.95	0.0020*	0	2
Winter/Heating/IVE	Winter/Cooling/in-situ	15.26	3.95	3.87	0.0028*	0	2
Winter/Heating/in-situ	Summer/Cooling/IVE	12.37	3.77	3.29	0.0227*	0	2
Winter/Heating/IVE	Summer/Cooling/IVE	12.22	3.85	3.18	0.0320*	0	2
Summer/Heating/in-situ	Summer/Cooling/in-situ	12.21	3.74	3.27	0.0241*	0	1
Summer/Heating/IVE	Summer/Cooling/in-situ	10.98	3.72	2.96	0.06	0	1
Summer/Heating/in-situ	Summer/Cooling/IVE	8.71	3.70	2.36	0.26	0	1
Summer/Heating/IVE	Summer/Cooling/IVE	7.71	3.70	2.08	0.43	0	1
Winter/Heating/in-situ	Summer/Heating/IVE	4.63	3.71	1.25	0.92	0	1
Winter/Heating/IVE	Summer/Heating/IVE	4.55	3.79	1.20	0.93	0	1
Winter/Heating/in-situ	Summer/Heating/in-situ	4.25	3.70	1.15	0.95	0	1
Winter/Heating/IVE	Summer/Heating/in-situ	4.17	3.78	1.10	0.96	0	1
Summer/Cooling/IVE	Summer/Cooling/in-situ	3.46	3.69	0.94	0.98	0	1
Winter/Heating/IVE	Winter/Heating/in-situ	-0.04	3.83	0.01	1.00	-1	1
Summer/Heating/IVE	Summer/Heating/in-situ	-0.55	3.65	0.15	1.00	-1	1
Winter/Cooling/IVE	Winter/Cooling/in-situ	-1.04	3.82	0.27	1.00	-1	1
Winter/Cooling/in-situ	Summer/Cooling/in-situ	-1.14	3.74	0.31	1.00	-1	1
Winter/Cooling/IVE	Summer/Cooling/in-situ	-2.45	3.71	0.66	1.00	-1	1
Winter/Cooling/in-situ	Summer/Cooling/IVE	-4.29	3.78	1.13	0.95	-1	0
Winter/Cooling/IVE	Summer/Cooling/IVE	-5.68	3.76	1.51	0.80	-1	0
Winter/Cooling/in-situ	Summer/Heating/IVE	-11.19	3.80	2.94	0.06	-2	0
Winter/Cooling/in-situ	Summer/Heating/in-situ	-12.29	3.81	3.23	0.0275*	-2	0
Winter/Cooling/IVE	Summer/Heating/IVE	-12.90	3.79	3.41	0.0152*	-2	0
Winter/Cooling/IVE	Summer/Heating/in-situ	-14.09	3.80	3.71	0.0051*	-2	0

