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Authors

Saeidi, Sanaz
Rentala, Girish
Rizzuto, Tracey
et al.

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EXPLORING THERMAL STATE IN MIXED IMMERSIVE VIRTUAL ENVIRONMENTS

Sanaz Saeidi[a], Girish Rentala[b], Tracey Rizzuto[c], Tianzhen Hong[d], Neil Johannsen[e], Yimin Zhu[f]

a – Former PhD student, Department of Construction Management, Louisiana State University, Baton Rouge, LA 70803, email: snazsaeidi@gmail.com
b – Ph.D. student, Department of Construction Management, Louisiana State University, Baton Rouge, LA 70803, email: grenta1@lsu.edu
c - Professor, School of Leadership and Human Resource Development, Louisiana State University, Baton Rouge, LA 70803, email: trizzut@lsu.edu
d – Staff scientist, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, email: THong@lbl.gov
e – Associate professor, School of Kinesiology, Louisiana State University, Baton Rouge, LA 70803, email: njohan1@lsu.edu
f – Professor, Department of Construction Management, Louisiana State University, Baton Rouge, LA 70803, phone: 225-578-5373, email: yiminzhu@lsu.edu (Corresponding Author)

ABSTRACT

Combining immersive virtual environment (IVE) with a controlled environment is a potential solution for analyzing human thermal experience during building design. Existing studies in this field have not adequately analyzed scenarios involving stabilized comfortable and uncomfortable temperature conditions using both thermal state votes and physiological responses, or the influence of the seasons. By combining IVE with a climate chamber, called mixed IVE (MIVE) in this study, experiments were conducted to test the hypothesis that participants' virtual experience did not significantly alter their thermal experience compared to their *in-situ* experience. Response variables were the *control temperature distribution*, the *thermal state vote* (at temperature steps 18.3 ℃, 23.8 ℃, and 29.4 ℃), and *physiological responses* (heart rate and skin temperature). The results show that the first two response variables were not significantly different between the MIVE and *in-situ* settings (except for one case). Due to the heat development of the head mounted display device, the mean forehead skin temperature in the MIVE experiments was significantly higher than that in the *in-situ* experiments in most cases. However, such difference in skin

temperature did not seem to affect general thermal state votes. In addition, significant skin temperature differences at some locations were also observed between the MIVE and *in-situ* settings.

Keywords: Mixed Immersive Virtual Environment (MIVE), thermal experience, thermal state, physiological responses, season

Abbreviations

AMOLED	Active-Matrix Organic Light-Emitting Diode
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMI	Body Mass Index
bpm	Beats Per Minute
CAVE	Cave Automatic Virtual Environment
CO_2	Carbon Dioxide
EEG	Electroencephalogram
HMD	Head Mounted Display
HR	Heart Rate
HVAC	Heating, Ventilation, and Air Conditioning
Hz	Hertz
IPQ	Igroup Presence Questionnaire
IVE	Immersive Virtual Environment
K-S	Kolmogorov-Smirnov
MIVE	Mixed Immersive Virtual Environment
NCDC	National Climate Data Center
PPM	Parts Per Million
PR_{temp}	Physiological Response at a certain Step Temperature in the *in-situ* setting
PR'_{temp}	Physiological Response at a certain Step Temperature in the MIVE setting
RH	Relative Humidity
SSQ	Simulator Sickness Questionnaire
T_{sk}	Skin Temperature
T_{level}	Control Temperature distributions across all levels of a thermal state scale in the *in-situ* setting
T'_{level}	Control Temperature distributions across all levels of a thermal state scale in the MIVE setting
V_{temp}	Thermal State Votes at different Step Temperatures in the *in-situ* setting
V'_{temp}	Thermal State Votes at different Step Temperatures in the MIVE setting

BACKGROUND

The importance of building occupant energy behavior, or occupant interactions with building energy-related components or systems, has regained the attention of the building energy research communities [1]. Recent studies showed that a better understanding of occupant energy behavior improved the design and engineering of sustainable buildings (e.g., [2]). Currently, knowledge of occupant energy behavior is mainly derived from field monitoring and observations, and surveys of occupants in real buildings. Since occupant energy behavior is often influenced by many contextual factors [3], such knowledge is likely contextualized to specific buildings, operations, and occupancy conditions, making it difficult to apply in other contexts. Especially, designers often face a unique challenge during the design stage, where the physical environment of a building is not yet available but the knowledge of occupant's experience in such environment is highly desirable. Thus, it will be beneficial to have a tool that allows designers to better analyze potential occupants' experience in the context of a building under design, as well as their behaviors in such context.

Thermally-driven behaviors such as adjusting thermostats or opening windows are considered an important category of occupant behaviors that affect building energy performance [4]. Such behaviors are influenced by thermal sensation, thermal comfort, and thermal acceptability (e.g., [5]), collectively called "thermal state" in this study. Thus, tools enabling designers to study thermally-driven behaviors should first support thermal state analysis during design. As a type of virtual reality environments offering a high level of immersion for users [6], immersive virtual environments (IVEs) have successfully allowed participants to experience a design (e.g., [7][8][9]), and researchers to observe participants' lighting-use [10] or wayfinding [8] behaviors in the context of the design. On the other hand, the use of immersive virtual

environments (IVEs) for studying thermal state and thermally-driven behavior is just emerging and requires more research attention. Therefore, in this study, the authors are interested in investigating the potential of a mixed IVE (MIVE), a combination of IVE and a climate chamber, to replicate the thermal state of participants, the comparability of participants' thermal experience between *in-situ* and MIVE settings, and the use of the thermal state and physiological responses of participants to measure their thermal experience.

IMMERSIVE VIRTUAL ENVIRONMENTS FOR THERMAL STATE STUDIES

Thermal State Studies

Field studies on the thermal experience of the occupants in indoor spaces have been ongoing for decades. For example, Fanger [11] developed a general theory of thermal comfort, in which key factors of thermal comfort such as environmental conditions and the human metabolic rate were identified. Later, the adaptive hypothesis [12] associated contextual factors such as climate and past experiences with occupant thermal comfort and preferences. Other studies attempted to understand thermal experience in different indoor conditions, such as examining thermal sensation and comfort when the indoor temperature changed [13], studying the type of controls (e.g., blinds and electric lighting) and their impact on thermal comfort [14], and discovering issues related to individual temperature controls in offices [15]. Thermal sensation, thermal comfort, and thermal acceptability are commonly used to measure thermal experience (e.g., [13][14][15][16][17][18][19]). Especially, Zhang and Zhao [19] explained the relationship and differences of the three measures. In addition, different physiological responses have also been identified as influential factors such as heart rate or heart rate variability (e.g., [20][21][22]), skin

temperature (e.g., [23][24][22]), pulse rate (e.g., [25]), and electroencephalogram (EEG) and oxygen saturation (e.g., [26]).

Controlled environments is one of the major methods applied to thermal comfort studies [27]. Climate chambers are common equipment to provide controlled environmental conditions. For example, climate chambers were used to study the relationship between the anticipated control over thermal conditions and the perceived thermal comfort (e.g., [16]), the impact of thermal history on thermal sensation and comfort (e.g., [28]), the impact of age, gender and body mass index (BMI) on thermal sensation (e.g., [29][30][31]), the evaluation of new technologies such as personalized conditioning systems (e.g., [32]). Typically, such climate chamber applications focused on providing different test conditions such as temperature and humidity conditions. Furthermore, a variation to climate chambers, semi-controlled environments with equivalent environmental conditioning capabilities to climate chambers and more office or residential space feeling were also applied in experiments (e.g. [22]).

The aforementioned literature showed parameters and methods that are commonly applied in traditional thermal comfort studies. The information is useful for designing experiments using immersive virtual environments (IVEs) with respect to creating different environmental conditions and selecting thermal state and physiological response parameters for data collection.

Immersive Virtual Environments and Thermal Perception

There are three known pathways, through which virtual reality-related technologies may influence human thermal perception. First, previous studies demonstrated that visual stimuli in IVEs had impacted human physiological responses measured by heart rate, skin conductance, respiratory rate, and blood pressure [33], as well as skin temperature [34][35]. Since there is a proven

association between human thermal sensation and physiological responses such as skin temperature [36], metabolism [37], and heart rate [38][39], it is possible that visual stimuli in IVEs may influence human thermal state through those physiological variables, although the extent and mechanism of such influence are not fully known.

Secondly, researchers attempted to integrate external thermal stimuli with virtual environments in order to create comparable thermal experiences for participants. One category of studies focused on the application of thermal haptic devices (e.g., [40]) or Peltier devices (e.g., [41]). These studies supported participants' thermal perception in virtual environments through touch of virtual objects (e.g., [42][43][44]). Other studies explored different technologies. For example, Hülsmann et al. [45] studied the use of infrared lamps in a Cave Automatic Virtual Environment (CAVE) to produce a heat stimulus. Although the study found a promising use of infrared lamps and fans to generate warmth and wind in the CAVE, the study did not measure or test the accuracy of the simulations compared to the real conditions. Similar ideas were applied to fire emergency in the built environments. For example, Shaw et al. [46] reported a study using infrared heaters to simulate the heat of fires. In the study, the actual temperature around the participants was not a major concern, as long as the heat generated a realistic feeling of fires. Thus, using these devices or methods to generate external thermal stimuli may be effective in their respective applications, but they are not ideal for studies on the human thermal state due to the lack of precise controls over the thermal conditions around participants as needed by thermal state studies.

Finally, the heat development of a head mounted display (HMD) device can be a factor affecting local thermal perception. For example, a recent study [47] investigated different head mounted display devices. Among others, the study reported that the hottest recorded temperature

at the center HTC Vive was 27.6°C. During an experiment, the ambient temperature can be different from the air temperature inside the device or the surface temperature of the device. When the difference is large enough, it may become obvious to participants and thus affects their thermal sensation. Since forehead is a location sensitive to thermal sensation [48], the heat development of the device may have an impact on the thermal perception of participants at least locally.

In addition to the above pathways, other known factors that may impact the outcomes of IVEs experiments are the virtual experience of participants. First, presence, "a psychological state of 'being there' mediated by an environment that activates the human senses, captures human attention, and encourages active involvement" [49], is an important measurement of virtual experience (e.g., [50][51][52]). Secondly, interactions with virtual reality, particularly using an HMD device, may trigger symptoms similar to motion sickness or cybersickness (e.g., [53][54][55][56]). Poor virtual experiences may negatively impact the quality of an IVE experiment. Thus, factors such as presence and cybersickness were often used to control the quality of participants' virtual experience and experiments.

Therefore, when comparative studies between IVE and *in-situ* are conducted, the potential impact of the pathways and the virtual experience factors need to be managed such as using comparable visual and thermal stimuli. Although the heat development of an HMD and the virtual experience factors cannot be controlled in comparative studies, their impact can be analyzed.

Mixed Immersive Virtual Environments
Given proven capabilities of controlled environments for thermal state studies and the reported potentials of IVEs, it is natural to explore the option of combining the two as a potential tool to support design with respect to thermal states. The idea has been explored recently. For example,

existing studies used an HMD and different approaches to provide thermal stimuli such as a climate chamber (e.g., [57][58]), a temperature and humidity controlled existing space (e.g., [59]), and a temperature and humidity controlled existing space with additional heating or cooling remedies such as a heater or a fan (e.g. [60]). Not only those studies used different approaches to generate thermal stimuli, key elements of their experiment protocols were also different. For example, in the studies conducted by Yeom et al. [57][61], participants were continuously surveyed every 10 minutes while the temperature was changing from 20°C to 30°C for heating and 30°C to 20°C for cooling. Based on this experimental design, the perceived environmental temperature at each thermal sensation level and participant's overall heart rate and skin temperature were analyzed and found significantly different between IVE and *in-situ* settings. On the other hand, with a focus on interactions between human and building systems in the built environment [60], participants were initially put in cold (18°C) and hot (28°C) conditions and then they used heating/cooling remedies to change the room temperature. Given the fact that the remedies included the thermostat, local heater/cooler, desk fan, and beverage in the actual or virtual office, the impact on the overall environmental temperature and the time to reach intended temperature could vary using different remedies. By examining actual versus perceived indoor air temperature, thermal comfort and satisfaction, and the number and types of interactions, the study reported a promising application of immersive virtual environment to human-building interaction studies.

Nevertheless, the two studies have not answered other important questions related to experimental protocols that make IVE experiments comparable to *in-situ* experiments. For example, the study [57][58] showed that the environmental temperature and measured physiological responses in the IVE setting were significantly different from those in the *in-situ* setting. However, the study did not discuss changes to its experimental protocol so that comparable

results between IVE and *in-situ* settings could be obtained. The other study [60] measured the thermal experience of participants associated with the use of thermal remedies and did not report physiological responses at different temperature steps as many thermal state studies (e.g., [37][38][62][48][23][63]). In addition, previous studies confirmed the seasonal influence on physiological responses (e.g., [64][65]), as well as thermal comfort adaptability, and thermal sensation (e.g., [66][67][68]). Since an IVE experiment may be administered in different seasons, such seasonal influence needs to be addressed in an experimental protocol.

