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Exploring thermal state in mixed immersive virtual environments

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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 °C, 23.8 °C, and 29.4 °C), 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.

1. 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., Ref. [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. In particular, 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 occupants' 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., Ref. [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., Refs. [7–9]), 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

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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

settings, and the use of the thermal state and physiological responses of participants to measure their thermal experience.

2. Immersive virtual environments for thermal state studies

2.1. 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., Refs. [13–19]). 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., Refs. [20–22]), skin temperature (e.g., Refs. [22–24]), pulse rate (e.g., Ref. [25]), and electroencephalogram (EEG) and oxygen saturation (e.g., Ref. [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., Ref. [16]), the impact of thermal history on thermal sensation and comfort (e.g., Ref. [28]), the impact of age, gender and body mass index (BMI) on thermal sensation (e.g., Refs. [29–31]), the evaluation of new technologies such as personalized conditioning systems (e.g., Ref. [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. Ref. [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.

2.2. 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 influences 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., Ref. [40]) or Peltier devices (e.g., Ref. [41]). These studies supported participants' thermal perception in virtual environments through touch of virtual objects (e.g., Refs. [42–44]). 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 experiences 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., Refs. [50–52]). Secondly, interactions with virtual reality, particularly using an HMD device, may trigger symptoms similar to motion sickness or cybersickness (e.g., Refs. [53–56]). 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.

2.3. *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., Refs. [57,58]), a temperature and humidity controlled existing space (e.g., Ref. [59]), and a temperature and humidity controlled existing space with additional heating or cooling remedies such as a heater or a fan (e.g. Ref. [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 min while the temperature was changing from 20 °C to 30 °C for heating and 30 °C–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 to be 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., Refs. [23,37,38,48,62,63]). In addition, previous studies confirmed the seasonal influence on physiological responses (e.g., Refs. [64,65]), as well as thermal comfort adaptability, and thermal sensation (e.g., Refs. [66–68]). 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., Refs. [20,48,63]).

2.4. *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 MIVE 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 MIVE 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 = 65 °F/18.3 °C, 75 °F/23.8 °C, and 85 °F/29.4 °C)

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

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

Alternate Hypothesis, H_1: $PR_{temp} \neq PR'_{temp}$ (temp = 65 °F/18.3 °C, 75 °F/23.8 °C, and 85 °F/29.4 °C)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 °F/18.3 °C, 75 °F/23.8 °C, and 85 °F/29.4 °C) 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 °F/18.3 °C, 75 °F/23.8 °C, and 85 °F/29.4 °C) of a cooling or heating sequence in the MIVE setting.

According to the ASHRAE psychrometric chart, 75 °F/23.8 °C (55% relative humidity) falls into the comfort zone range for both winter and summer conditions, while 65 °F/18.3 °C and 85 °F/29.4 °C (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 MIVE and *in-situ* experiments are analyzed and compared.

3. Research method

3.1. 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 h 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.

3.2. Research equipment, devices, and instruments

3.2.1. Climate chamber

The climate chamber is a renovated indoor office space. The basic layout of the climate chamber is shown in Fig. 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 4.2 m (L) x 3.2 m (W) x 2.7 m (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%–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.

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.

3.2.2. 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 m, 24 inches/0.6 m, and 34 inches/1.1 m, following the recommendation by ASHRAE 52–2010. The temperature measured by the sensor at 24 inches/0.6 m was specifically chosen as the control temperature for data analysis because the height of

