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Investigation of the physiological differences in the immersive virtual reality environment and real indoor environment: Focused on skin temperature and thermal sensation

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ABSTRACT

The goal of this research is to investigate and determine whether the effect of an IVE condition on an occupant's environmental sensations and physiological responses is different from the effect of a real environmental condition in the indoor environment. The research included a series of human subject experiments, with 16 participants in an environmental chamber. A thermal quality condition was selected as a primary environmental parameter, based on current IEQ-relevant studies. While the ambient thermal condition was gradually changed from 20 °C to 30 °C, the participants were asked to report their overall thermal sensations. Their skin temperatures were also continuously measured to collect physiological signal information in real time. The results of this experimental study revealed that the participants mostly generated higher skin temperature at the selected seven skin areas. Their reported thermal sensations were significantly higher in the IVE condition, than in the real environment, showing a difference of 12%.

1. Introduction

In research on human ergonomics and related factors, it is popular to employ an immersive virtual environment (IVE) and its relevant technologies because of its technical effectiveness and lack of a financial burden [1]. Since human physiological factors are significantly affected by building indoor environmental quality and energy performance [2], user studies have frequently utilized an IVE system to identify relationships between the human and environmental factors [3–6].

[7] investigated the potential of the IVE as a lighting environment experimental tool. They collected 89 participants' lighting-related behavior by using an IVE and integrated those collected data with a building simulation in order to quantify a preferred lux level. The results demonstrated the participants' significant preference for simulated daylight when all shades were open, and helped designers create spaces that were based on participants' needs [9]. also investigated a virtual reality (VR) system that provides wind and warmth for different environmental conditions, such as desert or volcano. The results revealed that a user's sense of presence was statistically higher when multi stimuli (i.e., wind and warmth) were provided, and also found a few factors that influenced the user's perception, including the distance to a thermal source and the time delay between VR images and actual perception of the images. Similarly [10], investigated the possibility of a head-mounted display system that included ambient temperature and wind, in addition to a common VR condition. The results demonstrated that sensory and realism factors improved significantly when a participant's face was exposed to additional wind and thermal stimuli, and the sense of presence was also enhanced when compared to the ordinary VR condition.

[11] used immersive virtual reality as a tool to assess noise levels, with regard to multi-perceptual factors. They combined virtual reality and audio rendering technology to assess environmental noise to help designers improve their decision making. The results revealed that noise produced by the new infrastructure had a negative impact on short-term verbal memory and generated visual and noise annoyance. In addition [12], investigated occupants' exit choices and waiting times for evacuation using elevators by conducting experiments involving exiting from high-rise building in VR. They verified that the VR experiment is a suitable replacement for a conventional lab experiment, with regard to human behavior. The experimental results demonstrated an optimum system for finding a way to exit in an emergency.

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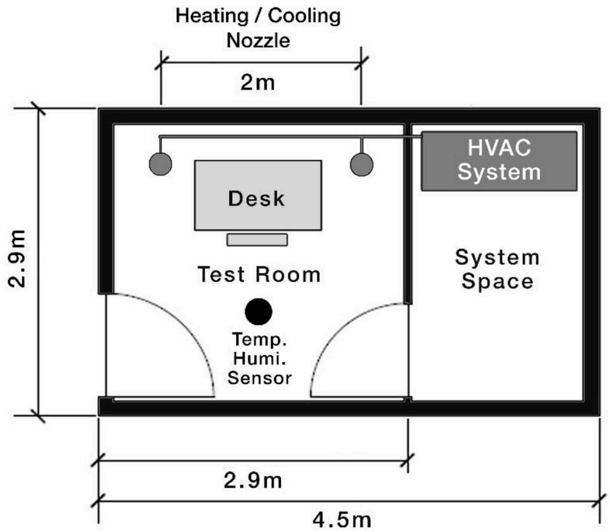

Fig. 1. Floor plan of Environmental Chamber at USC.

The behaviors of building occupants is a key element for indoor environmental control and building performance (as well as energy consumption in a built environment). Numorous researchers have conducted a number of experiments by using an IVE environment and taking it for granted that a condition was similar to an actual environment, but disregarding relevant technical considerations.

[13] investigated the influences of occupants' lighting control behavior on building energy consumption by using IVE. The participants were asked to perform a task while they were wearing a head-mounted display. The use of IVE allowed the researchers to measure and control different combinations of environmental elements. The results of the study demonstrated that the users preferred blinds and shading control in a building [14]. explored VR as an occupancy engagement tool for energy designs in a building. They reported that VR is beneficial in that it decreased the gaps in energy performance and validated lighting design controls in sampled residential building projects [15]. further investigated IVE as a tool to monitor the behavior of building occupant behavior and to collect data for simulation of building performance. They discovered that IVE has significant benefits for collecting behavioral information about occupants as well as for providing accurate representations of built environments.