Therefore, a protocol applying different environmental conditions and variables to studies on the thermal experience of participants in IVEs was desirable. This study used the mixed IVE (MIVE), an experimental environment combining IVE with a climate chamber to conduct experiments. Since heart rate, skin temperature, and thermal state votes were commonly applied in conventional thermal state and IVE studies, they were chosen, in addition to presence and cybersickness (for virtual experiments only), to measure participants' thermal experience during experiments. These variables were observed at different temperature steps, a technique commonly used in thermal comfort studies (e.g., [20][48][63]).

RESEARCH QUESTIONS AND HYPOTHESES

The overall goal of the study was to examine the thermal experience of participants in the MIVE as measured by the thermal state and physiological responses of participants; and to determine if such experience was comparable to the *in-situ* thermal experience. To achieve the goal, the authors managed the pathway and virtual experience factors by using comparable visual and thermal stimuli, evaluating participants' virtual presence and cybersickness, and analyzing the potential

influence of the heat development of the HMD. In particular, the authors were interested in the following questions:

1) Was the control temperature around the participants in the *in-situ* setting significantly different from that in the MIVE setting when the participants had the same level of thermal state?

2) Was the thermal state vote at a temperature step in the *in-situ* setting significantly different from those of the MIVE setting in comparable indoor environmental conditions?

3) Were the physiological responses of the same participants significantly different between MIVE and *in-situ* settings when the indoor environmental conditions of the two settings were comparable?

These questions were designed to determine if the MIVE altered participants' thermal experience compared to the *in-situ* setting. The first question sought comparability information between the MIVE and *in-situ* settings regarding the environmental temperature around participants in relation to thermal state levels. The second question was intended to understand the thermal state vote at a comparable environmental temperature step between IVE and *in-situ* settings. The environmental temperature around participants and the thermal state vote at each temperature step are two aspects of the participant's thermal experience. The third question focused on understanding the impact of IVE on the participants physiological factors.

To answer the questions, the authors considered three variables to describe participants' thermal experience, i.e., the control temperature distribution, the thermal state vote, and the physiological responses. Accordingly, the authors hypothesized:

1) There was no significant difference in the control temperature distribution across the thermal state levels (i.e., sensation, comfort, or acceptability) between the two settings;

Null Hypothesis, H_0: $T_{level} = T'_{level}$ (level = sensation, comfort, or acceptability)

Alternate Hypothesis, H_1: $T_{level} \neq T'_{level}$ (level = sensation, comfort, or acceptability)

where, T_{level} represents the control temperature distribution across all levels of a thermal state scale (i.e., sensation, comfort, or acceptability) in the *in-situ* setting; T'_{level} represents the control temperature distribution across all levels of a thermal state scale (i.e., sensation, comfort, or acceptability) in the MIVE setting. The thermal sensation scale has 7 levels (i.e., -3, -2, -1, 0, 1, 2, and 3). The thermal comfort scale and the thermal acceptability scale have 6 levels (i.e., -3, -2, -1, 1, 2, and 3).

2) There was no significant difference in the thermal state vote at each temperature step between the two settings.

Null Hypothesis, H_0: $V_{temp} = V'_{temp}$ (temp = 65ºF/18.3ºC, 75ºF/23.8ºC, and 85ºF/29.4ºC)

Alternate Hypothesis, H_1: $V_{temp} \neq V'_{temp}$ (temp = 65ºF/18.3ºC, 75ºF/23.8ºC, and 85ºF/29.4ºC)

where, V_{temp} represents the thermal state vote at a certain temperature step (65 ºF/18.3 ºC, 75 ºF/23.8 ºC, and 85 ºF/29.4 ºC) in the *in-situ* setting; V'_{temp} represents the thermal state vote at a certain temperature step (65 ºF/18.3 ºC, 75 ºF/23.8 ºC, and 85 ºF/29.4 ºC) in the MIVE setting.

3) There was no significant difference in the physiological responses (i.e., skin temperature (T_{sk}) and heart rate (HR)) at each temperature step between the two settings.

Null Hypothesis, H_0: $PR_{temp} = PR'_{temp}$ (temp = 65 ºF/18.3 ºC, 75 ºF/23.8 ºC, and 85 ºF/29.4 ºC)

Alternate Hypothesis, H_1: $PR_{temp} \neq PR'_{temp}$ (temp = 65 ºF/18.3 ºC, 75 ºF/23.8 ºC, and 85 ºF/29.4 ºC)

where, PR_{temp} represents the mean T_{sk} at each of eight body sites and the mean HR at a certain temperature step (i.e., 65 ºF/18.3 ºC, 75 ºF/23.8 ºC, and 85 ºF/29.4 ºC) of a cooling or heating sequence in the *in-situ* setting; PR'_{temp} represents the mean T_{sk} at each of eight body sites and the mean HR at a certain temperature step (i.e., 65 ºF/18.3 ºC, 75 ºF/23.8 ºC, and 85 ºF/29.4 ºC) of a cooling or heating sequence in the MIVE setting.

According to the ASHRAE psychrometric chart, 75 ºF/23.8 ºC (55% relative humidity) falls into the comfort zone range for both winter and summer conditions, while 65 ºF/18.3 ºC and 85 ºF/29.4 ºC (55% relative humidity) are outside the comfort zone range (cool and warm, respectively) [69]. Consequently, the three temperature steps may possibly cover both comfortable and uncomfortable conditions when the results of IVE and *in-situ* experiments are analyzed and compared.

RESEARCH METHOD

Recruitment

After the experiment protocol was approved by the Instructional Review Board, word of mouth and flyers were the methods used for inviting participants on the campus of a major university in the central-south region of the United States. Interested participants communicated with the experimenter regarding the inclusion/exclusion criteria. Participants were asked to avoid strong caffeine, alcohol, smoking, and intense physical activities at least 12 hours prior to each of the

experimental sessions. Then, the consent form was sent to them. Once the participant agreed to sign the consent form, the experimental session was scheduled. The participants were reimbursed for $10.00 per hour for their participation in the experiments.

Research Equipment, Devices, and Instruments

Climate Chamber

The climate chamber is a renovated indoor office space. The basic layout of the climate chamber is shown in Figure 1. The climate chamber has three enclosed spaces including the main testing area, the control/resting area, and a mechanical room. The size of the testing area is about 13'9" (L) x 10'5" (W) x 9' (H) or 4.2m (L) x 3.2m (W) x 2.7m (H). The climate chamber can simulate a temperature range of 60°F/15°C to 90°F/32°C and the relative humidity of 40% to 90%. Its HVAC system is equipped with temperature, humidity, and CO_2 sensors for the purpose of monitoring and controlling environmental conditions. Metasys® software provides coordinated control over the chamber's HVAC system.
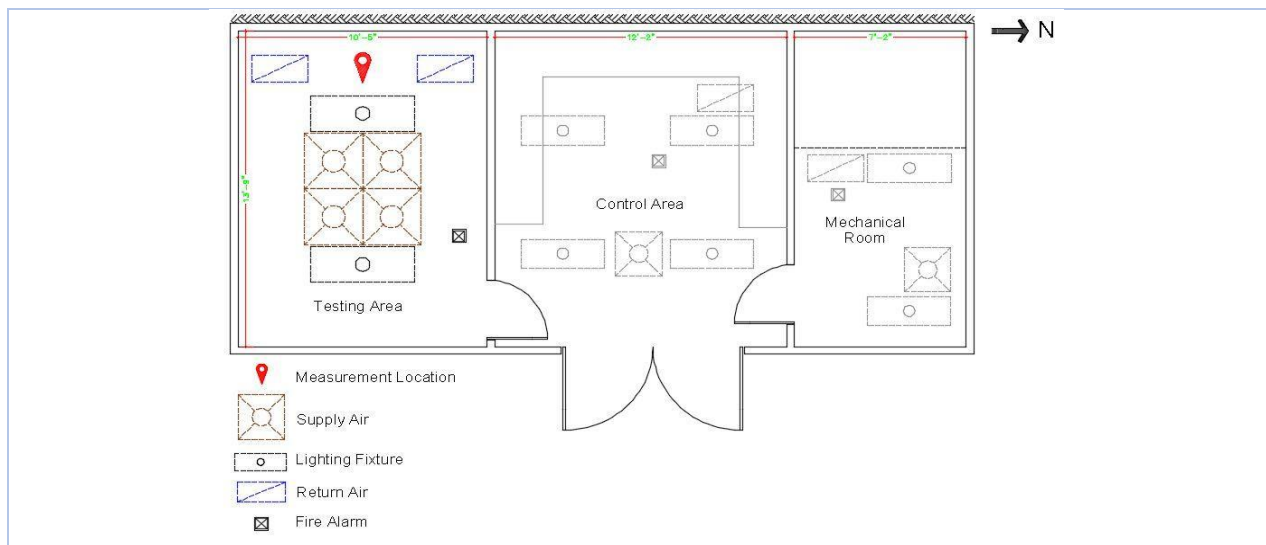

Figure 1. Climate Chamber Layout

The performance of the chamber was tested based on the zone temperature and humidity controlled by the HVAC system. The test showed that the sample mean of the zone temperature and standard deviation were 18.7°C (mean) and 0.7°C (standard deviation), 23.6°C (mean) and 0.4°C (standard deviation), and 29.2°C (mean) and 0.2°C (standard deviation), when the set point was 65°F/18.3°C, 75°F/23.8°C, and 85°F /29.4°, respectively. The chamber relative humidity was set to 55%. The sample mean and standard deviation were 51.2% and 8.1%, respectively.

Additional Environmental Monitoring Sensors

Additional devices were used to measure the environmental temperature around the participants. Three Vernier temperature sensors were installed at the height of 4 inches/0.1 meters, 24 inches/0.6 meters, and 34 inches/1.1 meters, following the recommendation by ASHRAE 52-2010. The temperature measured by the sensor at 24 inches/0.6 meters was specifically chosen as the control temperature for data analysis because the height of the sensor was close to the middle point of the participants' height when they were in a sitting position during experiments (Figure 2). Temperature data transmitted in 1-second intervals and was logged with Logger Pro 13. The specifications of these sensors are shown in Table 1.
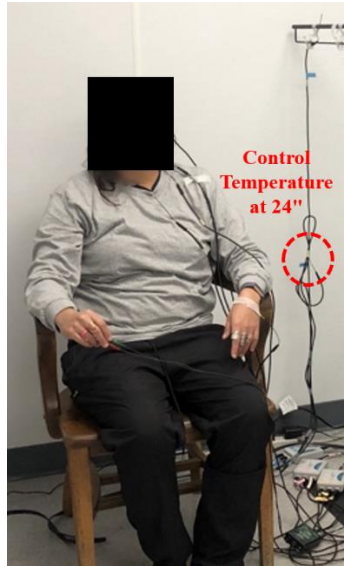
Figure 2. Environment Temperature Sensors

Outdoor Air Temperature and Relative Humidity

Online city-wide hourly weather data was the main source for outdoor weather information. The most commonly used databases for this purpose include the Integrated Surface Hourly Database at the NOAA's National Climate Data Center (NCDC) [70].

Heart Rate

A wireless electrode-base heart rate monitoring device, Polar Ft7 (specification shown in Table 1), was used to measure the heart rate (HR) of participants. The heart rate data was recorded using the Heart Rate Variability Logger application.

Skin Temperature

Vernier surface temperature sensors were used to record the skin surface temperatures at eight body locations (Figure 3) and the control temperature (Figure 2) using a software tool, Logger Pro. The yellow circles (Figure 3) show the body locations, from which the skin temperatures and

thermal sensation and acceptability votes were sampled. 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 [48][63][71].
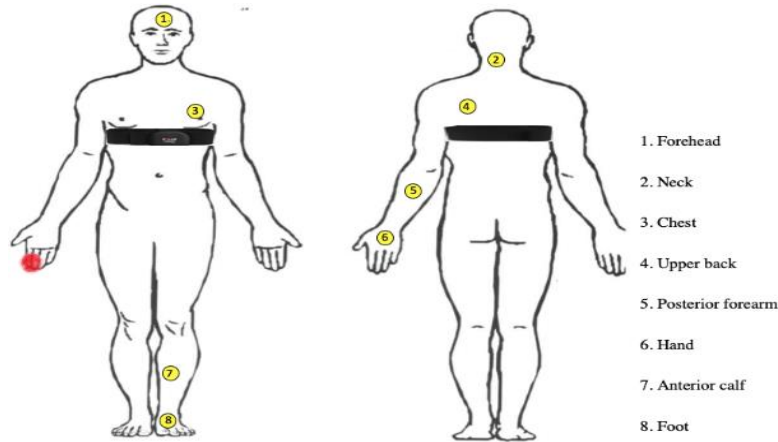

1. Forehead
2. Neck
3. Chest
4. Upper back
5. Posterior forearm
6. Hand
7. Anterior calf
8. Foot

Figure 3. Body Sensor Deployment

Table 1. Sensor Specifications

Sensing Equipment	Model	Specifications
Vernier surface temperature sensors	STS-BTA	Range: –25°C to 125°C (–13°F to 257°F)
		Accuracy: ± 0.2°C at 0°C; ± 0.5°C at 100°C
		Resolution: 0.1 °C
Heart rate sensor	POLAR Ft7	Accuracy: ± 1 bpm

IVE Apparatus

The head-mounted display (HMD) used in this study was an HTC-Vive, which supports a 2,160 x 1,200 resolution on a dual-AMOLED 91mm panels with 90Hz refresh rate and a 110-degree field of view. The 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.