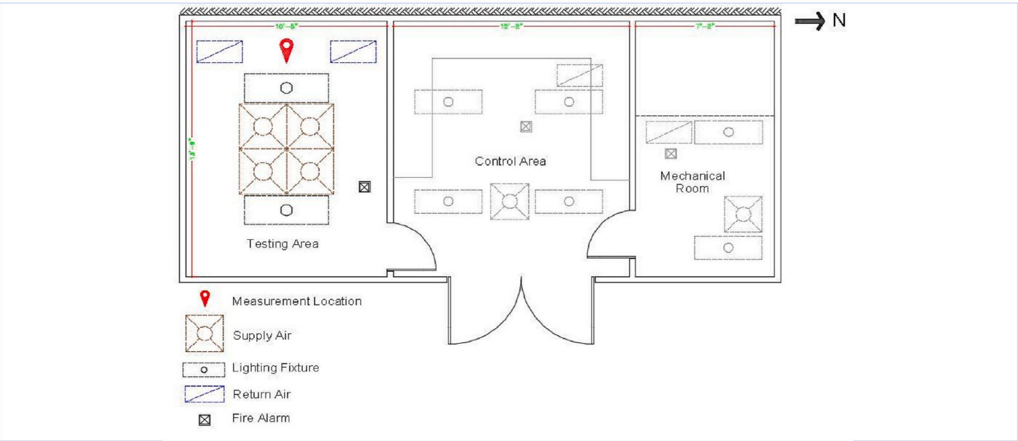


Fig. 1. Climate chamber layout.

the sensor was close to the middle point of the participants' height when they were in a sitting position during experiments (Fig. 2). Temperature data transmitted in 1-s intervals and was logged with Logger Pro 13. The specifications of these sensors are shown in Table 1.

3.2.3. 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].

3.2.4. 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.

3.2.5. Skin temperature

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

3.2.6. IVE apparatus

The head-mounted display (HMD) used in this study was an HTC-Vive, which supports a 2160 × 1200 resolution on a dual-AMOLED 91 mm panels with 90 Hz 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.

Table 1
Sensor specifications.

Sensing Equipment	Model	Specifications
Vernier surface temperature sensors	STS-BTA	Range: −25 °C–125 °C (−13 °F–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

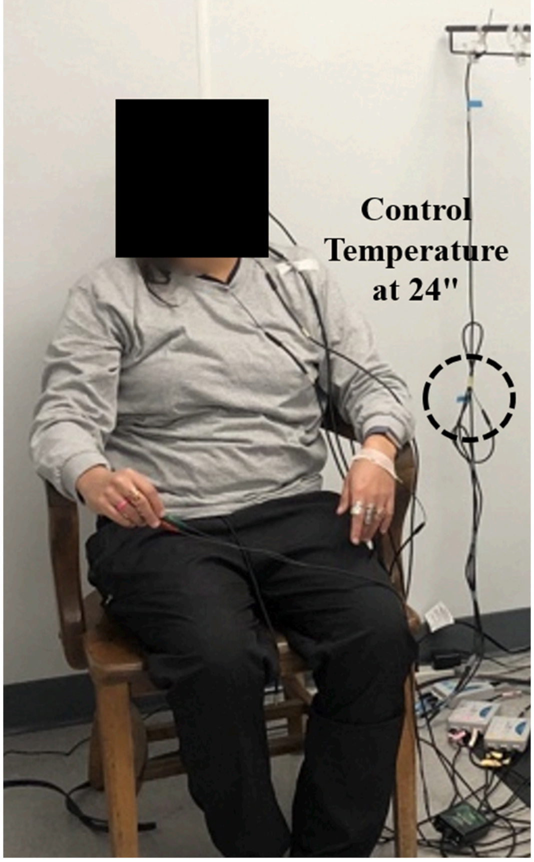

[redacted]

Fig. 2. Environment temperature sensors.

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 (Fig. 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.

3.2.7. 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 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 Ref. [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 (Fig. 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., Refs. [50–52]), 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 MIVE 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