To implement an IVE condition, a user is requested to wear an electric device or to remain in a VR setting, such as Ambiotherm [10], L-screen [16], etc. A few studies have reported that IVE may have physical and psychological impacts on human factors, such as heart rate, environmental perception, blood pressure, temperature, and electro dermal activity (EDA) [2] as well as occupants' productivity [17]. conducted experiments to determine any difference in an individual's work performance in a physical environment and in an IVE setting. The researchers reported that work performances were very similar in each of these environments, and they concluded that the IVE has the potential for receiving occupant feedback in an actual built environment [18]. also investigated the impact of warm-up on work performance, in an operating room, that is created by using VR. The results demonstrated that a short period of warm-up improved the quality of work performance. However [19], argued that IVE could

Fig. 2. Oculus rift DK2.

Fig. 3. IVE image view in Oculus Rift.

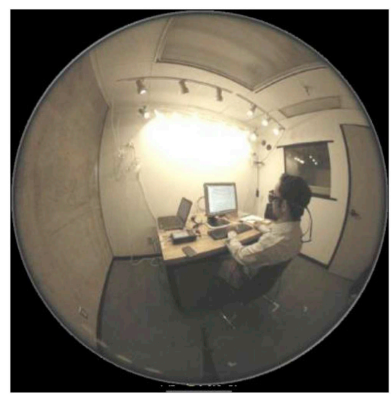

Fig. 4. IE view in the Experiment Chamber.

Table 2
Demographic information on participants.

	Age (Avg.: 24.6/St.Dev.: 2.64)
Female	6
Male	10
Total	16

Table 1
Specifications of data acquisition devices.

Device		Model	Specification
Air temperature sensor		LM35DT	Accuracy: ± 0.5 °C, Resolution: 0.01 °C
Skin temperature sensor		SBS-BTA	Accuracy: ± 0.5 °C, Resolution: 0.03 °C
Air velocity sensor		Testo 405-V2	Accuracy: ± 5 °C, Resolution: 0.01 m/s
CO_2 sensor		Telarire 6004	Accuracy: ± 40 ppm
Radiant temperature sensor		OS-542	Accuracy: ± 2 °C, Resolution: 0.1 °C
Humidity sensor		HIH-4000-003	Accuracy: 3.5%, Resolution: 0.5%
Data acquisition board 1	Sensor DAQ	Resolution: 13 bit, Sampling rate: 10 kS/s	
Data acquisition board 2	NI-DAQ 6008	Resolution: 12 bit, Sampling rate: 10 kS/s	

Table 3
Thermal sensation check-list using Likert 7-Point scale.

Thermal sensation	−3 Very cool	−2 Cool	−1 Slightly cool	0 Neutral	1 Slightly warm	2 Warm	3 Very warm

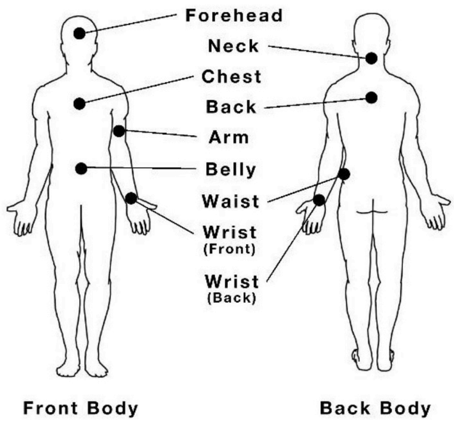

Fig. 5. Monitored local body areas [8].

significantly generate a negative side-effect, such as motion sickness or nausea in certain conditions, and suggested solutions to reduce it.

In recent research [1], reported a finding relevant to behavior, determined by a human subject experiment, which utilized a wearable VR device to assess human-environment interaction [16]. also used VR in their study, and found that the interpretation of visual cues (i.e., sky, sun, shadows, light effect, etc.) were subjective and affected by the cues added to the VR condition. Even though these studies reported technically sound findings from the IVE-adopted human subject experiments, the potential effects of the IVE and its relevant wearable sensors have not been confirmed with any technical validation.

In the domain of research on human built environments, four critical indoor environmental quality components are applicable, including thermal, lighting, acoustic, and air quality [20]. Among those IEQ parameters, thermal quality has been explored and determined to be the most significant variable that affects a user's environmental satisfaction and work productivity, compared to the other parameters and their conditions [21]. reported that work productivity increased by 5.5% when a user's ambient condition was individually controlled [22].'s study also revealed that thermal quality is more critical than other IEQ conditions when a user's ambient thermal condition has been controlled based on his/her preference.

Accordingly, it is crucial to identify whether an IVE-based user-study, focusing on a thermal quality component in a built environment, could generate any physiological issue, as compared to the real-world environmental condition. Therefore, the hypothesis was established that a human test participant would perceive different thermal sensations and his/her body would generate different physiological signals (i.e., skin as a consequence of the environments: i.e., the IVE and the real-world environmental conditions. To verify this hypothesis, the research team conducted a series of human subject experiments in the environmental chamber located at the University of Southern California (USC), and analyzed the results using various analytical methods with data-mining tools. Additionally, a predictive model of an occupant's thermal perception was suggested, which could provide optimum thermal comfort in IE and IVE conditions.