A virtual model of the chamber was created and rendered in the 3D Studio Max environment. The final model, along with the texture and light maps, was then exported into the Unreal Engine for the required programming of necessary visual cues (Figure 4). The model, an approximation of the chamber, has similar interior layout, and major furniture and equipment. An additional virtual component of the virtual model was the questionnaire boxes that were used to show thermal state vote options when collecting data, so that participants did not need to remove the HMD to answer the questions. For example, when they were ready to report their thermal sensation, the ASHRAE seven-point Likert scale was shown in the virtual model.
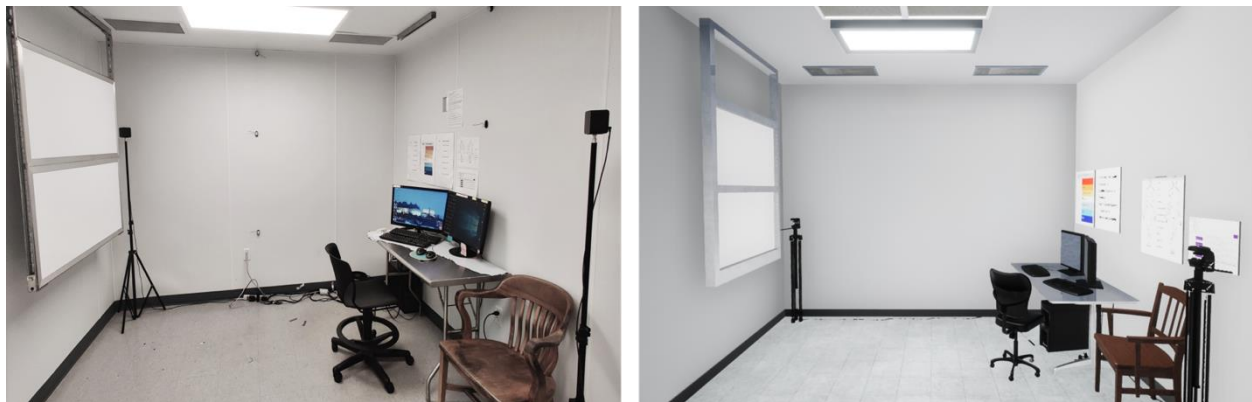
Figure 4. *in-situ* (Left) vs. virtual (Right) Space

Survey instruments

The following types of questionnaires were used through an online software platform, namely Qualtrics:

- Background Information: This questionnaire was administered only on the first visit. It included information such as age, gender, education level, and employment status.

- Thermal state: In this study, participants' votes on (i.e., self-reported perceptions of) their overall thermal sensation were measured using the descriptive 7-point Likert scale of the ASHRAE Standard 55 Thermal Comfort [12][17]. The thermal sensation scale

17

is: "+3, +2, +1, 0, -1, -2, -3" representing "Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool, Cold", respectively. A thermal comfort scale similar to the one in [18], and a customized thermal acceptability scale based on [19] were applied to measuring their overall thermal comfort and thermal acceptability, respectively. The thermal comfort scale is: "+3, +2, +1, -1, -2, -3" representing "Very Comfortable, Comfortable, Slightly Comfortable, Slightly Uncomfortable, Uncomfortable, Very Uncomfortable", respectively. The thermal acceptability scale is: "+3, +2, +1, -1, -2, -3" representing "Perfectly Acceptable, Acceptable, Slightly Acceptable, Slightly Unacceptable, Unacceptable, Totally Unacceptable", respectively. These scales were used to collect the general thermal state vote data in both MIVE and *in-situ* experiments, as well as the local thermal sensation and acceptability vote data at the eight body sites of participants (Figure 3).

- Igroup Presence Questionnaire (IPQ): The Igroup Presence Questionnaire (IPQ) [72], a commonly used questionnaire to measure the subjective depth of presence in IVE (e.g., [50][51][52]), was used. The IPQ is a 13-item questionnaire that consists of three sub-measures, i.e., 4 items for spatial presence (a sensation of being spatially located in the virtual environment), 4 items for involvement (degree to which the user is involved in the virtual experience), and 4 items for experienced realism (degree of similarity with the real world), as well as 1 item for a general presence item. It is administered after each IVE experimental session. All items are rated on a five-point Likert scale (1-strongly disagree; 5-strongly agree). The score for each sub-measure is obtained by adding the responses of the respective sub-measure items, and then converting the sum to a percentage (multiplying by 100 and then dividing by the

number of points on the Likert scale, which in this case is 5). Thus, the score for each item, each sub-measure, and the general item ranges from 20 to 100. A higher score indicates that the person has a greater presence in IVE. Consequently, lower scores indicate poor presence in IVE.

- Simulator Sickness Questionnaire (SSQ): SSQ [73] is a 16-item questionnaire with three sub-measures, i.e., nausea (7 items), oculomotor (7 items), and disorientation (7 items), along with a total cybersickness score. All items are rated on a four-point scale (0-none; 3-severe). The scores for each sub-measure and the total cybersickness are calculated as follows: Nausea = [A] x 9.54, Oculomotor = [B] x 7.58, Disorientation = [C] x 13.92 and Total Cybersickness = [A] + [B] + [C] x 3.74, where [A], [B], [C] represent the summation of the responses of the items related to nausea, oculomotor and disorientation respectively. A higher score in each sub-measure indicates that the person feels more unformattable in virtual reality.

Experimental Design and Procedure

A within-subject design was applied to the study. All participants repeated experimental sessions in two periods, one in colder outdoor temperature (Period 1, January to February of 2019 and 2020, average outdoor temperature was 16.83°C) and the other in warmer outdoor temperature (Period 2, April to September 2019, average outdoor temperature was 28°C). In each period, participants finished four experimental sessions (i.e., heating and cooling exposures in both MIVE and *in-situ* settings). The heating and cooling exposures were at least two weeks apart; and the MIVE and *in-situ* experimental sessions were on the same day, either a heating exposure or a cooling exposure.

Figure 5 illustrates the experimental sessions, the type of data to be collected, and the estimated timelines for each step of the experiments.

				A week before	Rest (10 min) - 75°F/23.8°C; 50% RH in the waiting area				Rest (10 min) - 75°F/23.8°C; 50% RH in the waiting area			
Dependent Variables and Covariates	Physiological Measurements	Skin Temperature				← →				← →		
		Heart Rate				← →				← →		
	Psychological Measurements	Demographics		✓		← →				← →		
		General Information			✓							
		Thermal States				✓	✓	✓		✓	✓	✓
		Presence										✓
		Cybersickness										✓
Independent Variables/Manipulations	Period 1 (Colder)	Session 1	Heating Exposure (MIVE)			65°F/18.3°C	75°F/23.8°C	85°F/29.4°C				
			Heating Exposure (in-situ)							65°F/18.3°C	75°F/23.8°C	85°F/29.4°C
		Session 2	Cooling Exposure (MIVE)			85°F/29.4°C	75°F/23.8°C	65°F/18.3°C				
			Cooling Exposure (in-situ)							85°F/29.4°C	75°F/23.8°C	65°F/18.3°C
	Period 2 (Warmer)	Session 3	Heating Exposure (MIVE)			65°F/18.3°C	75°F/23.8°C	85°F/29.4°C				
			Heating Exposure (in-situ)							65°F/18.3°C	75°F/23.8°C	85°F/29.4°C
		Session 4	Cooling Exposure (MIVE)			85°F/29.4°C	75°F/23.8°C	65°F/18.3°C				
			Cooling Exposure (in-situ)							85°F/29.4°C	75°F/23.8°C	65°F/18.3°C

Figure 5. Experiment and Data Collection Procedure

Participants were instructed to come to the lab with the predefined set of clothing in all the sessions, i.e., shoes, socks, underwear, light pants, and a light long-sleeved shirt/T-shirt. The clothing insulation (0.5-0.6 clo) was considered as the standard clothing insulation in some studies of office buildings [74][75]. There was always a 10-minute resting period in the rest area after participants arrived at the lab, to ensure that the participants were acclimatized to the indoor condition. Afterwards, they were asked to enter the chamber and sit down on a chair before the experiment started.

Participants' tasks in this study were limited to sedentary or near sedentary physical activities, i.e., seated at rest, while the study examined a heating exposure and a cooling exposure. In particular, the heating exposure included a heating sequence with three increasing temperature steps from 65°F/18.3°C to 75°F/23.8°C and to 85°F/29.4°C. The cooling exposure had a cooling sequence with three reverse temperature steps. For example, in a heating exposure, the temperature in the chamber was first set to 65°F/18.3°C; then the experimenter waited for the chamber temperature to stabilize around the temperature setpoint. After stabilization, participants' thermal state responses were recorded and then the experimenter re-set the chamber temperature to

75°F/23.8°C. After the chamber temperature stabilized at 75°F/23.8°C, the experimenter repeated the data collection process. A similar process took place when the temperature was set to 85°F/29.4°C. In a similar but reverse order, the temperature in the chamber was first set to 85°F/29.4°C in a cooling exposure, and then lowered to 75°F/23.8°C and 65°F/18.3°C after data collection at each temperature step.

Each of the heating and cooling exposures was performed in two experimental settings, i.e., 1) heating exposure in *in-situ* and the MIVE, and 2) cooling exposure in *in-situ* and the MIVE. Participants were assigned to each of the experimental sessions and sub-sessions in a random fashion to counterbalance and minimize the order effects. About half of the participants performed the heating sequence first, then cooling, while the other half did the cooling sequence first, then heating. Likewise, about half of the participants completed the *in-situ* trial first, while the other half experienced the MIVE in their first trial.

All physiological measurements were collected continuously and recorded at one-second intervals. The thermal state votes (i.e., thermal sensation, thermal comfort, and thermal acceptability) were recorded three times, at 18.3°C/65°F, 23.8°C/75°F, and 29.4°C/85°F. The experimenter read the questions to the participants and saved their responses to an online web-based questionnaire using an iPad.

As mentioned before, every session included two sub-sessions, *in-situ* and MIVE experimental sessions, with a 10-minute break in between. During the break, the skin temperature sensors were detached from the participants, so they could move outside the chamber, rest, and most importantly get acclimatized to the comfort temperature (23.8°C/75°F) in the resting area. In the meantime, the climate chamber temperature was set back to its starting state (18.3°C/65°F for a heating exposure and 29.4°C/85°F for a cooling exposure) for the second sub-session. The

chamber controlled the space relative humidity (set to 55%) and the CO_2 level (set to below 1,000 ppm). The same procedure for data collection was repeated in both MIVE and *in-situ* settings. Before each MIVE experiment, there was a familiarization step for participants to calm down and get ready. Besides, the MIVE experiment had an additional post-experiment questionnaire, measuring participants' sense of presence and their cybersickness.

Data Collection, Synchronization, and Cleaning

All sensors were set to continuously measure and record data in one-second intervals; they were then averaged at different time scales, *i.e.,* zone 1, 2, and 3 as illustrated in Figure 6. The exact starting time of each zone was when the indoor temperature was stabilized at the target temperature; and the ending time was when thermal state questionnaires were completed. For instance, in a heating exposure session, the beginning of the experiment was when the indoor temperature was stabilized at 18.3°C/65ºF. After the chamber temperature was stabilized, participants were exposed to that temperature condition for 5-7 minutes, and then the thermal state questionnaires were administered. Once the responses were collected, the indoor temperature set-point was then increased to the next step (23.8°C/75 ºF), which signaled the ending time of the entire data collection process at that temperature step.