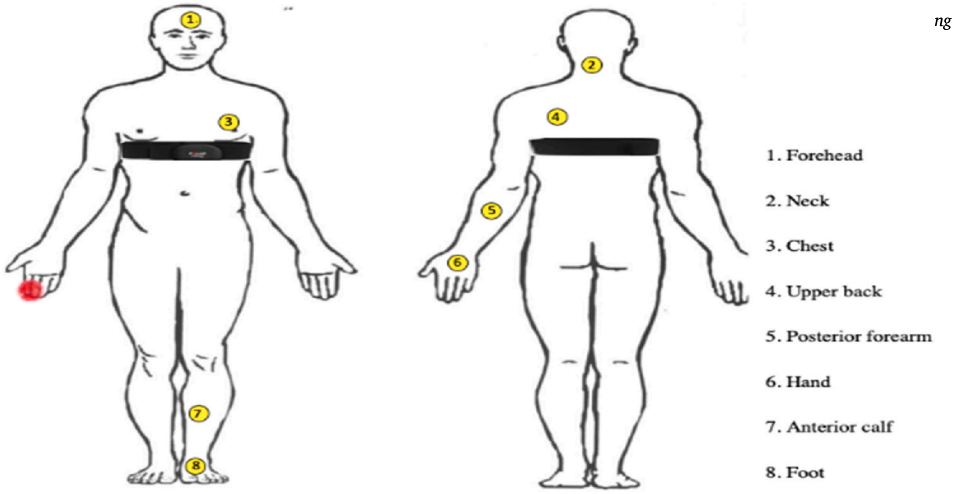


Fig. 3. Body sensor deployment.

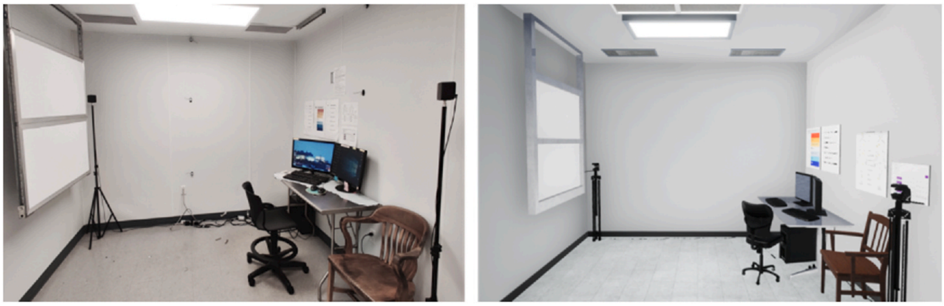


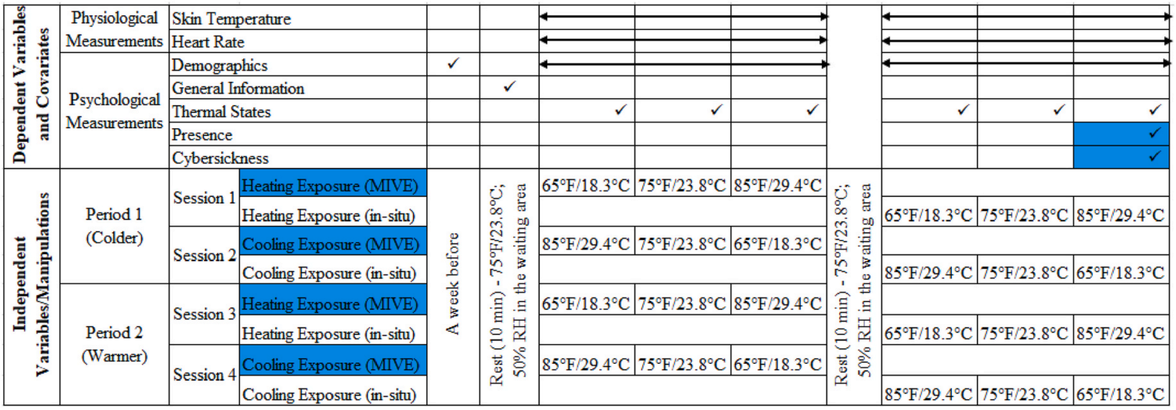
Fig. 4. *In-situ* (Left) vs. virtual (Right) Space.

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 MIVE. Consequently, lower scores indicate poor presence in MIVE.

- 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.

3.3. 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



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)	A week before	Rest (10 min) - 75°F/23.8°C; 50% RH in the waiting area	65°F/18.3°C	75°F/23.8°C	85°F/29.4°C	Rest (10 min) - 75°F/23.8°C; 50% RH in the waiting area			
			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

Fig. 5. Experiment and data collection procedure.

apart; and the MIVE and *in-situ* experimental sessions were on the same day, either a heating exposure or a cooling exposure. Fig. 5 illustrates the experimental sessions, the type of data to be collected, and the estimated timelines for each step of the experiments.

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-min 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 1-s 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-min 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 1000 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. The MIVE experiment had an additional post-experiment questionnaire, measuring participants' sense of presence and their cybersickness.