2. Methodology

2.1. Experiment Chamber

This study conducted a human subject experiment in USC's Environment Chamber to collect skin temperature and thermal sensation data for each subject in the IE and IVE condition. The floor plan of the Experiment Chamber is shown in Fig. 1.

A HVAC system was installed with a multiple sensing device in the Chamber. The air velocity was maintained at less than 0.2 m/s, based on the ASHRAE-55 [23]. As illustrated in Fig. 1, the Chamber consists of two separate areas, a test room and system space. A chair and a desk are provided in the test room along with data collection devices. Indoor air temperature was monitored at four points at different heights (0.1 m, 0.6 m, 1.1 m, and 1.6 m). Relative humidity (RH) and CO_2 density were

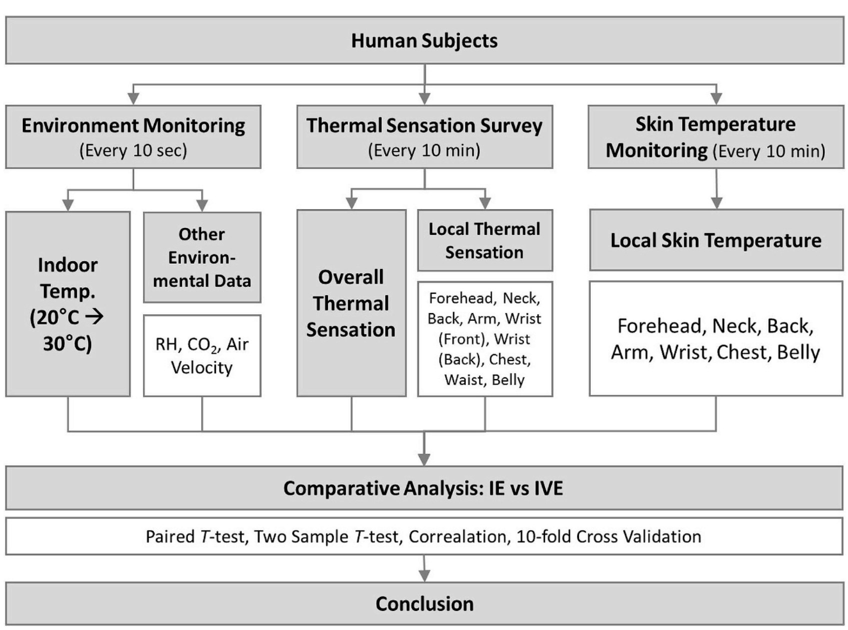

Fig. 6. Experiment procedure.

Table 4
Correlation of skin temperatures and indoor temperatures for IE and IVE.

		Fore head	Arm	Wrist Back	Wrist Inner	Chest	Belly	Waist	Back	Neck
IE	Pearson R	0.336	0.171	0.194	0.375	0.407	0.269	0.101	0.205	0.265
	p-value	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*
IVE	Pearson R	0.311	0.036	−0.125	−0.095	0.174	0.087	0.116	0.018	0.306
	p-value	$P < 0.001$*	0.062	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	0.334	$P < 0.001$*

*: Statistically significant.

Table 5
Two sample *T*-tests of local skin temperatures in the IVE and the IE.

		Fore head	Arm	Wrist Back	Wrist Inner	Chest	Belly	Waist	Back	Neck
Avg.	IE	35.7	34.0	33.1	33.3	35.0	34.4	34.9	34.8	34.7
	IVE	35.9	33.7	32.8	33.5	34.0	34.0	33.9	33.9	34.5
Delta		0.2	0.3	0.3	0.2	1.0	0.4	1.0	0.9	0.2
p-value		0.000*	0.000*	0.000*	0.003*	0.000*	0.000*	0.000*	0.000*	0.000*
St.Dev.	IE	1.33	1.16	2.29	2.29	0.92	1.82	1.59	1.67	1.19
	IVE	1.40	1.63	2.65	2.33	2.68	3.25	3.28	2.82	1.70

*: Statistically significant.