Table G.5 Oneway Analysis of General Thermal Acceptability by Season/Experiment Type/Experiment Setting Target Room Temp=75.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Upper CL
Winter/Heating/IVE	Summer/Heating/IVE	6.80	3.80	1.79	0.63	0	1
Winter/Heating/IVE	Summer/Heating/in-situ	6.05	3.79	1.60	0.75	0	1
Winter/Heating/IVE	Winter/Cooling/in-situ	5.02	3.88	1.30	0.90	0	1
Winter/Heating/in-situ	Summer/Heating/IVE	4.51	3.85	1.17	0.94	-1	1
Winter/Cooling/IVE	Summer/Heating/IVE	3.92	3.80	1.03	0.97	-1	1
Winter/Heating/in-situ	Summer/Heating/in-situ	3.84	3.86	0.99	0.98	-1	1
Winter/Heating/in-situ	Winter/Cooling/in-situ	3.40	3.94	0.86	0.99	-1	1
Winter/Cooling/IVE	Summer/Heating/in-situ	3.14	3.80	0.83	0.99	-1	1
Winter/Heating/IVE	Summer/Cooling/IVE	3.13	3.84	0.81	0.99	-1	1
Winter/Heating/IVE	Winter/Cooling/IVE	2.47	3.84	0.64	1.00	-1	1
Winter/Cooling/IVE	Winter/Cooling/in-situ	2.28	3.88	0.59	1.00	-1	1
Winter/Heating/IVE	Summer/Cooling/in-situ	1.88	3.81	0.49	1.00	-1	1
Winter/Heating/in-situ	Summer/Cooling/IVE	1.59	3.89	0.41	1.00	-1	1
Winter/Heating/IVE	Winter/Heating/in-situ	1.33	3.90	0.34	1.00	-1	1
Winter/Cooling/in-situ	Summer/Heating/IVE	1.21	3.83	0.32	1.00	-1	1
Winter/Heating/in-situ	Winter/Cooling/IVE	1.04	3.91	0.27	1.00	-1	1
Winter/Cooling/IVE	Summer/Cooling/IVE	0.53	3.85	0.14	1.00	-1	1
Winter/Cooling/in-situ	Summer/Heating/in-situ	0.41	3.83	0.11	1.00	-1	1
Winter/Heating/in-situ	Summer/Cooling/in-situ	0.25	3.87	0.06	1.00	-1	1
Winter/Cooling/IVE	Summer/Cooling/in-situ	-0.41	3.82	-0.11	1.00	-1	1
Summer/Heating/IVE	Summer/Heating/in-situ	-1.02	3.72	-0.27	1.00	-1	1
Summer/Cooling/IVE	Summer/Cooling/in-situ	-1.13	3.81	-0.30	1.00	-1	1
Winter/Cooling/in-situ	Summer/Cooling/IVE	-1.67	3.88	-0.43	1.00	-1	1
Summer/Heating/in-situ	Summer/Cooling/IVE	-2.25	3.79	-0.59	1.00	-1	1
Winter/Cooling/in-situ	Summer/Cooling/in-situ	-2.98	3.85	-0.77	0.99	-1	1
Summer/Heating/IVE	Summer/Cooling/IVE	-3.02	3.78	-0.80	0.99	-1	1
Summer/Heating/in-situ	Summer/Cooling/in-situ	-3.71	3.76	-0.99	0.98	-1	1
Summer/Heating/IVE	Summer/Cooling/in-situ	-4.56	3.75	-1.22	0.93	-1	1

Table G.6 Oneway Analysis of General Thermal Comfort by Season/Experiment Type/Experiment Setting Target Room Temp=75.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Upper CL
Winter/Heating/in-situ	Summer/Heating/in-situ	5.35	3.91	1.37	0.87	-1	1
Winter/Heating/IVE	Summer/Heating/in-situ	5.25	3.90	1.35	0.88	-1	1
Winter/Heating/in-situ	Summer/Heating/IVE	5.13	3.85	1.33	0.89	-1	1
Winter/Heating/IVE	Summer/Heating/IVE	5.04	3.83	1.32	0.89	0	1
Winter/Cooling/IVE	Summer/Heating/in-situ	4.04	3.80	1.06	0.96	-1	1
Winter/Cooling/IVE	Summer/Heating/IVE	3.92	3.72	1.05	0.97	-1	1
Winter/Cooling/in-situ	Summer/Heating/in-situ	3.10	3.92	0.79	0.99	-1	1
Winter/Cooling/in-situ	Summer/Heating/IVE	2.92	3.86	0.76	1.00	-1	1
Winter/Heating/in-situ	Winter/Cooling/in-situ	2.00	3.96	0.51	1.00	-1	1
Winter/Heating/in-situ	Winter/Cooling/IVE	1.80	3.92	0.46	1.00	-1	1
Winter/Heating/in-situ	Summer/Cooling/IVE	1.63	3.86	0.42	1.00	-1	1
Winter/Heating/IVE	Winter/Cooling/in-situ	1.49	3.99	0.37	1.00	-1	1
Winter/Heating/IVE	Winter/Cooling/IVE	1.22	3.90	0.31	1.00	-1	1
Winter/Heating/IVE	Summer/Cooling/IVE	1.00	3.82	0.26	1.00	-1	1
Winter/Cooling/IVE	Winter/Cooling/in-situ	0.24	3.93	0.06	1.00	-1	1
Summer/Heating/IVE	Summer/Heating/in-situ	0.21	3.71	0.06	1.00	-1	1
Winter/Cooling/IVE	Summer/Cooling/IVE	0.00	3.70	0.00	1.00	-1	1
Winter/Cooling/in-situ	Summer/Cooling/IVE	-0.25	3.87	-0.06	1.00	-1	1
Winter/Heating/IVE	Winter/Heating/in-situ	-0.59	3.97	-0.15	1.00	-1	1
Winter/Heating/in-situ	Summer/Cooling/in-situ	-1.18	3.84	-0.31	1.00	-1	1
Winter/Heating/IVE	Summer/Cooling/in-situ	-2.12	3.81	-0.56	1.00	-1	1
Winter/Cooling/in-situ	Summer/Cooling/in-situ	-3.06	3.86	-0.79	0.99	-1	1
Winter/Cooling/IVE	Summer/Cooling/in-situ	-3.23	3.69	-0.87	0.99	-1	1
Summer/Cooling/IVE	Summer/Cooling/in-situ	-3.25	3.59	-0.90	0.99	-1	0
Summer/Heating/IVE	Summer/Cooling/IVE	-4.00	3.62	-1.11	0.96	-1	0
Summer/Heating/in-situ	Summer/Cooling/IVE	-4.04	3.72	-1.09	0.96	-1	1
Summer/Heating/in-situ	Summer/Cooling/in-situ	-7.21	3.71	-1.94	0.52	-1	0
Summer/Heating/IVE	Summer/Cooling/in-situ	-7.24	3.62	-2.00	0.48	-1	0