3.4. Data collection, synchronization, and cleaning

All sensors were set to continuously measure and record data in 1-s intervals; they were then averaged at different time scales, *i.e.,* zone 1, 2, and 3 as illustrated in Fig. 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/65 °F. After the chamber temperature was stabilized, participants were exposed to that temperature condition for 5–7 min, 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 °F), 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 outliers. Specifically, the *control temperatures* of MIVE and *in-situ* experiments were compared with each other to ensure they were not significantly different.

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

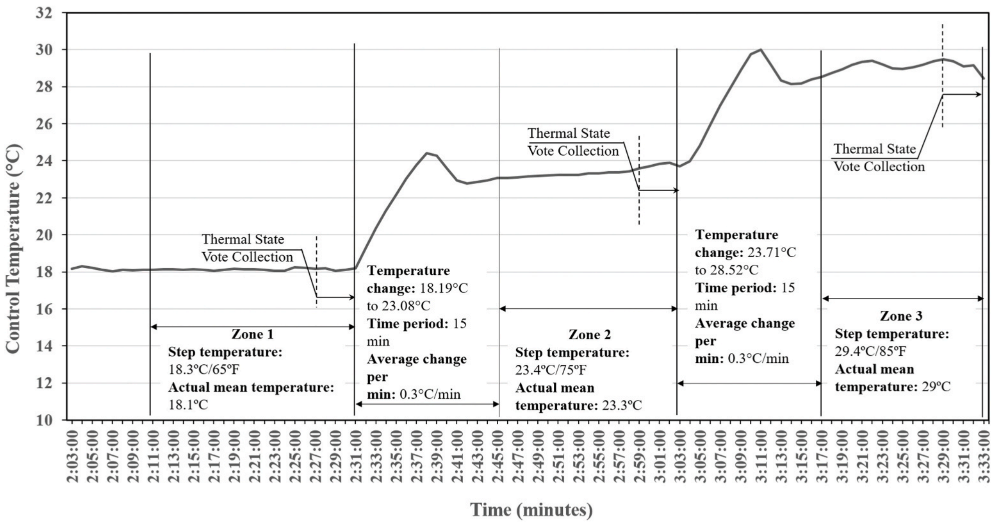


Fig. 6. Data collection schematic timeline (sensor at 24 inches/0.6 m).

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 min or more (10 min 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 °F/18.3 °C *in-situ* vs. period 1/cooling/65 °F/18.3 °C 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.

4. Analysis, results, and discussions

4.1. 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%;
- East Asian: 8, 26.66%; and
- Other ethnicities: 5, 6.66%.

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

4.2. 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 Sign Rank test and the sample mean difference between MIVE 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 1.5 °C. It means the test can reliably differentiate the MIVE 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 MIVE and *in-situ* is larger than 1.5 °C. Table 4 shows the trade-off between the sample size of a *t*-test and the sample mean difference between MIVE and *in-situ* settings with a significance level of 0.05 and a statistical power of 0.8.

Since all 30 participants took the three-temperature-step experiment in both MIVE 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 (Fig. 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 MIVE and *in-situ*) were applied (Fig. 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 MIVE and *in-situ* settings that the K-S tests can differentiate is at least 1.5 °C for general thermal acceptability and general thermal comfort, and 0.75 °C 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 1 °C and 8 bpm, respectively. To be able to differentiate smaller mean differences between the two settings, larger samples are needed.

4.3. Control temperature distribution

Fig. 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 (Fig. 7), only 8 pairs have a sample size more than 26 for both MIVE 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).

Table 5 shows the results of comparing the control temperature

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

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

	Δ_{mean}	General Thermal Sensation	General Thermal Acceptability	General Thermal Comfort	Local Thermal Sensation	Local Thermal Acceptability
Estimated Sample Sizes K-S Test	0.25 °C	671	2795	3061	437	512
	0.5 °C	168	699	765	109	128
	0.75 °C	**75**	311	340	**49**	**57**
	1 °C	42	175	191	27	32
	1.25 °C	27	112	122	17	20
	1.5 °C	19	**78**	**85**	12	14
	1.7 °C	15	60	66	9	11
Estimated Sample Sizes Wilcoxon Test	0.1	875	2776	2219	1211	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 MIVE.
The bold numbers represent the sample sizes that can be satisfied in this study.