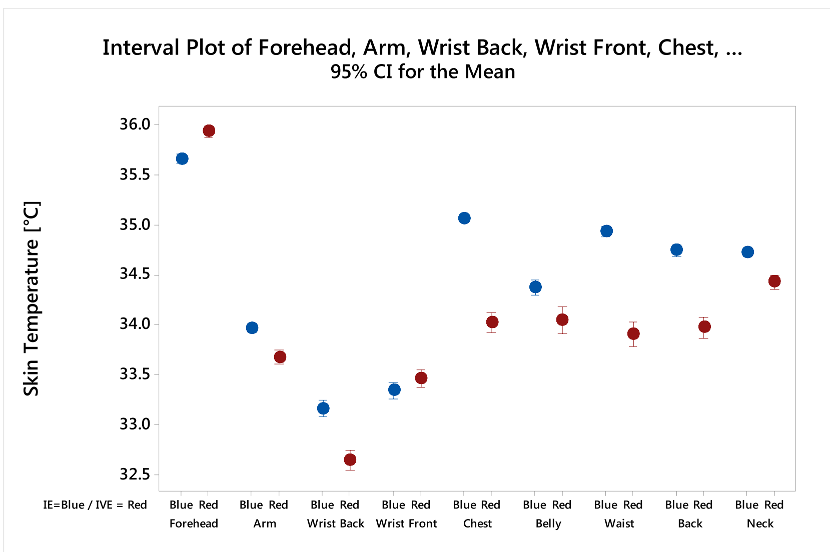

Fig. 7. Interval plot of local skin temperature differences in IE and IVE.

monitored, as well, to control the environmental condition, based on the ASHRAE-55 [23]. RH was maintained at 35% (± 5%), and CO_2 density was controlled between 700 and 900 ppm. The outlets (air diffuser), located at each side of the desk, were controlled to minimize the air velocity around the desk and chair. The HVAC control system was equipped in the system space. The air velocity in the test room was controlled within 0.1 ± 0.05 m/s at the floor (0.6 m, 1.2 m, and 1.6 m), which is acceptable, considering the allowed maximum of 0.2 m/s, based on the ASHRAE-55 [23]. The temperature in the test room was controlled for heating from 20 °C to 30 °C, and the order of conditions, IE and IVE, was randomly chosen to prevent any possibility of a biased test.

2.2. Experiment equipment

Physiological and environmental data were collected through a DAQ (data acquisition) system installed on a desktop computer in the test room. The indoor air temperature, RH, CO_2 density, and air velocity was monitored and recorded through that system. The skin temperature was also measured by surface sensors (STS-BTA), an exposed type of thermistor with a rapid response rate. The skin temperature was measured, by direct contact with the skin surface, and recorded in the DAQ system as well. Specifications of the data acquisition equipment are presented in Table 1.

To generate a virtual environment, a 3D model of the test room in the Experiment Chamber was built using AutoCAD and Adobe Photoshop. Based on this model, lighting and a shadow effect were added to generate a virtual 3D environment by using the Unreal Engine 4 program. The Oculus Rift DK2 model was used to provide an immersive virtual scene (Fig. 2). This was the latest IVE kit at the time of the study. The Oculus Rift DK2 provides 960 × 1080 resolution image per eye. The generated IVE scene (Fig. 3) was realistic and compatible with the actual test room environment (Fig. 4).

2.3. Procedures of human subject experiment

Every participant was required to wear the same type of clothing during the experiment, including 0.55 or 0.59 Clo. (i.e., long sleeve T-shirt (0.25) and long pants (0.25) with regular socks (0.02), panties (0.03), and/or bra (0.04)). Basic demographic information, such as age, gender, and height were surveyed, as summarized in Table 2. A total of 18 volunteers (11 males and 7 females) participated in the experiment;

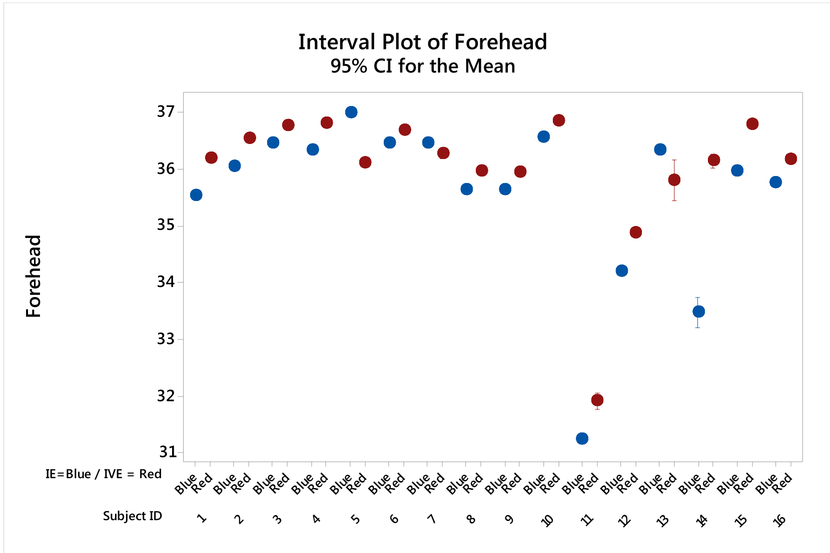

Fig. 8. Interval plot of individual forehead skin temperatures in IE and IVE conditions.

all of them were either undergraduate or graduate students at USC. Two results (1 male and 1 female) were excluded from the analysis due to false records. Most participants were in their 20's, and only one was 32 years old. All were in a healthy or normal condition. Each test participant was asked questions regarding his/her current health, such as having certain diseases or health issues, in order to confirm eligibility to participate in the experiment, based on the Institutional Review Board's approval for research by the University of Southern California.