Table G.7 Oneway Analysis of General Thermal Sensation by Season/Experiment Type/Experiment Setting Target Room Temp=85.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Upper CL
Winter/Heating/in-situ	Winter/Cooling/IVE	11.3571	3.923986	2.89429	0.0737	0	1
Winter/Heating/in-situ	Winter/Cooling/in-situ	9.3886	3.867738	2.42741	0.2279	0	1
Winter/Heating/in-situ	Summer/Heating/IVE	8.2075	3.698421	2.21919	0.34	0	1
Winter/Heating/IVE	Winter/Cooling/IVE	5.1864	3.908184	1.32707	0.8888	0	1
Winter/Heating/in-situ	Summer/Cooling/IVE	4.6142	3.638008	1.26832	0.9106	0	1
Winter/Heating/in-situ	Summer/Heating/in-situ	4.4917	3.548038	1.26596	0.9114	0	1
Winter/Heating/in-situ	Summer/Cooling/in-situ	4.2058	3.539877	1.18813	0.9356	0	1
Winter/Heating/IVE	Winter/Cooling/in-situ	2.6121	3.877701	0.67363	0.9977	-1	1
Winter/Heating/IVE	Summer/Heating/IVE	2.0825	3.742437	0.55646	0.9993	-1	1
Summer/Heating/in-situ	Summer/Cooling/IVE	0.25	3.634937	0.06878	1	-1	1
Summer/Heating/in-situ	Summer/Cooling/in-situ	-0.375	3.5468	-0.10573	1	-1	1
Winter/Cooling/in-situ	Summer/Heating/IVE	-0.4256	3.878336	-0.10974	1	-1	1
Summer/Cooling/IVE	Summer/Cooling/in-situ	-0.7083	3.62211	-0.19556	1	-1	1
Winter/Heating/IVE	Summer/Cooling/IVE	-1.5517	3.744028	-0.41444	0.9999	-1	1
Winter/Heating/IVE	Summer/Heating/in-situ	-2.0008	3.70543	-0.53997	0.9994	-1	1
Winter/Cooling/IVE	Winter/Cooling/in-situ	-2.4643	4.022744	-0.61259	0.9987	-1	1
Winter/Heating/IVE	Summer/Cooling/in-situ	-2.5725	3.684709	-0.69816	0.9971	-1	1
Winter/Cooling/IVE	Summer/Heating/IVE	-2.747	3.904654	-0.70353	0.9969	-1	1
Summer/Heating/IVE	Summer/Cooling/IVE	-3.4583	3.722178	-0.92912	0.9833	-1	1
Summer/Heating/IVE	Summer/Heating/in-situ	-3.875	3.677129	-1.05381	0.966	-1	0
Winter/Cooling/in-situ	Summer/Cooling/IVE	-4.2173	3.879803	-1.08698	0.9597	-1	0
Summer/Heating/IVE	Summer/Cooling/in-situ	-4.4583	3.661182	-1.21773	0.927	-1	0
Winter/Cooling/in-situ	Summer/Heating/in-situ	-4.7202	3.843854	-1.228	0.9238	-1	0
Winter/Cooling/in-situ	Summer/Cooling/in-situ	-5.3006	3.824066	-1.38611	0.8639	-1	0
Winter/Cooling/IVE	Summer/Cooling/IVE	-6.3839	3.917166	-1.62973	0.7323	-1	0
Winter/Heating/IVE	Winter/Heating/in-situ	-6.56	3.73292	-1.75734	0.6492	-1	0
Winter/Cooling/IVE	Summer/Heating/in-situ	-6.8869	3.890543	-1.77017	0.6405	-1	0
Winter/Cooling/IVE	Summer/Cooling/in-situ	-7.622	3.873541	-1.96771	0.5039	-1	0