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

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

Note: Δ_{mean} - assumed minimum sample mean difference of skin temperatures and heart rate per minute between *in-situ* and MIVE.
The bold numbers represent the sample sizes that can be satisfied in this study.

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).

4.4. Thermal state votes

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

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 [78, 79]. 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 (Fig. 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 °F/18.3 °C in colder period, 75 °F/23.8 °C and 85 °F/29.4 °C in warmer period (Fig. 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 °F/23.8 °C, where the votes between the MIVE and *in-situ* settings were significantly different because the mean vote difference in this case was 0.33 (Fig. 8). In all other cases, the mean comfort vote differences between MIVE and *in-situ* settings were less than 0.25.

4.5. Physiological response analysis

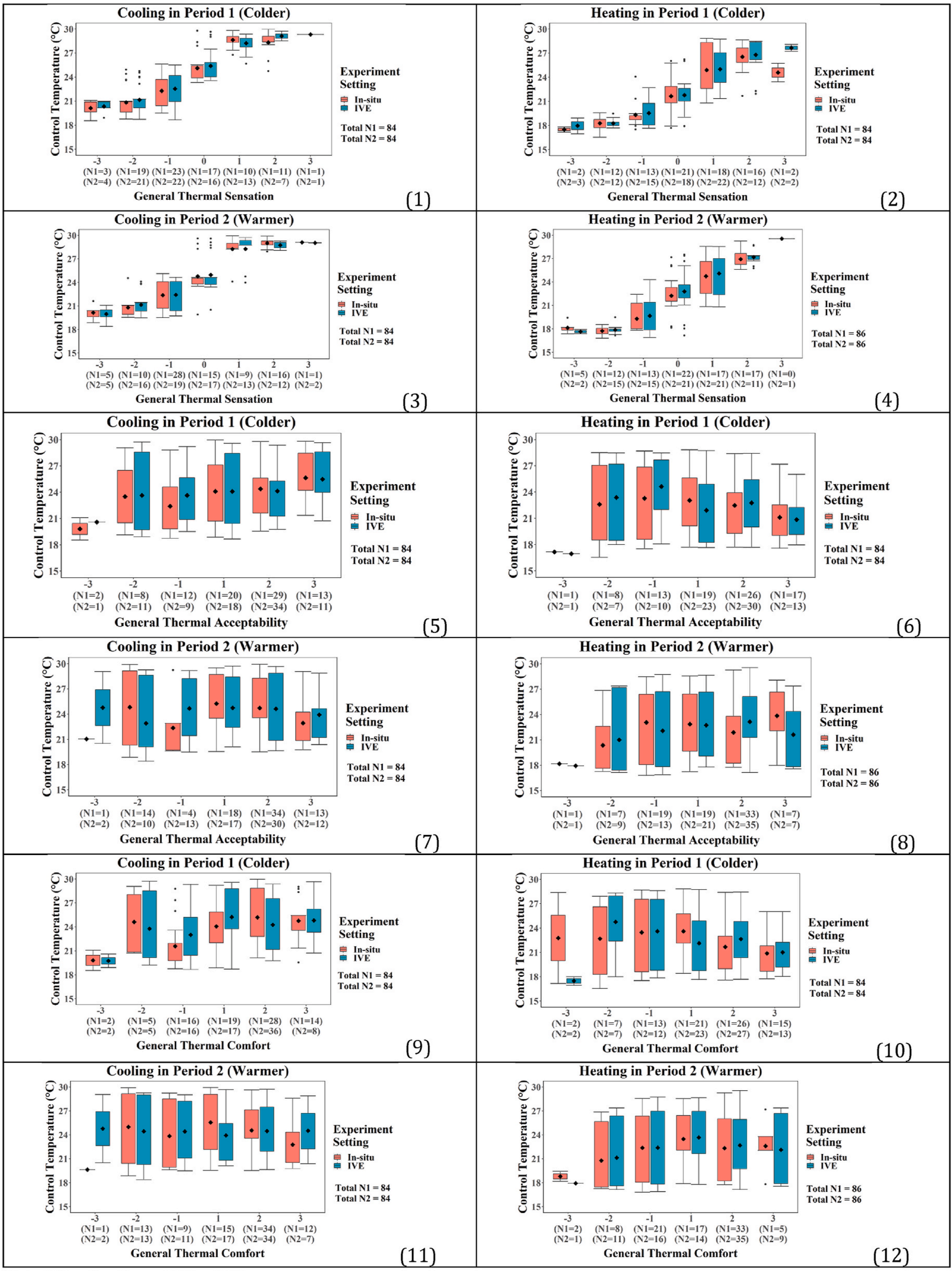
The comparisons between PR_{temp} and PR'_{temp} were performed using *t*-test. Given the large number of test results, the authors only reported the tests with a significant result (Table 7). The results show that the significantly different responses were mostly related to the forehead skin temperature, along with two other instances (i.e., the neck skin temperature at 85 °F/29.4 °C during heating, and the upper-back skin temperature at 75 °F/23.8 °C 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.