Data collected using different sensors or instruments was synchronized using the universal timestamp. After synchronization, the authors cleaned the data by removing extreme data points, or the outliers. Specifically, the *control temperatures* of MIVE and *in-situ* experiments were compared with each other to ensure they were not significantly different.
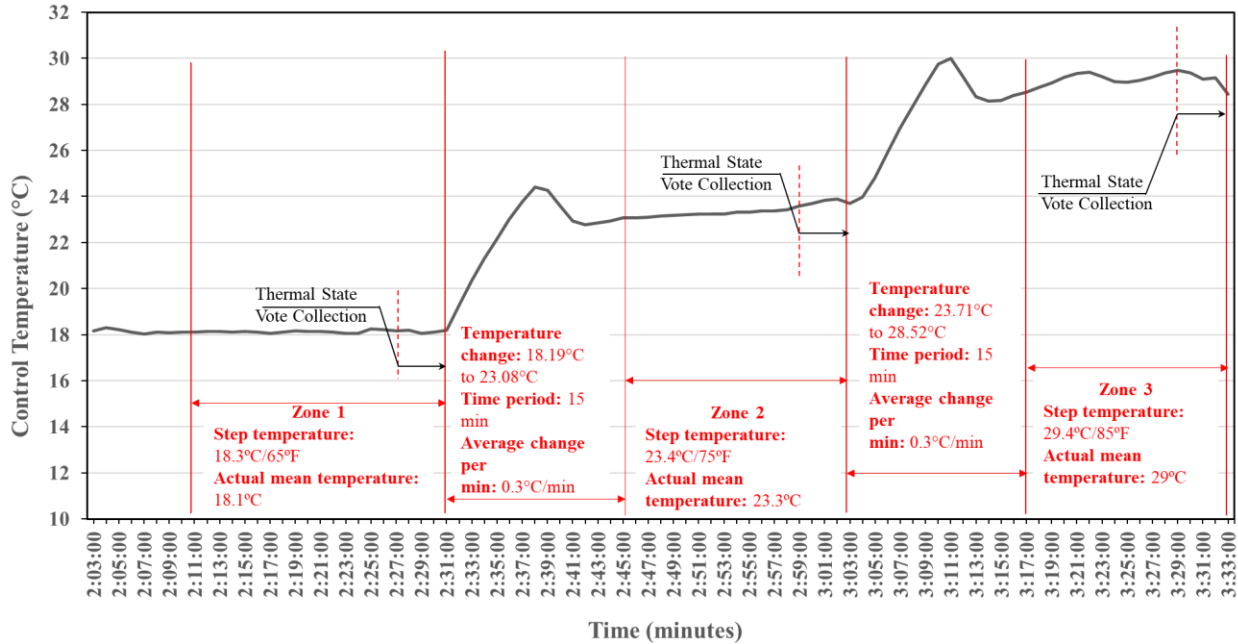
Figure 6. Data Collection Schematic Timeline (Sensor at 24 inches/0.6 meters)

This process was critical to ensure the environmental thermal conditions were comparable between MIVE and *in-situ* for data analysis. Since the control temperature in a climate chamber could fluctuated slightly over time and there was a possibility that the temperature of an *in-situ* experiment was different from its counterpart MIVE experiment, an acceptable range of temperature differences between the two experiment settings was needed. Many factors can affect how individuals detect temperature changes in their surroundings, but the rate of temperature changes is the major factor, i.e., if the temperature changes at a rate of less than 0.5°C (0.9°F) per minute, a person can be unaware of temperature changes of 4 – 5°C (or 7.2 – 9°F) [76]. In the climate chamber used in this study, the average control temperature change per minute between two temperature steps was about 0.5°C or less. With this rate, it was assumed that the participants had not been aware of at least ±1.7°C/3°F in about 10 minutes or more (10 minutes is the approximate duration for the chamber to rise or drop for 5.6°C/10°F). With this assumption, data

pairs of MIVE and *in-situ* were removed from the analysis, if their mean control temperature difference was more than 1.7°C/3°F,

After data cleaning, paired t-tests were performed to ensure the average control temperature at each temperature step in the MIVE setting was not significantly different from the *in-situ* setting (*e.g.,* period 1/cooling/65 ℉/18.3 ℃ in-situ vs. period 1/cooling/65 ℉/18.3 ℃ in MIVE). The results of the tests showed that all p-values were greater than 0.05 with the lowest p-value being 0.13, which indicates that the control temperature of the MIVE setting and that of the *in-situ* setting were comparable.

ANALYSIS, RESULTS, AND DISCUSSIONS

Participants

There were 14 female and 16 male participants, including undergraduate and graduate students, and a few staff members. The race and ethnicity distribution of the participants was:

- Caucasian: 9, 30.00%;

- Middle Eastern: 8, 26.66%;

- Asian: 8, 26.66%; and

- Other ethnicities: 5, 6.66%.

Table 2 shows age, education, and employment status of the participants.

Table 2. General information of the participants

Age	Mean	Highest level of Education	Count (%)	Employment	Count (%)	BMI	Count (%)
Mean	26.9	Postgraduate degree	9 (30)	Employed full time	8 (26.6)	Underweight	1 (3.3)
Std Dev	6.15	College graduate	8 (26.6)	Employed part time	7 (23.3)	Normal weight	17 (56.6)
Std Err Mean	2.29	Some college	10 (33.3)	Student (unemployed)	11 (36.6)	Over weight	10 (33.3)
Upper 95% Mean	29.2	High school graduate	3 (10)	Unemployed looking for work	4 (13.3)	Obese	2 (6.6)
Lower 95% Mean	24.6	**Total**	30	**Total**	30	**Total**	30

Sample Size Analysis and Potential Impact

In this study, three types of variables were tested, the control temperature distribution across the thermal state levels (two-tailed Kolmogorov-Smirnov (K-S) test), the thermal state vote at a temperature step (two-tailed Wilcoxon Sign Rank test), and the physiological responses (skin temperature and heart rate) (two-tailed pairwise t-test). Usually, the sample size of a statistical test is affected by several factors, including the significance level, the statistical power, and the sample mean difference between MIVE and *in-situ* settings. With a significance level of 0.05 and an acceptable statistical power of 0.8, the sample mean difference can be determined with a given sample size by applying the power analysis formula [77].

Table 3 shows the trade-off between the sample size of a K-S or Wilcoxon test and the sample mean difference between IVE and *in-situ* settings with a significance level of 0.05 and a statistical power of 0.8. For example, if the sample size is 78 for a K-S test on general thermal acceptability, the corresponding sample mean difference is 1.5ºC. It means the test can reliably differentiate the IVE sample from the *in-situ* sample with the selected significance level and the statistical power, if the two samples are truly from two different distributions and the sample mean difference between IVE and *in-situ* is larger than 1.5ºC. Table 4 shows the trade-off between the sample size of a t-test and the sample mean difference between IVE and *in-situ* settings with a significance level of 0.05 and a statistical power of 0.8.

Table 3. Estimated sample sizes for K-S and Wilcoxon tests at different sample mean differences between IVE and *in-situ* settings

		Δ_{mean}	General Thermal Sensation	General Thermal Acceptability	General Thermal Comfort	Local Thermal Sensation	Local Thermal Acceptability
Estimated Sample		0.25ºC	671	2,795	3,061	437	512
		0.5ºC	168	699	765	109	128
		0.75ºC	**75**	311	340	**49**	**57**

25

1ºC	42	175	191	27	32
1.25ºC	27	112	122	17	20
1.5ºC	19	**78**	**85**	12	14
1.7ºC	15	60	66	9	11
Estimated Sample Sizes Wilcoxon Test — 0.1	875	2,776	2,219	1,211	2010
0.25	140	348	355	194	322
0.5	35	87	89	48	80
0.75	**16**	39	39	**22**	36
1	9	**22**	**22**	12	**20**

Note: Δ_{mean} – assumed minimum sample mean difference of control temperatures in K-S tests and assumed mean difference of vote interval scales in Wilcoxon tests between *in-situ* and IVE

Table 4. Estimated sample sizes for t-tests at different assumed minimum sample mean differences

Δ_{mean}	**Skin Temperature**	Δ_{mean}	**Heart Rate**
0.25ºC	305	1 bpm	1351
0.5ºC	78	4 bpm	86
0.75ºC	36	8 bpm	**23**
1ºC	**21**	10 bpm	16

Note: Δ_{mean} - assumed minimum sample mean difference of skin temperatures and heart rate per minute between *in-situ* and IVE

Since all 30 participants took the three-temperature-step experiment in both IVE and *in-situ* experiments, the total data points for each participant in one experimental setting including data for all three temperature steps are 90 for the K-S test. Due to data cleaning, the sample size for the K-S test varied slightly, i.e., in most cases the sample size is 84 and in three cases the sample size is 86 (Figure 7). For the Wilcoxon test, since the test is on the thermal state vote at each temperature step, the total data points are 30 for each experimental setting. After data cleaning, at least 25 pairs of data (between IVE and *in-situ*) were applied (Figure 8). Similar to the Wilcoxon test, the t-test for the average skin temperature and the average heart rate was also on data categorized based on each temperature step. Therefore, the minimum sample size is 25 for each experimental setting in the t-test.

With the sample sizes in this study, the mean control temperature difference between IVE and *in-situ* settings that the K-S tests can differentiate is at least 1.5ºC for general thermal acceptability and general thermal comfort, and 0.75 ºC for general thermal sensation and the two local thermal state votes (Table 3). The Wilcoxon tests can differentiate the mean thermal vote difference between the two settings at 1 interval scale for general thermal acceptability, general thermal comfort, and local thermal acceptability, and 0.75 interval scale for general thermal sensation and local thermal sensation (Table 3). The mean skin temperature difference and the mean heart rate difference between the two settings that can be reliably differentiated by the t-tests are 1ºC and 8 bpm, respectively. To be able to differentiate smaller mean differences between the two settings, larger samples are needed.

Control Temperature Distribution

Figure 7 shows the thermal state scale vs. the control temperature. It needs to be noted that the sample size at a certain level is small in most cases. For example, out of 76 MIVE and *in-situ* pairs of all thermal state levels (Figure 7), only 8 pairs have a sample size more than 26 for both IVE and *in-situ* settings. In addition, the control temperature pair between MIVE and *in-situ* at each thermal state level can include both paired (same participant) and non-paired (different participants) data. Considering these two factors, a test at each thermal state level, such as a t-test, was not applied in this study. Instead, the Kolmogorov-Smirnov (K-S) test was used to determine whether the control temperature distribution across all thermal state levels was significantly different between the MIVE and *in-situ* settings at a significance level of 95%. Future studies using two random MIVE and *in-situ* samples should be considered to compare data at each thermal state level. For example, if a two-tail independent sample t-test is applied, the sample size should be at