Table G.8 Oneway Analysis of General Thermal Acceptability by Season/Experiment Type/Experiment Setting Target Room Temp=85.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Upper CL
Summer/Heating/IVE	Summer/Cooling/IVE	2.92	3.88	0.75	1.00	-1	2
Winter/Cooling/IVE	Summer/Cooling/IVE	2.55	4.11	0.62	1.00	-1	2
Winter/Heating/IVE	Summer/Cooling/IVE	2.29	3.97	0.58	1.00	-1	2
Summer/Heating/IVE	Summer/Cooling/in-situ	2.00	3.83	0.52	1.00	-1	1
Summer/Heating/IVE	Summer/Heating/in-situ	2.00	3.89	0.51	1.00	-1	2
Winter/Cooling/IVE	Summer/Heating/in-situ	1.66	4.11	0.41	1.00	-1	2
Winter/Cooling/in-situ	Summer/Cooling/IVE	1.43	4.11	0.35	1.00	-1	2
Winter/Cooling/IVE	Summer/Cooling/in-situ	1.35	4.08	0.33	1.00	-2	1
Winter/Heating/IVE	Summer/Heating/in-situ	1.35	3.96	0.34	1.00	-1	2
Winter/Heating/IVE	Summer/Cooling/in-situ	1.31	3.94	0.33	1.00	-2	1
Winter/Heating/in-situ	Summer/Cooling/IVE	1.23	3.98	0.31	1.00	-2	2
Winter/Heating/IVE	Winter/Heating/in-situ	0.96	4.02	0.24	1.00	-1	2
Winter/Heating/IVE	Winter/Cooling/in-situ	0.87	4.15	0.21	1.00	-2	1
Winter/Cooling/IVE	Winter/Cooling/in-situ	0.82	4.27	0.19	1.00	-2	1
Summer/Heating/in-situ	Summer/Cooling/IVE	0.79	3.92	0.20	1.00	-2	2
Winter/Cooling/in-situ	Summer/Heating/in-situ	0.77	4.11	0.19	1.00	-1	2
Winter/Heating/in-situ	Summer/Heating/in-situ	0.33	3.98	0.08	1.00	-2	2
Winter/Heating/in-situ	Summer/Cooling/in-situ	0.08	3.96	0.02	1.00	-2	1
Winter/Cooling/in-situ	Summer/Cooling/in-situ	-0.12	4.08	-0.03	1.00	-1	1
Winter/Cooling/IVE	Summer/Heating/IVE	-0.15	4.07	-0.04	1.00	-2	1
Winter/Heating/IVE	Winter/Cooling/IVE	-0.19	4.14	-0.05	1.00	-1	2
Winter/Heating/in-situ	Winter/Cooling/in-situ	-0.27	4.16	-0.06	1.00	-2	1
Summer/Heating/in-situ	Summer/Cooling/in-situ	-0.33	3.91	-0.09	1.00	-2	1
Winter/Heating/IVE	Summer/Heating/IVE	-0.41	3.93	-0.10	1.00	-2	1
Winter/Heating/in-situ	Winter/Cooling/IVE	-1.14	4.15	-0.27	1.00	-2	2
Summer/Cooling/IVE	Summer/Cooling/in-situ	-1.17	3.89	-0.30	1.00	-2	1
Winter/Heating/in-situ	Summer/Heating/IVE	-1.47	3.95	-0.37	1.00	-2	1
Winter/Cooling/in-situ	Summer/Heating/IVE	-1.78	4.08	-0.44	1.00	-1	1