All participants were asked to remain in a waiting area for 30 min to stabilize physiological conditions before the test, where the room temperature was controlled at 24 °C. Once a participant was ready, he or she moved to the test room, where the room temperature was set at 20 °C. Each participant was required to sit on a chair by a desk. In addition, a mesh-type office chair, which includes thin polyester fabric mesh on the bottom and back support, was used to minimize any insulating effect the chair might have on the participant's thermal sensation.

The indoor temperature was changed from 20 °C to 30 °C, and the thermal sensation survey and collections of indoor environmental data and skin temperatures were conducted simultaneously. To avoid an effect from a particular arrangement of conditions, the order of IE and IVE was randomly chosen. A temperature change rate was set at 1 °C/10 min, for the human subject research [24], and participants were asked to check his or her thermal sensation on a check list every 10 min. The duration of the experiment was 90 min per each condition (IE and IVE). A Likert 7-point scale (based on the ASHRAE PMV survey designation) was used to record thermal sensation levels (Table 3) [23]. Both whole body thermal sensations and seven local body thermal sensations were surveyed at the same time, and their relationships were compared.

Skin temperatures and indoor temperatures were recorded every 10 s. Thermal sensations were measured on seven local body areas and skin temperatures were measured on nine body areas (Fig. 5), based on 16 thermo-regulation models of thermal sensations and physiological responses [25].

All collected data were analyzed using multiple statistical methods (including 2-sample T-test, correlation analysis, and 10-fold cross validation) to verify the physiological differences in the IE and the IVE. Microsoft Excel, Minitab, and WEKA [26] were used for data analysis, based on a 95% significant level. This experiment was approved by the USC IRB (Institutional Review Board/UP-16-00104). Before the test was administered, a consent form was provided to each participant with detailed explanations concerning test procedures, and a research investigator collected the signed consent forms. Experimental procedures are illustrated in Fig. 6.

3. Results

This paper focused on the comparison of each participant's physiological response (skin temperature) and a subjective response (thermal sensation) in the immersive virtual environment and the actual environment. Therefore, most of the analysis was performed between two groups, the IE (indoor environment) and the IVE (immersive virtual environment).

3.1. Skin temperature in the IE and the IVE conditions

Skin temperature responses to the surrounding indoor temperature, and a synthetic combination of these skin temperatures, have an influence on the core body temperature and the overall thermal sensation. Thus, correlation analyses of skin temperatures and indoor temperatures were conducted to compare the difference between the IE and the IVE conditions (Table 4).

In the IE condition, all skin temperatures were positively correlated with indoor temperatures with a significant *P*-value, and the chest, wrist (inner), and forehead measurements correlated relatively higher than the others did. However, the IVE condition demonstrated that skin temperatures on the wrist (inner) and wrist (back) showed negative correlations with indoor temperatures, and the arm and back were not statistically correlated. The forehead and neck demonstrated relatively higher correlations than other local skin temperatures with significant *P*-value ($P < 0.001$) in the IVE condition. Therefore, there are different correlations for local skin temperatures and indoor temperatures between the IE and IVE conditions, and certain local body spots (arm and back) in an IVE condition did significantly correlate with indoor temperature.

Table 5 demonstrates the results of two sample *T*-tests of the local skin temperature in the IE and IVE conditions, while Fig. 7 illustrates interval plots of local skin temperature in the IE and IVE conditions. It was clear that the skin temperatures of every local body spot in the IE condition were higher than those in the IVE condition, except for the wrist (inner) and forehead (Fig. 7).

According to the two sample *T*-test results (Table 5), the temperature difference between the IE and IVE condition was about 0.2–1.0 °C, with a significant *P*-value, depending on the local body spot. Also, the standard deviation of every local spot in the IVE condition appeared larger than that in the IE condition. Therefore, it was evident that the chest, waist, and back had demonstrated significant temperature differences between the IE and the IVE conditions, and that the local skin temperature variation was relatively unstable in the IVE condition, as compared with the IE condition.

Fig. 8 illustrates an interval plot of local skin temperature (forehead) in the IE and the IVE conditions as examples of local body segments. The forehead skin temperature of most participants ranged from 35 °C–37 °C, but each individual demonstrated different skin temperatures than others did. Additionally, most participants showed a skin temperature difference between the IE and the IVE conditions. Two sample *T*-tests of forehead skin temperature (Table 6) demonstrated that there was a significant difference between the IE and the IVE conditions for every participant ($P < 0.005$). Ten participants showed higher skin temperatures in the IVE condition than in the IE condition, and six participants demonstrated the opposite results. However, only seven participants showed a difference, larger than 0.5 °C, while only one subject showed a difference larger than 1 °C. By considering sensing instrument accuracy (0.5 °C) and the analysis results for forehead skin temperatures, it is safe to say that there is no significant difference in local skin temperature in conjunction with the IE and IVE conditions, respectively.