least 26 at each thermal state level for both MIVE and *in-situ* data samples to achieve a large effective size (i.e., 0.8) and an acceptable statistical power (i.e., 0.8) at a significance level of 0.05. To achieve a smaller effective size or higher statistical power, a larger sample is needed. This analysis is based on the G*Power software (version 3.1.9.7).
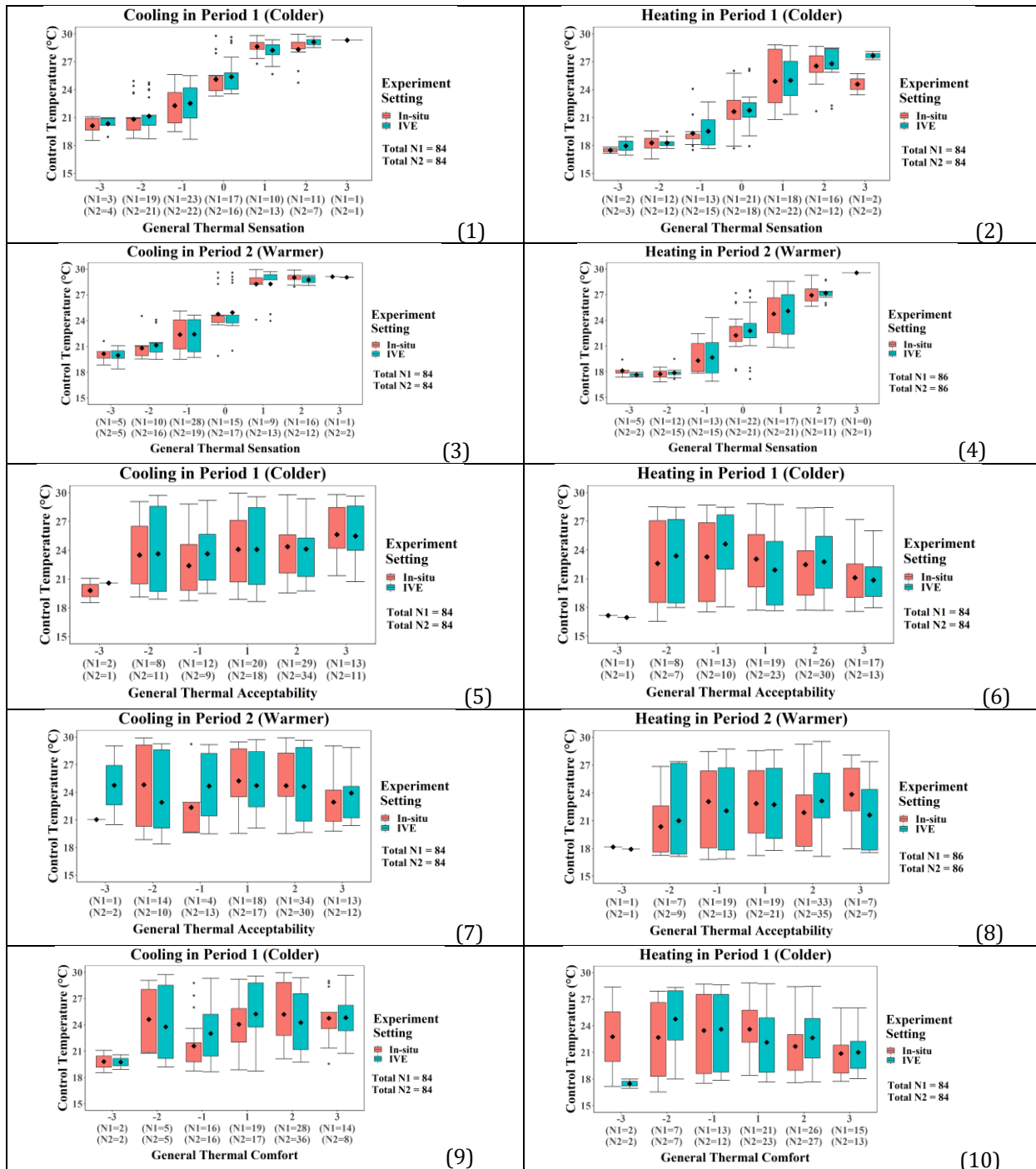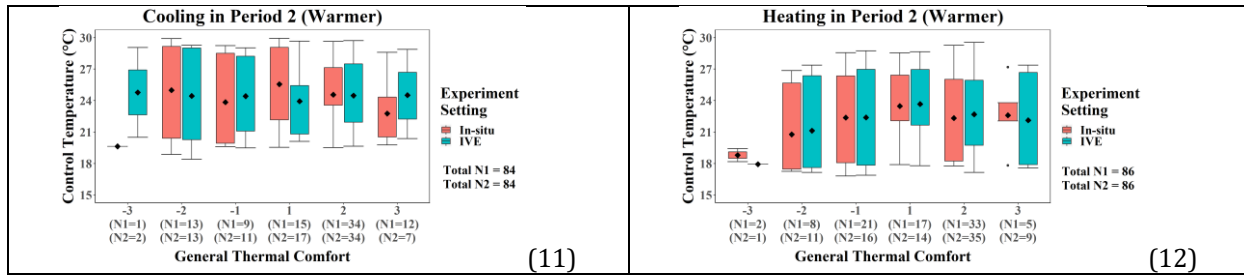
Note: N1 = In-situ and N2 = IVE

Figure 7. Thermal State Votes and Control Temperature

Table 5 shows the results of comparing the control temperature distribution between the MIVE and *in-situ* settings over the general thermal sensation, general thermal acceptability and general thermal comfort scales. The p-value of all tests was greater than 0.05, i.e., none of the null hypotheses were rejected. The results suggest when participants voted for their thermal sensation, thermal acceptability, or thermal comfort in both the MIVE and *in-situ* settings, the corresponding control temperature distributions of both settings were similar, regardless of the exposure type (heating vs cooling) or the experiment period (warmer vs colder).

Table 5. MIVE and *in-situ* comparisons: control temperature distribution

General Thermal State		K-S test (*p* Value) (*significance level, 0.05*)			
		Period 1, Colder Control Temperature		Period 2, Warmer Control Temperature	
		Heating	Cooling	Heating	Cooling
Sensation	65 °F/18.3 °C	0.699	0.600	0.699	0.229
	75 °F/23.8 °C	1.000	1.000	0.600	0.771
	85 °F/29.4 °C	0.771	0.771	0.400	0.771
Acceptability and Comfort	65 °F/18.3 °C	1.000*, 0.931**	0.931*, 1.000**	0.474*, 0.931**	0.893*, 0.139**
	75 °F/23.8 °C	0.699*, 1.000**	0.819*, 0.563**	0.771*, 0.771**	0.699*, 0.746**
	85 °F/29.4 °C	0.873*, 0.967**	0.873*, 0.873**	0.873*, 0.873**	0.922*, 0.991**

Note: * - thermal acceptability result; ** - thermal comfort result
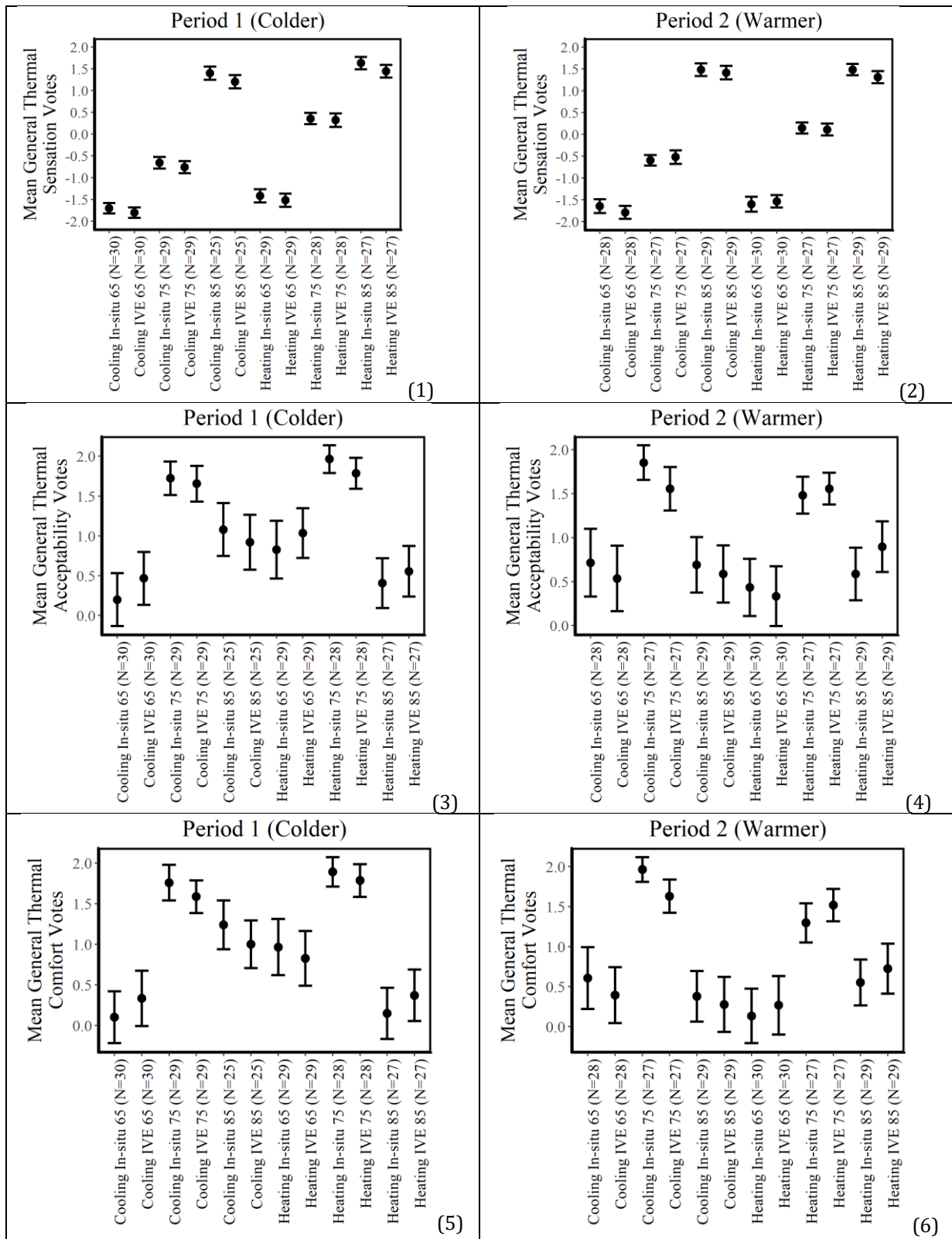
Thermal State Votes

29

Figure *8* shows the mean thermal state votes between IVE and in-situ settings at each temperature
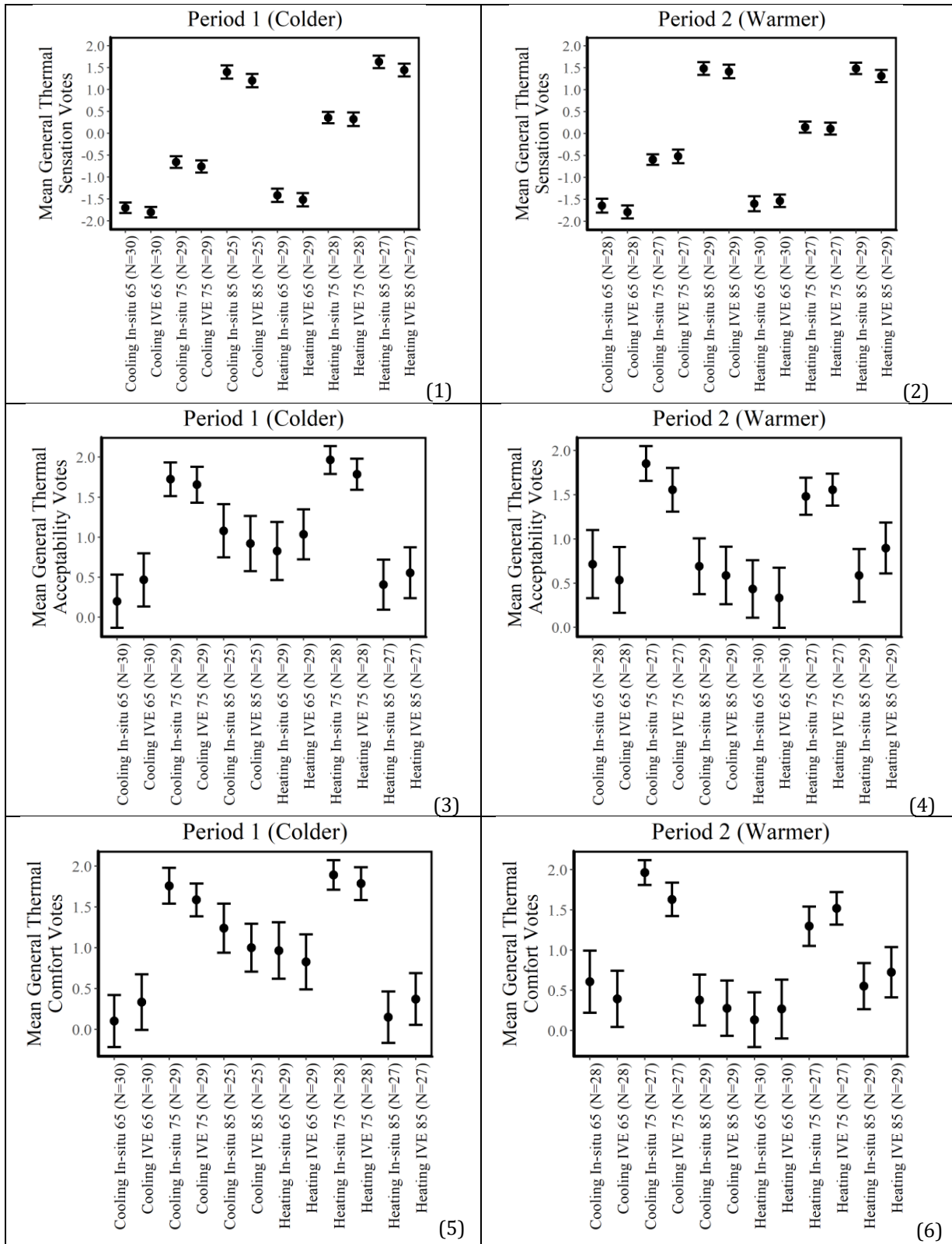
step for both Period 1 and Period 2.

Figure 8. Mean Thermal State Votes Between IVE and *in-situ* at Each Temperature Step

The Wilcoxon Sign Rank Test was applied to determine whether the thermal state votes at each temperature step were significantly different between the MIVE and *in-situ* settings at a significance level of 0.05. Table 6 shows the test results of the MIVE and *in-situ* comparisons. The votes were categorized according to the temperature steps, the exposure type, and the experiment period.