Table G.9 Oneway Analysis of General Thermal Comfort by Season/Experiment Type/Experiment Setting Target Room Temp=85.00

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Lower CL	Upper CL
Winter/Cooling/IVE	Summer/Cooling/IVE	5.18452	4.095727	1.26584	0.9114	-1	3
Winter/Cooling/in-situ	Summer/Cooling/IVE	4.17857	4.110887	1.01646	0.9721	-1	3
Summer/Heating/IVE	Summer/Cooling/IVE	3.83333	3.92347	0.97703	0.9777	-1	3
Summer/Heating/in-situ	Summer/Cooling/IVE	3	3.920192	0.76527	0.9948	-1	3
Winter/Cooling/IVE	Summer/Cooling/in-situ	2.97917	4.071296	0.73175	0.9961	-1	1
Winter/Heating/in-situ	Summer/Cooling/IVE	2.53167	3.989655	0.63456	0.9984	-2	2
Summer/Heating/IVE	Summer/Cooling/in-situ	2.29167	3.896602	0.58812	0.999	-2	1
Winter/Cooling/IVE	Summer/Heating/in-situ	2.28274	4.05926	0.56235	0.9993	-1	1
Winter/Heating/IVE	Summer/Cooling/IVE	1.96	3.991467	0.49105	0.9997	-2	2
Winter/Cooling/in-situ	Summer/Cooling/in-situ	1.66369	4.083205	0.40745	0.9999	-1	1
Summer/Heating/IVE	Summer/Heating/in-situ	1.375	3.894896	0.35303	1	-1	2
Winter/Cooling/IVE	Winter/Cooling/in-situ	1.28571	4.223543	0.30442	1	-1	1
Winter/Cooling/in-situ	Summer/Heating/in-situ	0.92857	4.076604	0.22778	1	-1	1
Summer/Heating/in-situ	Summer/Cooling/in-situ	0.79167	3.883498	0.20385	1	-2	1
Winter/Cooling/IVE	Summer/Heating/IVE	0.65774	4.067475	0.16171	1	-1	1
Winter/Heating/in-situ	Summer/Cooling/in-situ	0	3.971382	0	1	-2	1
Winter/Cooling/in-situ	Summer/Heating/IVE	-0.3869	4.090259	-0.09459	1	-2	1
Winter/Heating/IVE	Summer/Cooling/in-situ	-0.53083	3.97652	-0.13349	1	-2	1
Winter/Heating/IVE	Winter/Heating/in-situ	-0.56	4.034039	-0.13882	1	-2	2
Winter/Heating/in-situ	Summer/Heating/in-situ	-0.69417	3.96377	-0.17513	1	-2	1
Winter/Heating/IVE	Summer/Heating/in-situ	-1.26583	3.971382	-0.31874	1	-2	1
Winter/Heating/in-situ	Summer/Heating/IVE	-1.5925	3.973631	-0.40077	0.9999	-2	1
Winter/Heating/in-situ	Winter/Cooling/in-situ	-1.74143	4.143367	-0.42029	0.9999	-2	1
Summer/Cooling/IVE	Summer/Cooling/in-situ	-2.04167	3.918383	-0.52105	0.9996	-3	1
Winter/Heating/IVE	Summer/Heating/IVE	-2.0825	3.975557	-0.52383	0.9995	-2	1
Winter/Heating/IVE	Winter/Cooling/in-situ	-2.34714	4.150389	-0.56552	0.9992	-2	1
Winter/Heating/in-situ	Winter/Cooling/IVE	-2.83929	4.130608	-0.68738	0.9973	-2	1
Winter/Heating/IVE	Winter/Cooling/IVE	-3.36929	4.134924	-0.81484	0.9924	-2	1

APPENDIX H ADDITIONAL TESTS

Table H.1 Correlation test results between covariates and total number of selected eco-friendly behaviors