3.2. Thermal sensation in IE and IVE conditions

Skin temperatures are significantly affected by the ambient thermal condition. Thus, this study also analyzed the thermal sensation data on whole body and local body segments. Fig. 9 illustrates an interval plot of the overall thermal sensation in the IE and the IVE condition. The standard deviation was 1.15 in the IE and 1.14 in the IVE condition, which also demonstrated that the variations in thermal sensations for each condition are similar. The difference between the average thermal sensation in the IE and the IVE condition was 0.08 (IE: 0.88/IVE: 0.50), and the overall thermal sensation was not statistically significant (*p*-value: 0.008).

Table 7 demonstrates the two sample *T*-tests of the local thermal sensation in the IE and the IVE condition. The average local thermal sensation of the forehead, arm, and wrist was lower in the IE condition than that in the IVE condition, while the average thermal sensation of the chest, belly, back, and neck appeared higher in the IE condition than that in the IVE condition. However, only the arm, wrist, and neck showed any significant differences in the thermal sensations of the IE and the IVE condition ($p < 0.005$), while the other local thermal sensations were statistically insignificant.

3.3. Gender

Gender has been a critical physical factor that exerts influence on the thermal comfort and sensations of users. Recent studies revealed that significant differences exist between gender groups in thermal sensations and comfort [24,27]. Thus, comparative analyses were conducted with consideration given to gender groups, (10 males and 6 females).

Two sample *T*-tests of each local skin temperature in the IE and the IVE conditions were conducted, and the results are demonstrated in Table 8. In the male group, most local skin temperatures in the IE condition were higher than those in the IVE condition, except that the forehead, and all local skin temperatures showed significant differences between the IE and the IVE condition ($P < 0.001$). However, local skin temperatures of the female group were mostly higher in the IVE condition than those in the IE condition, except for those of the chest and waist. The differences between the IE and the IVE conditions of the belly were not statistically significant. Additionally, the wrist (inner), chest, belly, and waist demonstrated larger standard deviation differences between the IE and IVE conditions than other local skin temperatures, regardless of gender differences. Therefore, it was revealed that there is no difference in local skin temperatures between the IE and

Table 6
Two sample *T*-tests of local skin temperature (forehead) in IVE and IE.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IE	35.5	36.1	36.5	36.3	37.0	36.5	36.5	35.6	35.6	36.6	31.2	34.2	36.3	33.5	36.0	35.8
IVE	36.2	36.5	36.8	36.8	36.1	36.8	36.3	36.0	35.9	36.8	31.9	34.9	35.8	36.1	36.8	36.2
Delta	0.65	0.48	0.3	0.47	0.89	0.35	0.18	0.24	0.22	0.27	0.66	0.68	0.55	2.67	0.76	0.42
p-value	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	0.003*	P < 0.001*	P < 0.001*	P < 0.001*

*: Statistically significant.

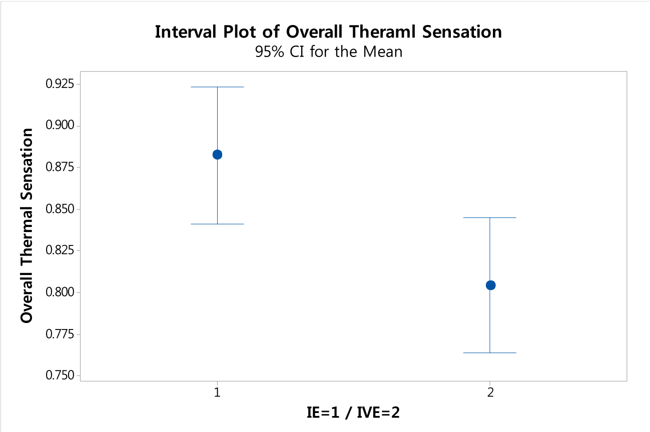

Fig. 9. Interval plot of overall thermal sensation difference in IE and IVE conditions.

Table 7
Two sample *T*-tests of local thermal sensations in IE and IVE conditions.

		Fore head	Arm	Wrist	Chest	Belly	Back	Neck
Avg.	IE	0.824	0.47	0.487	0.773	0.897	0.824	0.826
	IVE	0.850	0.61	0.72	0.730	0.863	0.80	0.756
Delta		0.026	0.14	0.233	0.043	0.034	0.024	0.07
p-value		0.309	0.000*	0.000*	0.060	0.163	0.358	0.005*
St.Dev.	IE	0.987	1.05	0.972	0.811	0.884	0.930	0.957
	IVE	0.974	1.08	1.09	0.956	0.999	1.00	0.979

IVE conditions in each gender group, respectively. There is, however, a clear difference in certain local skin temperatures in the gender groups.