The results (Table 6) show that for thermal sensation and acceptability, the votes between MIVE and in-situ settings were not significantly different at each temperature step regardless of the experiment period, the exposure type, and the temperature step. This was due to the fact that mean sensation vote differences between MIVE and in-situ settings (Figure 8) were less than 0.2 in all the cases. Similarly, for acceptability votes, the mean differences between MIVE and in-situ settings were less than 0.2 in all cases except at 65 ºF/18.3 ºC in colder period, 75 ºF/23.8 ºC and 85 ºF/29.4 ºC in warmer period (Figure 8) where the mean vote differences were closer to 0.3. In case of thermal comfort, there was one case in warmer period, cooling, at 75 ºF/23.8 ºC, where the votes between the MIVE and in-situ settings were significantly different because the mean vote difference in this case was 0.33 (Figure 8). In all other cases, the mean comfort vote differences between MIVE and in-situ settings were less than 0.25.

Table 6. MIVE and *in-situ* comparisons: thermal state votes

General Thermal State		Wilcoxon Sign Rank Test (*p* Value) (*significance level, 0.05*)			
		Period 1, Colder Thermal State Vote		Period 2, Warmer Thermal State Vote	
		Heating	Cooling	Heating	Cooling
Sensation	65 ºF/18.3 ºC	0.510	0.299	0.644	0.308
	75 ºF/23.8 ºC	0.894	0.351	0.802	0.675
	85 ºF/29.4 ºC	0.303	0.212	0..073	0.675
Acceptability and Comfort	65 ºF/18.3 ºC	0.478*, 0.904**	0.234*, 0.209**	0.751*, 0.683**	0.343*, 0.245**
	75 ºF/23.8 ºC	0.36*, 714**	0.595*, 0.276**	0.824*, 0.378**	0.13*, *0.023***+
	85 ºF/29.4 ºC	0.598*, 0.547**	0.478*, 0.347**	0.174*, 0.275**	0.653*, 0.79**

Note: * - thermal acceptability result; ** - thermal comfort result; + - significant result

Physiological Response Analysis

The comparisons between PR_{temp} and PR'_{temp} were performed using t-test. Given the large number of test results, the authors only reported the tests with a significant result (Table 7). The results show that the significantly different responses were mostly related to the forehead skin temperature, along with two other instances (i.e., the neck skin temperature at 85 ºF/29.4 ºC during heating, and the upper-back skin temperature at 75 ºF/23.8 ºC during heating). There was no significant difference in the heart rate comparisons. Since the skin temperature sensor was covered by the HMD at forehead, the average skin temperature difference at the location was most likely because of the heat development of the HMD, i.e., the forehead skin temperature in the MIVE experiments was slightly higher than the *in-situ* experiments (Table 7). There is no obvious explanation to the difference associated with the neck skin temperature and the upper-back skin temperature.

Table 7. MIVE and *in-situ* comparisons: significantly different mean skin temperature

		Setting	Response Variable	in-situ			IVE			DF	t	p-value
				N	Mean	St. Dev.	N	Mean	St. Dev.			
Period 1, Colder	Cooling	65 ºF/18.3 ºC	Forehead Skin Temperature (ºC)	30	34.3	0.85	30	35.8	1.18	29	-5.4	7.49E-06
		75 ºF/23.8 ºC	Forehead Skin Temperature (ºC)	29	35	0.53	29	35.8	0.63	28	-6.1	1.39E-06
	Heating	65 ºF/18.3 ºC	Forehead Skin Temperature (ºC)	29	33.7	0.95	29	34.5	0.63	28	-5.1	1.85E-05
		75 ºF/23.8 ºC	Forehead Skin Temperature (ºC)	28	34.2	0.92	28	35.2	0.69	27	-6.2	1.30E-06
		85 ºF/29.4 ºC	Forehead Skin Temperature (ºC)	27	35.1	0.77	27	35.9	0.51	26	-6.2	1.33E-06
		85 ºF/29.4 ºC	Neck Skin Temperature (ºC)	27	33.9	1.21	27	33.3	1.88	26	2.42	0.022
Period 2,	Cooling	65 ºF/18.3 ºC	Forehead Skin Temperature (ºC)	28	34.4	0.64	28	35.9	1.05	27	-7	1.79E-07
		75 ºF/23.8 ºC	Forehead Skin Temperature (ºC)	27	34.9	0.64	27	36.1	0.52	26	-8.1	1.56E-08

	85 °F/29.4 °C	Forehead Skin Temperature (°C)	29	35.2	0.89	29	35.9	0.5	28	-4	0.0003
Heating	75 °F/23.8 °C	Upper back Skin Temperature (°C)	27	33.3	0.99	27	33.6	1.03	26	-2.3	0.02
Heating	85 °F/29.4 °C	Forehead Skin Temperature (°C)	29	35.2	0.52	29	35.8	1.48	28	-2.4	0.02

Local Skin Temperature Distribution and Thermal Sensation and Thermal Acceptability Votes

To further investigate the local thermal state in relation to the physiological responses, the local thermal sensation and thermal acceptability votes at the same eight sites were analyzed. Similar to general thermal state analysis, the authors applied the Kolmogorov-Smirnov (K-S) test to analyze the skin temperature distribution over the local thermal sensation and acceptability scales, and the Wilcoxon Sign Rank test to analyze the local thermal state votes at each temperature step. Since there are many tests, only statistically significant results are shown in **Error! Not a valid bookmark self-reference.** and Table 9.

Table 8. MIVE and *in-situ* comparisons: significantly different local skin temperature distribution

			Scale	Local skin temperature (in-situ)		Local skin temperature (MIVE)		K-S Test (p-value) (significance level, 0.05)
				N	Mean (°C)	N	Mean (°C)	
Forehead	Period 1, Colder, Thermal Sensation	Cooling	-3	-	-	-	-	0.026
			-2	5	33.98	2	35.73	
			-1	9	34.17	4	35.74	
			0	45	35.01	51	35.71	
			1	15	35.12	19	35.92	
			2	9	34.96	8	35.46	
			3	1	35.75	-	-	
	Period 2, Warmer, Thermal Sensation	Cooling	-3	2	33.93	1	36.73	0.012
			-2	3	34.44	2	36.25	
			-1	15	34.48	5	35.28	
			0	37	34.84	39	36.11	
			1	15	35.3	16	35.93	
			2	10	34.84	17	36.05	
			3	2	34.44	4	35.31	
	Period	Cool	-3	-	-	-	-	0.008

			Scale	Count	Temp	Count	Temp	p Value
			-2	5	34.63	3	35.3	
			-1	6	34.44	4	35.67	
			1	17	35.14	19	35.91	
			2	45	34.82	41	35.93	
			3	11	35.13	17	35.16	
		Heating	-3	-	-	-	-	0.008
			-2	3	34.26	3	35.24	
			-1	5	34.39	4	36.29	
			1	26	34.6	19	35.27	
			2	29	34.18	38	35.16	
			3	21	34.05	20	34.93	
	Period 2, Warmer, Thermal Acceptability	**Cooling**	-3	-	-	1	34.57	0.045
			-2	6	34.62	6	36.02	
			-1	10	34.57	11	35.64	
			1	10	34.72	15	36.2	
			2	51	34.89	40	36.05	
			3	7	34.89	11	35.92	
Forearm	**Period 2, Warmer, Thermal Acceptability**	**Cooling**	-3	-	-	1	31.93	0.048
			-2	5	32.72	9	33.12	
			-1	10	33.26	9	32.5	
			1	13	33.48	18	32.4	
			2	45	33.14	36	33.1	
			3	11	33.35	11	33.03	

Table 9. MIVE and *in-situ* comparisons: significantly different local thermal state votes

Local Thermal State		**Wilcoxon Sign Rank Test (p Value)** (Significance Level, 0.05)	
		Period 1, Colder	**Period 2, Warmer**
		Cooling	**Cooling**
Forehead Sensation	65 ℉/18.3 ℃	0.035	0.005
	75 ℉/23.8 ℃	-	0.005
Forehead Acceptability	65 ℉/18.3 ℃	0.034	-

Most significant results are all related to the forehead skin temperature distributions over the thermal sensation and acceptability scales in both periods. These results are in general consistent with those in Table 7. In addition, one significant result at forearm is also reported (Local Skin **Temperature Distribution and Thermal Sensation and Thermal Acceptability Votes**

To further investigate the local thermal state in relation to the physiological responses, the local thermal sensation and thermal acceptability votes at the same eight sites were analyzed. Similar to general thermal state analysis, the authors applied the Kolmogorov-Smirnov (K-S) test to analyze the skin temperature distribution over the local thermal sensation and acceptability scales, and the Wilcoxon Sign Rank test to analyze the local thermal state votes at each temperature step. Since there are many tests, only statistically significant results are shown in **Error! Not a valid bookmark self-reference.** and Table 9.

Table *8*). Furthermore, significant differences in forehead thermal sensation votes were observed at 65 ℉/18.3 ℃ and 75 ℉/23.8 ℃ during cooling, as well as in forehead thermal acceptability votes at 65 ℉/18.3 ℃ during cooling as shown in Table 9. The thermal sensation and acceptability votes in other skin sites were not significantly different.

Post-experiment Questionnaire Results

Presence

The presence results are shown in Table 10 organized by the order of the MIVE experimental sessions. MIVE-1 and MIVE-2 refer to the first round of data collection (Period 1, colder) and MIVE-3 and MIVE-4 refer to the second round (Period 2, warmer). However, since the experiments were counterbalanced and randomized, each of the sessions included both cooling and heating exposures.

Often, researchers compare their presence scores with published scores to determine the acceptability of their scores (e.g., [50][51]). For example, according to a previous study [51], the IPQ online datasets reported a mean general presence score of 38.16 with a standard deviation of 17.53. In this study, the general presence and the subscale presence scores are all larger than the

reported average score with a smaller standard deviation. The results suggest that the perceived presence by the participants of this study was comparable with reported studies.

Table 10. Presence and cybersickness scores

| | Order | Size | Presence | | | Cybersickness | | |
			Measure	Mean	Std. Dev.	Measure	Mean	Std. Dev.
Period 1, Colder	MIVE-1	28	General Presence	62.14	16.63	Nausea	19.42	18.99
	MIVE-2	29		50.34	14.76		15.13	18.3
	MIVE-1	28	Spatial Presence	66.57	11.13	Oculomotor	25.99	26.21
	MIVE-2	29		62.59	13.14		20.13	21.56
	MIVE-1	28	Presence Involvement	65	7.45	Disorientation	23.37	28.36
	MIVE-2	29		63.1	7.49		16.32	24.7
	MIVE-1	28	Presence Realness	53.75	15.25	Total	26.71	24.99
	MIVE-2	29		50.34	14.01		20.25	22.89
Period 2, Warmer	MIVE-3	28	General Presence	48.97	15.66	Nausea	9.21	12.62
	MIVE-4	29		50.71	13.86		14.99	13.35
	MIVE-3	28	Spatial Presence	62.07	13.24	Oculomotor	15.16	17.54
	MIVE-4	29		62.93	14.33		18.68	16.95
	MIVE-3	28	Presence Involvement	62.59	6.21	Disorientation	8.64	13.11
	MIVE-4	29		61.96	6.29		12.43	15.78
	MIVE-3	28	Presence Realness	52.93	14.67	Total	13.41	15.85
	MIVE-4	29		52.14	14.62		18.43	15.73

Cybersickness

The results of the cybersickness scores are presented in (Table 10). According to literature, a wide range of SSQ total mean scores were reported, from 6.62 to 27.25 [56]. On the subscales, the ranges of mean scores were 1.75 – 30.21 for nausea, 11.0 – 25.74 for oculomotor, and 8.7 – 41.47 for disorientation [55], respectively. The results (Table 10) show that the mean scores fall within the reported ranges; and the mean scores of MIVE-3 and MIVE-4 are smaller in all categories than those of MIVE-1 and MIVE-2, which suggests that the participants might feel more uncomfortable during the first period than the second period. None of the participants reported significant discomfort or asked to terminate the experiment.

Discussion

Comparing participants' control temperature distribution, and their thermal state votes, the authors observed that there were not significantly difference between the MIVE and *in-situ* settings in all cases (except for one case in thermal state vote test). The results suggest that when the MIVE experimental conditions are well-controlled and comparable to the *in-situ* experimental conditions, the control temperature distribution and the thermal state votes may serve as reliable measures in virtual experiments. However, it needs to be noted that the results are limited to the sample mean differences discussed in the previous section (Table 3 and Table 4).

This observation was reinforced by the analysis on the physiological data. Most of physiological responses were not significantly different between the MIVE and *in-situ* settings, measured by the mean heart rate, the mean local skin temperature at each nominal temperature step (Table 7), and the mean local skin temperature distribution (Table 8). The only differences between the two settings were mostly related to forehead (Table 7 and Local Skin **Temperature Distribution and Thermal Sensation and Thermal Acceptability Votes**

To further investigate the local thermal state in relation to the physiological responses, the local thermal sensation and thermal acceptability votes at the same eight sites were analyzed. Similar to general thermal state analysis, the authors applied the Kolmogorov-Smirnov (K-S) test to analyze the skin temperature distribution over the local thermal sensation and acceptability scales, and the Wilcoxon Sign Rank test to analyze the local thermal state votes at each temperature step. Since there are many tests, only statistically significant results are shown in **Error! Not a valid bookmark self-reference.** and Table 9.