4.6. 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 Table 8 and Table 9.

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



Note: N1 = In-situ and N2 = IVE

Fig. 7. Thermal state votes and control temperature.

4.7. Post-experiment questionnaire results

4.7.1. 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., Refs. [50,51]). For example, according to a previous study [51], the IPQ online datasets

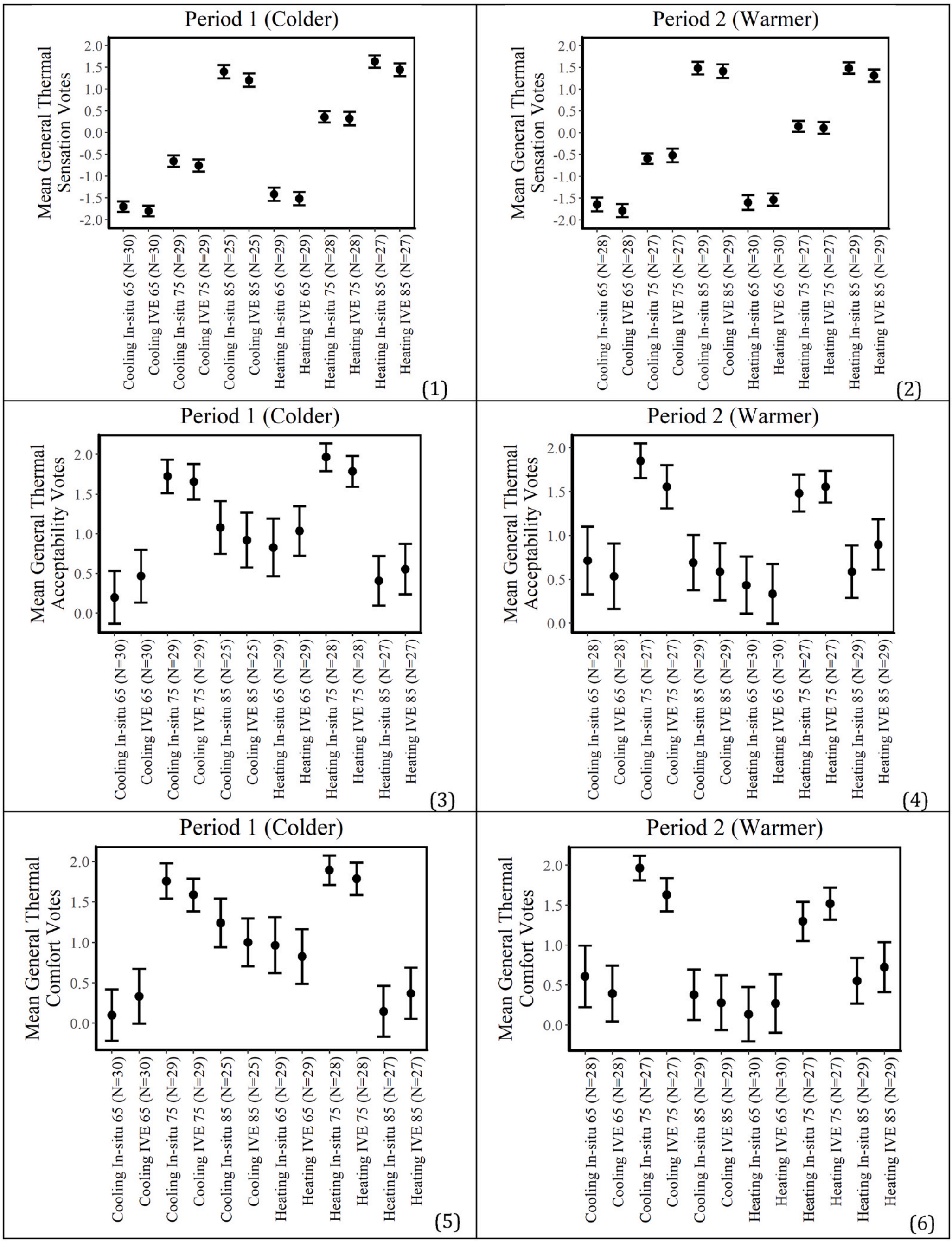


Fig. 8. Mean Thermal State Votes Between IVE and *in-situ* at Each Temperature Step.

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.

4.7.2. *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.

5. 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

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.

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 °F/ 18.3 °C	0.510	0.299	0.644	0.308
	75 °F/ 23.8 °C	0.894	0.351	0.802	0.675
	85 °F/ 29.4 °C	0.303	0.212	0..073	0.675
Acceptability and Comfort	65 °F/ 18.3 °C	0.478*, 0.904**	0.234*, 0.209**	0.751*, 0.683**	0.343*, 0.245**
	75 °F/ 23.8 °C	0.36*, 714**	0.595*, 0.276**	0.824*, 0.378**	0.13*, 0.023**+
	85 °F/ 29.4 °C	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.

limited to the sample mean differences discussed in the previous section (Tables 3 and 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 (Tables 7 and 8), as well as neck and upper-back (Table 7), and forearm (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, 65 °F/18.3 °C and 75 °F/23.8 °C. 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 °C; while at other step temperatures, the mean differences are less than 1.0 °C. On the other hand, the mean skin temperature differences at neck, upper-back, and forearm are relatively small, mostly less than 0.62 °C at neck, 0.37 °C at upper-back and about 1.0 °C 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 [80], 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 (Tables 5 and 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 (Table 8). In the case of cooling at 75 °F/23.8 °C, 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 Fig. 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. [81] found that the