Table 9 summaries overall thermal sensation differences by gender group. The average overall thermal sensation of the male group was higher than that of the female group. The standard deviation also showed that the variations of overall thermal sensations in the female group was larger than that in the male group. Considering the difference between the IE and the IVE condition, the overall thermal sensation of the male group in the IE condition was higher than that in the IVE condition with a significant *p*-value. However, the female group did not show a statistical difference for the overall thermal sensation between the IE and IVE conditions ($p > 0.005$). Therefore, it was evident that there are clear differences in the overall thermal sensations of the IE and the IVE condition for the male group, but the female group did not show any significant difference.

Table 10 demonstrates local thermal sensation differences by gender group. In the male group, most of the local thermal sensations were higher in the IE condition than that in the IVE condition, except for the wrist and belly. However, only the forehead, arm, chest, and back

Table 9
Two sample *T*-tests of overall thermal sensation by gender group.

Group	Condition	Avg.	St.Dev.	P-Value
Male	IE	1.08	1.01	0.005*
	IVE	0.99	1.04	
Female	IE	0.57	1.27	0.189
	IVE	0.50	1.23	

showed a statistically significant difference between the IE and the IVE condition ($p < 0.005$). The female group demonstrated the opposite results, in that most of the local thermal sensations in the IVE condition were higher than those in the IE condition. The forehead, arm, wrist, belly, and back showed significant differences ($p < 0.005$).

Additionally, every local skin temperature variation in the male group appeared larger in the IVE condition than it did in the IE condition, while a few local spots showed larger variations in thermal sensations at the forehead, back, and neck in the IE condition, than it did in the IVE condition in the female group. Therefore, it is clear that there is a difference in local thermal sensations in the IE and IVE conditions in each gender group. The variation in thermal sensations also demonstrates the difference in the gender groups.

4. Discussion

As discussed in the results, there were no significant differences between the IE and the IVE condition in terms of overall thermal sensations and local thermal sensations. However, there was a significant skin temperature difference on the core body area (chest, back and waist), and gender differences generated significant differences in the skin temperature as well as the overall and local thermal sensations. In this study, the ambient temperatures were controlled from 20 °C to 30 °C, which significantly affected each participant's thermal sensation. Therefore, the average indoor temperature and skin temperature differences between the IE and the IVE conditions were further analyzed at each overall thermal sensation level, and co-variation effects of local skin temperature were analyzed to identify the contribution of each local skin temperature to the overall thermal sensation in the IE and IVE conditions.

4.1. Indoor temperature and overall thermal sensation

The number of data sample at overall thermal sensation levels (OTS) −3, −2, and 3 were either not available for one condition (OTS: 3 and −2) or too small to be significant (OTS 3). Consequently, those were excluded from the analysis. Table 11 illustrates the results of two sample T-tests of the indoor temperature difference between the IE and the IVE conditions at each overall thermal sensation level. They reveal the gradual increase in the indoor temperature, when the overall

Table 8
Two sample *T*-tests of skin temperature by gender group.

		Fore head	Arm	Wrist Back	Wrist Inner	Chest	Belly	Waist	Back	Neck
Male Avg.	IE	35.39	34.12	33.91	34.20	34.82	34.99	34.78	34.40	34.27
	IVE	35.63	33.66	32.94	33.51	33.68	34.25	34.32	33.51	33.93
	Delta	−0.25	0.46	0.96	0.69	1.14	0.74	0.45	0.89	0.34
	p-value	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*	P < 0.001*
Female Avg.	IE	36.17	33.70	31.83	31.92	35.36	33.50	35.09	35.34	35.46
	IVE	36.39	33.89	32.70	33.66	34.86	33.71	33.38	34.79	35.65
	Delta	−0.22	−0.19	−0.86	−1.75	0.50	−0.20	1.71	0.54	−0.18
	p-value	P < 0.001*	0.002*	P < 0.001*	P < 0.001*	P < 0.001*	0.165	P < 0.001*	P < 0.001*	P < 0.001*
Male St.Dev.	IE	1.54	1.07	1.65	1.33	1.01	1.15	1.31	2.00	1.22
	IVE	1.66	1.70	2.77	2.46	3.07	2.74	2.38	2.97	1.76
Female St.Dev.	IE	0.59	1.24	2.58	2.76	0.59	2.17	1.94	0.46	0.61
	IVE	0.43	1.50	2.26	1.89	1.17	3.83	4.23	2.09	0.70

*: Statistically significant.

Table 10
Two sample *T*-tests of local thermal sensations by gender group.