Table *8*Table *9*), as well as neck and upper-back (Table 7), and forearm (Local Skin **Temperature Distribution and Thermal Sensation and Thermal Acceptability Votes**

To further investigate the local thermal state in relation to the physiological responses, the local thermal sensation and thermal acceptability votes at the same eight sites were analyzed. Similar to general thermal state analysis, the authors applied the Kolmogorov-Smirnov (K-S) test to analyze the skin temperature distribution over the local thermal sensation and acceptability scales, and the Wilcoxon Sign Rank test to analyze the local thermal state votes at each temperature step. Since there are many tests, only statistically significant results are shown in **Error! Not a valid bookmark self-reference.** and Table 9.

Table *8*). The difference observed at forehead is more obvious than the difference at the neck, upper-back, or forearm. While the difference at forehead is most likely caused by wearing the heard mounted display (HMD); there is no obvious reason to explain the difference at other locations and additional studies are needed. Furthermore, the local thermal sensation and acceptability votes at forehead were also significantly different (Table 9) at two temperature steps, 65ºF/18.3ºC and 75 ºF/23.8 ºC. This is likely due to the fact that the mean forehead skin temperature differences between MIVE and *in-situ* at those step temperatures are about 1.5 ºC; while at other step temperatures, the mean differences are less than 1.0 ºC. On the other hand, the mean skin temperature differences at neck, upper-back, and forearm are relatively small, mostly less than 0.62 ºC at neck, 0.37 ºC at upper-back and about 1.0ºC or less at forearm. This may explain that the local thermal sensation and acceptability votes at neck, upper-back, and forearm between the MIVE and *in-situ* settings were not significantly different. Since the votes such as thermal comfort may be satisfied with a range of temperature and humidity settings [78], this observation may also explain that their general thermal state vote distribution was not significantly differently.

In addition, although the skin temperature distribution at forearm over the thermal acceptability scale (Table 8) was significantly different between the MIVE and *in-situ* settings, the average skin temperature at forearm in MIVE was not significantly different from *in-situ* (i.e., not reported in Table 7), nor were the local thermal sensation and thermal acceptability votes. This means that the average forearm skin temperature at each of the three temperature steps during cooling in Period 2 was comparable between the MIVE and *in-situ* settings; and the participants' thermal state vote responses at forearm were also comparable. This study does not have an obvious explanation to the discrepancy among those observations.

The analysis of the two periods (Table 5 and Table 6) did not produce many different results between the MIVE and *in-situ* settings, except for one case in thermal state vote (Table 6), the reported mean skin temperature (Table 7) and the reported local skin temperature distributions (Local Skin **Temperature Distribution and Thermal Sensation and Thermal Acceptability Votes**

To further investigate the local thermal state in relation to the physiological responses, the local thermal sensation and thermal acceptability votes at the same eight sites were analyzed. Similar to general thermal state analysis, the authors applied the Kolmogorov-Smirnov (K-S) test to analyze the skin temperature distribution over the local thermal sensation and acceptability scales, and the Wilcoxon Sign Rank test to analyze the local thermal state votes at each temperature step. Since there are many tests, only statistically significant results are shown in **Error! Not a valid bookmark self-reference.** and Table 9.

Table *8*). In the case of cooling at 75 ºF/23.8 ºC, the thermal comfort vote comparison between MIVE and *in-situ* in Period 2 is significantly different because of a larger mean difference between the votes, whereas in all other cases, the mean vote differences were smaller (Table 6 and

Figure 8). The causes of the difference in the mean skin temperature or the local skin temperature distributions have been discussed. The similarity in the control temperature distribution and the thermal state votes may be attributed to many factors such as the relatively small seasonal difference at the experiment location and the acclimation step at the beginning of each experiment. Empirical studies in this field have produced different results. For example, Umemiya [64] reported seasonal difference in thigh skin temperature, in addition to metabolic rate and body fat. Lee at al. [65] found difference in mean body temperature between summer and winter. However, Zhang et al. [79] found that the skin temperatures in summer were consistent with that in winter and the heart rates in summer were significantly lower than those in winter. However, no significant seasonal impacts on human thermal sensation and comfort were observed. On the other hand, the analysis in this study is limited to comparing the MIVE and *in-situ* settings in either period 1 or period 2. Comparisons between the two periods directly have not been performed.

LIMITATIONS

Major limitations of the study include:

1) Resting and acclimatization period: the resting and acclimatization period was relatively short in this study for both before the first experimental session and between the two consecutive experimental sessions. The decision was made due to the mild climatic condition of the experiment location. However, the impact of this decision on the outcomes of this study has not be investigated.

2) Thermal acceptability scale: a 6-point Likert scale was applied to collecting thermal acceptability data, instead of a typical binary scale. Although the responses of the 6-point

Likert scale may be aggregated into a binary scale, the potential of the 6-point scale to make sufficient differentiation among votes has not been investigated.

3) Data analysis: Due to a limited sample size, the control temperature distribution across thermal state scales for all three temperature steps was tested. Such a test only provides an overall picture about the comparability between IVE and *in-situ* settings. A test at each thermal state level will provide more information about the comparability, which requires a larger sample size and different analysis.

CONCLUSIONS AND FUTURE WORK

The study has shown promising potential of the experimental protocol using MIVE to replicate thermoception and collect data, when environmental conditions are comparable and MIVE has adequate presence and don't cause significant cybersickness. The findings of the sample-wide analysis suggest that thermal state votes and physiological responses in the MIVE experiments are potentially reliable indicators of their *in-situ* counterparts. Although there were several observations of differences between the MIVE and *in-situ* settings with respect to skin temperature at the forehead, neck, and upper-back, such differences did not have a significant impact on the general thermal state votes. In other words, the MIVE experiments using the proposed protocol did not altered participants' thermal experience compared to the *in-situ* experiments. It needs to be noted that the scope of this study is limited to comparing the thermal state of participants. Behavioral factors and analysis in [60] are not part of the scope.

This conclusion is based on the control temperature distribution, the thermal state vote, and selected physiological responses using the sample described in Table 2. In order words, other variables such as the thermal state vote at a specific level or the heart rate variability may be used

to analyze the thermal experience of participants between the MIVE and *in-situ* settings in the future. Also, due to smaller sample sizes at most thermal state levels, the control temperature distribution across all thermal state levels was applied in this study, rather than the control temperature at a specific thermal state level. Thus, future studies are needed to include the investigation of other variables, recruit participants of different socio-demographic and individual characteristics, and obtain a larger sample size.

In addition, when experimental conditions were well-controlled, physiological responses were mostly comparable between the MIVE and *in-situ* settings. Small physiological response differences such as skin temperature differences may be unavoidable, but they don't seem to affect participants' thermal state vote responses except at forehead, which was due to the impact of the head development of the HMD device. This observation suggests that physiological and thermal state vote measures may have different levels of sensitivity. Although both are effective, thermal state vote measures may be more stable.

Differences between virtual and actual scenes always exist, because digitally developed objects often lack the affordability of the real-life. Thus, in this study presence was used to measure the participant's "state of being there". Also, the results of analysis suggest that any such difference has not significantly affected the comparisons of the response variables between the MIVE and *in-situ* settings. Nevertheless, future studies are needed to better understand the significance of stimuli (e.g., certain visual objects) that may be included or excluded from a virtual scene.

Furthermore, this study used the IVE model of the same chamber to provide participants with a virtual experience. Future studies should consider applying the experimental protocol to a real office environment to achieve more compelling results and a more robust validation of MIVE.

ACKNOWLEDGEMENT

REFERENCES

[1] H. B. Gunay, W. O'Brien, and I. Beausoleil-Morrison, "A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices," *Build. Environ.*, vol. 70, pp. 31–47, 2013.

[2] T. Hong and H.-W. Lin, "Occupant Behavior: Impact on Energy Use of Private Offices," in *ASim 2012 - 1st Asia conference of International Building Performance Simulation Association.*, 2013, p. 12.

[3] W. O'Brien and H. B. Gunay, "The contextual factors contributing to occupants' adaptive comfort behaviors in offices - A review and proposed modeling framework," *Build. Environ.*, vol. 77, pp. 77–88, 2014.

[4] J. Langevin, P. L. Gurian, and J. Wen, "Tracking the human-building interaction: A longitudinal field study of occupant behavior in air-conditioned offices," *J. Environ. Psychol.*, vol. 42, no. February, pp. 94–115, 2015.

[5] T. Hong, S. D'Oca, S. C. Taylor-Lange, W. J. N. Turner, Y. Chen, and S. P. Corgnati, "An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML schema," *Build. Environ.*, vol. 94, no. P1, pp. 196–205, 2015.

[6] M. A. Muhanna, "Virtual reality and the CAVE: Taxonomy, interaction challenges and research directions," *J. King Saud Univ. - Comput. Inf. Sci.*, vol. 27, no. 3, pp. 344–361, 2015.

[7] S. F. Kuliga, T. Thrash, R. C. Dalton, and C. Hölscher, "Virtual reality as an empirical research tool - Exploring user experience in a real building and a corresponding virtual model," *Comput. Environ. Urban Syst.*, vol. 54, pp. 363–375, 2015.

[8]   E. Vilar, F. Rebelo, and P. Noriega, "Indoor Human Wayfinding Performance Using Vertical and Horizontal Signage in Virtual Reality," *Hum. Factors Ergon. Manuf.*, vol. 24, no. 6, pp. 601–615, 2014.

[9]   K. D. Maldovan, J. I. Messner, and M. Faddoul, "Framework for Reviewing Mockups in an Immersive Environment," in *CONVR 2006*, 2006.

[10]   A. Heydarian, E. Pantazis, A. Wang, D. Gerber, and B. Becerik-Gerber, "Towards user centered building design: Identifying end-user lighting preferences via immersive virtual environments," 2017.

[11]   P. O. Fanger, *Thermal comfort: Analysis and applications in environmental engineering.* Copenhagen, Denmark: Danish Technical Press, 1970.

[12]   R. J. de Dear and G. S. Brager, "Developing an adaptive model of thermal comfort and preference," *ASHRAE Trans.*, vol. 104, no. 1, pp. 1–18, 1998.

[13]   K. B. Velt and H. A. M. Daanen, "Thermal sensation and thermal comfort in changing environments," *J. Build. Eng.*, vol. 10, no. January, pp. 42–46, 2017.

[14]   G. R. Newsham, "Manual control of window blinds and electric lighting: Implications for comfort and energy consumption," *Indoor Environ.*, vol. 6, no. 3, pp. 135–144, 1994.

[15]   S. Karjalainen and O. Koistinen, "User problems with individual temperature control in offices," *Build. Environ.*, vol. 42, no. 8, pp. 2880–2887, 2007.

[16]   X. Zhou, Q. Ouyang, Y. Zhu, C. Feng, and X. Zhang, "Experimental study of the influence of anticipated control on human thermal sensation and thermal comfort," *Indoor Air*, vol. 24, no. 2, pp. 171–177, 2014.

[17]   ASHRAE, "Standard 55-2013-Thermal environmental conditions for human occupancy," *ASHRAE. Atlanta, USA*, 2013.

[18] H. Zhang, C. Huizenga, E. Arenas, and D. Wang, "Thermal sensation and comfort in transient non-uniform thermal environments," *Eur. J. Appl. Physiol.*, vol. 92, no. 6, pp. 728–733, 2004.

[19] Y. Zhang and R. Zhao, "Overall thermal sensation, acceptability and comfort," *Build. Environ.*, vol. 43, no. 1, pp. 44–50, 2008.

[20] W. Ji, B. Cao, M. Luo, and Y. Zhu, "Influence of short-term thermal experience on thermal comfort evaluations: A climate chamber experiment," *Build. Environ.*, vol. 114, pp. 246–256, 2017.

[21] J. H. Choi, V. Loftness, and D. W. Lee, "Investigation of the possibility of the use of heart rate as a human factor for thermal sensation models," *Build. Environ.*, vol. 50, pp. 165–175, 2012.

[22] M. Schweiker, S. Brasche, W. Bischof, M. Hawighorst, and A. Wagner, "Explaining the individual processes leading to adaptive comfort : Exploring physiological , behavioural and psychological reactions to thermal stimuli," *Build. Phys.*, vol. 36, no. 4, pp. 438–463, 2013.

[23] S. Takada, S. Matsumoto, and T. Matsushita, "Prediction of whole-body thermal sensation in the non-steady state based on skin temperature," *Build. Environ.*, vol. 68, pp. 123–133, 2013.

[24] N. Hashiguchi and Y. Tochihara, "Effects of low humidity and high air velocity in a heated room on physiological responses and thermal comfort after bathing: an experimental study.," *Int. J. Nurs. Stud.*, vol. 46, no. 2, pp. 172–180, 2009.