Variable	by Variable	Spearman ρ	Prob> ρ
Age	total number of the eco-friendly behaviors	-0.1459	0.0005*
Gender	total number of the eco-friendly behaviors	-0.1057	0.0123*
Behavior_Attitude	total number of the eco-friendly behaviors	-0.1192	0.0047*
Behavior_Intention	total number of the eco-friendly behaviors	-0.1333	0.0016*
Behavior Saving Energy	total number of the eco-friendly behaviors	-0.0140	0.7406

Table H.2 Correlation Test Results between covariates and demographics

Variable	by Variable	Spearman ρ	Prob> ρ
Behavior_Saving Energy	Age	0.1471	0.0005*
Behavior_Awareness	Age	0.1547	0.0002*
Age	Cybersickness_Disorientation_IVE	0.1750	0.0033*
Immersiveness Tendency_Focus	Presence_Involvement_IVE	0.1144	0.0559
Immersiveness Tendency_Focus	Cybersickness_Disorientation_IVE	-0.1205	0.0439*
Immersiveness Tendency_Focus	Computer Skills and Experience with VR	0.1034	0.0841
Immersiveness Tendency_Emotion	Presence_Involvement_IVE	0.1054	0.0783
Immersiveness Tendency_Entertainment	Presence_Spatial Presence_IVE	0.1342	0.0247*
Immersiveness Tendency_Entertainment	Age	0.1992	0.0008*
Immersiveness Tendency_Entertainment	Computer Skills and Experience with VR	0.2573	<.0001*

APPENDIX I IRB APPROVAL

ACTION ON PROTOCOL APPROVAL REQUEST



Institutional Review Board
Dr. Dennis Landin, Chair
130 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.5983
irb@lsu.edu
lsu.edu/research

TO: Yimin Zhu
Construction Management

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: January 31, 2018

RE: IRB# 3998

TITLE: Exploring Occupant Thermally-Driven Behavior in Immersive Virtual Environment for Building Design

New Protocol/Modification/Continuation: New Protocol

Review type: Full ☐ Expedited ☒ **Review date:** 1/29/2018

Risk Factor: Minimal ☒ Uncertain ☐ Greater Than Minimal ☐

Approved ☒ **Disapproved** ☐

Approval Date: 1/31/2018 **Approval Expiration Date:** 1/30/2019

Re-review frequency: (annual unless otherwise stated)

Number of subjects approved: 100

LSU Proposal Number (if applicable):

Protocol Matches Scope of Work in Grant proposal: (if applicable)

By: Dennis Landin, Chairman 

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –

Continuing approval is **CONDITIONAL** on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. **SPECIAL NOTE: When emailing more than one recipient, make sure you use bcc.**

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at <http://www.lsu.edu/irb>*

VITA

Sanaz Saeidi was born in Tehran, Iran on May 23rd, 1984. From 1999 to 2002, she studied mathematics-physics in Maryam High School in Tehran and there she developed a life-long interest in sketching and designing built environments. From 2002 to 2006, she studied in Azad Central Tehran University, School of Art and Architecture. Her major was Architectural Engineering, and she won several awards in student contests and special projects related to the curriculum. In 2004 she became an Architect Intern at Aran Co., developing her freehand architectural design. Upon graduating, Sanaz began her professional career as an Architectural Designer for Tarh-o-Takvin Co. in Tehran, where she collaborated to prepare technical drafts and architectural details of several commercial and residential buildings, as well as the world's sixth tallest tower, Milad Tower of Tehran. Her experience led her to become the site supervisor on another construction project for Ab-Omran Co. on Kish Island, Iran, 2008-2009. She then moved to Cyprus to continue her education, and earned a M.Sc. degree in Urban Design in 2012. She entered Louisiana State University (LSU) in August 2014 to pursue a M.Sc.-Ph.D. dual degree in Construction Management. Her research provides future building occupants with experience of new design in context-aware experimental platforms—Immersive Virtual Environments. Besides her research, she assisted several classes as a TA throughout her time at LSU and later became an instructor of record for a senior level course— Building Information Modeling (BIM) in Fall 2018 and Spring 2019; she successfully applied various cutting-edge technologies (*e.g.*, VR/AR, 3D Laser Scanning, 4D/5D Simulations) into the curriculum. She is an associate member of the American Institute of Architects (AIA), the Society of Women Engineers (SWE), and the American Society of Civil Engineers (ASCE). She continues to explore opportunities to make further contribution in both academia and industry.