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 °F/18.3 °C	Forehead Skin Temperature (°C)	30	34.3	0.85	30	35.8	1.18	29	−5.4	7.49E-06
		75 °F/23.8 °C	Forehead Skin Temperature (°C)	29	35	0.53	29	35.8	0.63	28	−6.1	1.39E-06
	Heating	65 °F/18.3 °C	Forehead Skin Temperature (°C)	29	33.7	0.95	29	34.5	0.63	28	−5.1	1.85E-05
		75 °F/23.8 °C	Forehead Skin Temperature (°C)	28	34.2	0.92	28	35.2	0.69	27	−6.2	1.30E-06
		85 °F/29.4 °C	Forehead Skin Temperature (°C)	27	35.1	0.77	27	35.9	0.51	26	−6.2	1.33E-06
		85 °F/29.4 °C	Neck Skin Temperature (°C)	27	33.9	1.21	27	33.3	1.88	26	2.42	0.022
Period 2, Warmer	Cooling	65 °F/18.3 °C	Forehead Skin Temperature (°C)	28	34.4	0.64	28	35.9	1.05	27	−7	1.79E-07
		75 °F/23.8 °C	Forehead Skin Temperature (°C)	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
		85 °F/29.4 °C	Forehead Skin Temperature (°C)	29	35.2	0.52	29	35.8	1.48	28	−2.4	0.02

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 1, Colder, Thermal Acceptability	Cooling	−3	–	–	–	–	0.008
			−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 °F/18.3 °C	0.035	0.005
	75 °F/23.8 °C	–	0.005
Forehead Acceptability	65 °F/18.3 °C	0.034	–

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.

6. 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 MIVE 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.

7. 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

Table 10
Presence and cybersickness scores.

			Presence			Cybersickness		
	Order	Size	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

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 Ref. [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.

CRediT authorship contribution statement

Sanaz Saeidi: Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Girish Rentala:** Data curation, Formal analysis, Visualization, Writing – review & editing. **Tracey Rizzuto:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Tianzhen Hong:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Neil Johannsen:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Yimin Zhu:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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