[25] T. Chaudhuri, Y. C. Soh, H. Li, and L. Xie, "Machine learning driven personal comfort prediction by wearable sensing of pulse rate and skin temperature," *Build. Environ.*, vol.

170, p. 106615, Mar. 2020.

[26] Y. Lin, L. Yang, W. Zheng, and Y. Ren, "Study on Human Physiological Adaptation of Thermal Comfort under Building Environment," *Procedia Eng.*, vol. 121, pp. 1780–1787, 2015.

[27] R. F. Rupp, N. G. Vásquez, and R. Lamberts, "A review of human thermal comfort in the built environment," *Energy Build.*, vol. 105, pp. 178–205, 2015.

[28] C. Chun, A. KwoK, T. Mitamura, N. Miwa, and A. Tamura, "Thermal diary: Connecting temperature history to indoor comfort," *Build. Environ.*, vol. 43, no. 5, pp. 877–885, 2008.

[29] L. Schellen, W. D. van Marken Lichtenbelt, M. G. L. C. Loomans, J. Toftum, and M. H. de Wit, "Differences between young adults and elderly in thermal comfort , productivity , and thermal physiology in response to a moderate temperature drift and a steady-state condition," *Indoor Air*, vol. 20, pp. 273–283, 2010.

[30] L. Lan, Z. Lian, W. Liu, and Y. Liu, "Investigation of gender difference in thermal comfort for Chinese people," *Eur. J. Appl. Physiol. Physiol.*, vol. 102, pp. 471–480, 2008.

[31] J. H. Choi, A. Aziz, and V. Loftness, "Investigation on the impacts of different genders and ages on satisfaction with thermal environments in office buildings," *Build. Environ.*, vol. 45, no. 6, pp. 1529–1535, 2010.

[32] W. Pasut, H. Zhang, S. Kaam, E. Arens, and Y. Zhai, "Effect of a heated and cooled office chair on thermal comfort," *HVAC&R Res.*, pp. 574–583, 2013.

[33] M. E. Costanzo *et al.*, "Psychophysiological response to virtual reality and subthreshold posttraumatic stress disorder symptoms in recently deployed military.," *Psychosom. Med.*, vol. 76, no. 9, pp. 670–7, 2014.

[34] M. Slater, P. Khanna, J. Mortensen, and I. Yu, "Visual Realism Enhances Realistic

Response in an Immersive Virtual Environment," *IEEE Comput. Graph. Appl.*, pp. 76–84, 2009.

[35] G. Tieri, A. Gioia, M. Scandola, E. F. Pavone, and S. M. Aglioti, "Visual appearance of a virtual upper limb modulates the temperature of the real hand: a thermal imaging study in Immersive Virtual Reality," *Eur. J. Neurosci.*, vol. 45, no. 9, pp. 1141–1151, 2017.

[36] A. P. Gagge, J. A. J. Stolwijk, and J. D. Hardy, "Comfort and thermal sensations and associated physiological responses at various ambient temperatures," *Environ. Res.*, vol. 1, no. 1, pp. 1–20, 1967.

[37] T. Goto, J. Toftum, R. De Dear, and P. O. Fanger, "Thermal sensation and thermophysiological responses to metabolic step-changes," *Int. J. Biometeorol.*, vol. 50, no. 5, pp. 323–332, 2006.

[38] W. Liu, Z. Lian, and Y. Liu, "Heart rate variability at different thermal comfort levels," *Eur. J. Appl. Physiol.*, vol. 103, no. 3, pp. 361–366, 2008.

[39] J. Choi and V. Loftness, "Investigation of human body skin temperuatres as a bio-signal to inidcate overall thermal sensations.pdf," vol. 58, pp. 258–269, 2012.

[40] B. Deml, A. Mihalyi, and G. Hannig, "Development and experimental evaluation of a thermal display," *Proc. 2006 EuroHaptics ...*, pp. 0–5, 2006.

[41] N. Ranasinghe *et al.*, "A demonstration of season traveller: Multisensory narration for enhancing the virtual reality experience," *Conf. Hum. Factors Comput. Syst. - Proc.*, vol. 2018-April, pp. 1–13, 2018.

[42] L. A. Jones and M. Berris, "The psychophysics of temperature perception and thermal-interface design," in *Proceedings - 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS 2002*, 2002, pp. 137–142.

[43]   S. W. Kim *et al.*, "Thermal display glove for interacting with virtual reality," *Sci. Rep.*, vol. 10, no. 1, pp. 1–12, 2020.

[44]   L. Fricoteaux, I. M. Thouvenin, and T. Voillequin, "QUIVER: an informed virtual environment with thermal data perception for housing," *Poster Progr.*, no. December 2016, p. 25, 2009.

[45]   F. Hülsmann, N. Mattar, J. Fröhlich, and I. Wachsmuth, "Simulating wind and warmth in virtual reality: conception, realization and evaluation for a CAVE environment," *JVRB - J. Virtual Real. Broadcast.*, vol. 11, no. 10, 2014.

[46]   E. Shaw, T. Roper, T. Nilsson, G. Lawson, S. V. G. Cobb, and D. Miller, "The heat is on: Exploring user behaviour in a multisensory virtual environment for fire evacuation," *Conf. Hum. Factors Comput. Syst. - Proc.*, pp. 1–13, 2019.

[47]   A. Mehrfard, J. Fotouhi, G. Taylor, T. Forster, N. Navab, and B. Fuerst, "A comparative analysis of virtual reality head-mounted display systems," *arXiv*, 2019.

[48]   H. Liu *et al.*, "The response of human thermal perception and skin temperature to step-change transient thermal environments," *Build. Environ.*, vol. 73, pp. 232–238, 2014.

[49]   B. G. Witmer, C. J. Jerome, and M. J. Singer, "The factor structure of the Presence Questionnaire," *Presence: Teleoperators and Virtual Environments*, vol. 14, no. 3. MIT Press 238 Main St., Suite 500, Cambridge, MA 02142-1046 USA journals-info@mit.edu , pp. 298–312, Jun-2005.

[50]   Z. Cao, Y. Wang, and L. Zhang, "Real-time Acute Stress Facilitates Allocentric Spatial Processing in a Virtual Fire Disaster," *Sci. Rep.*, vol. 7, no. 1, pp. 1–11, 2017.

[51]   D. Hartanto, I. L. Kampmann, N. Morina, P. G. M. Emmelkamp, M. A. Neerincx, and W. P. Brinkman, "Controlling social stress in virtual reality environments," *PLoS One*, vol. 9,

no. 3, 2014.

[52]   A. Felnhofer *et al.*, "Is virtual reality emotionally arousing? Investigating five emotion inducing virtual park scenarios," *Int. J. Hum. Comput. Stud.*, vol. 82, pp. 48–56, 2015.

[53]   J. J. LaViola, "A discussion of cybersickness in virtual environments," *ACM SIGCHI Bull.*, vol. 32, no. 1, pp. 47–56, 2000.

[54]   M. Kinateder *et al.*, "The effect of dangerous goods transporters on hazard perception and evacuation behavior - A virtual reality experiment on tunnel emergencies," *Fire Saf. J.*, vol. 78, pp. 24–30, 2015.

[55]   R. R. Mourant and T. R. Thattacherry, "Simulator Sickness in a Virtual Environments Driving Simulator," *Hum. Factors Ergon. Soc. Annu. Meet. Proc.*, vol. 44, no. July 2000, pp. 534–537, 2000.

[56]   S. A. Balk, M. A. Bertola, and V. W. Inman, "Simulator Sickness Questionnaire: Twenty Years Later," pp. 257–263, 2013.

[57]   D. Yeom, J.-H. Choi, and Y. Zhu, "Investigation of physiological differences between immersive virtual environment and indoor environment in a building," *Indoor Built Environ.*, 2017.

[58]   D. Yeom, J.-H. Choi, and Y. Zhu, "Investigation of the Physiological Differences between Immersive Virtual Environment and Indoor Enviorment in a Building," *Indoor adn Built Enviornment*, vol. 28, no. 2, pp. 46–62, 2019.

[59]   S. Saeidi, A. Lowe, N. Johannsen, and Y. Zhu, "Application of Immersive Virtual Environment (IVE) in Occupant Energy-Use Behavior Studies Using Physiological Responses," in *Computing in Civil Engineering 2017*, 2017, pp. 381–389.

[60]   G. Ozcelik and B. Becerik-Gerber, "Benchmarking thermoception in virtual environments

to physical environments for understanding human-building interactions," *Adv. Eng. Informatics*, vol. 36, pp. 254–263, 2018.

[61] D. Yeom, J. H. Choi, and S. H. Kang, "Investigation of the physiological differences in the immersive virtual reality environment and real indoor environment: Focused on skin temperature and thermal sensation," *Build. Environ.*, vol. 154, no. March, pp. 44–54, 2019.

[62] Y. Yao, Z. Lian, W. Liu, C. Jiang, Y. Liu, and H. Lu, "Heart rate variation and electroencephalograph - The potential physiological factors for thermal comfort study," *Indoor Air*, vol. 19, no. 2, pp. 93–101, 2009.

[63] J. Xiong, X. Zhou, Z. Lian, J. You, and Y. Lin, "Thermal perception and skin temperature in different transient thermal environments in summer," *Energy Build.*, vol. 128, pp. 155–163, 2016.

[64] N. Umemiya, "Seasonal Variations of Physiological Characteristics and Thermal Sensation," *J. Physiol. Anthropol.*, vol. 25, no. 1, pp. 29–39, 2006.

[65] J. Lee, T. Kim, Y. Min, and H. Yang, "Seasonal Acclimatization in Summer versus Winter to Changes in the Sweating Response during Passive Heating in Korean Young Adult Men," *Korean J. Physiol. Pharmacol.*, vol. 19, pp. 9–14, 2015.

[66] M. Elbayoumi, N. A. Ramili, N. F. F. Md Yusof, and W. Al Madhoun, "Influence of seasonal variation on thermal comfort and ventilation rates in Gaza Strip climate," *Turkish J. Eng. Environ. Sci.*, vol. 38, pp. 197–208, 2014.

[67] B. Cao, Y. Zhu, Q. Ouyang, X. Zhou, and L. Huang, "Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing," *Energy Build.*, vol. 43, no. 5, pp. 1051–1056, 2011.

[68] H. Liu, Y. Wu, B. Li, Y. Cheng, and R. Yao, "Seasonal variation of thermal sensations in

residential buildings in the Hot Summer and Cold Winter zone of China," *Energy Build.*, vol. 140, pp. 9–18, 2017.

[69] Y. Bhattacharya and M. Milne, "Psychrometric chart tutorial: A tool for understanding human thermal comfort conditions," *38th ASES Natl. Sol. Conf. 2009, Sol. 2009*, vol. 8, pp. 4628–4640, 2009.

[70] "Integrated Surface Database (ISD) | National Centers for Environmental Information (NCEI)." [Online]. Available: https://www.ncdc.noaa.gov/isd.

[71] T. Matsumoto, T. Miyawaki, H. Ue, T. Kanda, C. Zenji, and T. Moritani, "Autonomic responsiveness to acute cold exposure in obese and non-obese young women," *Int. J. Obes.*, vol. 23, no. 8, p. 793, 1999.

[72] T. Schubert, F. Friedmann, and H. Regenbrecht, "Embodied Presence in Virtual Environments," *Vis. Represent. Interpret.*, pp. 269–278, 1999.

[73] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness," *Int. J. Aviat. Psychol.*, vol. 3, no. 3, pp. 203–220, Jul. 1993.

[74] R. J. de Dear and M. E. Fountain, "Field experiments on occupant comfort and office thermal environments in a hot-humid climate," *ASHRAE Trans.*, vol. 100, no. 2, pp. 457–474, 1994.

[75] G. Schiller, E. Arens, F. Bauman, C. Benton, M. Fountain, and T. Doherty, "A field study of thermal environments and comfort in office building," *ASHRAE Trans.*, vol. 94 Part 2, 1988.

[76] I. Darian-Smith and K. O. Johnson, "THERMAL SENSIBILITY AND THERMORECEPTORS," *J. Invest. Dermatol.*, vol. 69, no. 1, pp. 146–153, Jul. 1977.

[77] L. Sullivan, "Power and Sample Size Determination." [Online]. Available: https://sphweb.bumc.bu.edu/otlt/mph-modules/bs/bs704_power/bs704_power_print.html. [Accessed: 05-Sep-2020].

[78] S. Schiavon, T. Hoyt, and A. Piccioli, "Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55," *Build. Simul.*, vol. 7, no. 4, pp. 321–334, 2014.

[79] Y. Zhang, H. Chen, J. Wang, and Q. Meng, "Thermal comfort of people in the hot and humid area of China—impacts of season, climate, and thermal history," *Indoor Air*, vol. 26, no. 5, pp. 820–830, 2016.