		Fore head	Arm	Wrist	Chest	Belly	Back	Neck
Male Avg.	IE	0.906	0.779	0.680	0.825	0.846	0.909	0.797
	IVE	0.744	0.65	0.71	0.73	0.88	0.76	0.72
	Delta	0.162	0.149	0.030	0.095	0.034	0.149	0.077
	p-value	0.000*	0.000*	0.328	0.002*	0.347	0.000*	0.024
Female Avg.	IE	0.70	−0.02	0.181	0.691	0.976	0.691	0.872
	IVE	1.027	0.54	0.73	0.732	0.839	0.865	0.809
	Delta	0.327	0.56	0.549	0.041	0.137	0.174	0.063
	p-value	0.000*	0.000*	0.000*	0.216	0.000*	0.000*	0.110
Male St.dev.	IE	0.959	0.906	0.911	0.856	0.928	0.894	0.965
	IVE	0.965	1.04	1.07	1.00	1.04	1.03	1.00
Female St.dev.	IE	1.02	1.08	0.988	0.727	0.803	0.970	0.942
	IVE	0.963	1.14	1.11	0.874	0.933	0.950	0.940

* Statistically significant.

Table 11
Two Sample *T*-tests of indoor temperature at the overall TS level in the IE and IVE condition.

Overall TS Level	−1	0	1	2
IE	25.94	25.62	26.60	27.15
IVE	25.42	25.93	27.22	28.13
Delta	0.518	0.308	0.624	0.986
P-value	0.001*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*

thermal sensation changes from −1 to 2, and also shows the temperature difference between the IE and the IVE condition at each overall thermal sensation level. It is also clear that there is a significant difference at every overall thermal sensation level, although the difference at the OTS level 0 was too small to be significant statistically. When a participant's response was slightly cool (OTS: 1), the indoor temperature of the IE condition was higher than that of the IVE condition. However, the indoor temperature of the IVE condition appeared higher than that of the IE condition, when the overall thermal sensation level was at 0, 1, and 2. Although the indoor temperature difference at the OTS level 0 was too small to be significant, other level delta values

Table 12
Two Sample *T*-tests of Aggregated Local Skin Temperature at the same overall TS level in the IE and IVE condition.

		Overall TS Level			
Local Body Area	Condition	−1	0	1	2
Forehead	IE	35.1	35.6	35.6	35.8
	IVE	35.5	35.8	35.7	36.2
Delta		0.4	0.2	0.1	0.4
P-value		0.003*	0.007	0.098	$P < 0.001$*
Arm	IE	33.2	33.3	34.2	34.1
	IVE	33.6	33.0	33.3	34.1
Delta		0.4	0.3	0.9	–
P-value		$P < 0.001$*	0.010	$P < 0.001$*	0.865
Wrist (Back)	IE	32.6	33.2	33.3	32.9
	IVE	32.9	31.9	32.4	33.2
Delta		0.3	1.3	0.9	0.3
P-value		0.059	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*
Wrist (Inner)	IE	32.9	32.8	33.6	33.3
	IVE	33.9	32.8	33.0	34.4
Delta		1.0	–	0.6	1.1
P-value		$P < 0.001$*	0.973	$P < 0.001$*	$P < 0.001$*
Chest	IE	35.4	34.7	35.0	34.9
	IVE	34.1	33.2	33.7	34.9
Delta		1.3	1.5	1.3	–
P-value		$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	0.594
Belly	IE	34.2	34.4	34.5	33.7
	IVE	37.7	36.2	37.7	32.6
Delta		3.5	1.8	3.2	1.1
P-value		$P < 0.001$*	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*
Waist	IE	34.9	34.8	35.2	34.4
	IVE	34.6	34.1	33.3	34.0
Delta		0.3	0.7	1.9	0.4
P-value		0.082	$P < 0.001$*	$P < 0.001$*	0.005
Back	IE	34.6	34.9	34.4	34.8
	IVE	34.5	33.3	33.3	35.1
Delta		0.1	1.6	1.1	0.3
P-value		0.896	$P < 0.001$*	$P < 0.001$*	$P < 0.001$*
Neck	IE	34.7	34.4	34.8	34.6
	IVE	35.0	34.0	33.8	34.8
Delta		0.3	0.4	1.0	0.2
P-value		0.010	$P < 0.001$*	$P < 0.001$*	0.024

* Statistically significant.

Table 13
Cross-Validation results of Estimated OTS Accuracy by the local skin temperature.

#	IE Condition		IVE Condition	
	Factor	Accuracy (%)	Factor	Accuracy (%)
1	Waist	55.238	Wrist (Back)	56.221
2	Back	55.171	Waist	55.656
3	Chest	54.147	Wrist (front)	51.688
4	Wrist (Front)	54.041	Neck	51.555
5	Wrist (Back)	53.775	Belly	51.456
6	Fore head	52.145	Chest	51.191
7	Arm	49.884	Back	49.669
8	Belly	49.352	Arm	49.173
9	Neck	47.755	Fore head	44.408
10	Gender	34.253	Gender	33.322

were large enough, and *P*-values were statistically significant. Therefore, it was evident that overall thermal sensations become less sensitive in the IVE condition when the temperature is relatively warm.

4.2. Skin temperature and local thermal sensation

Overall thermal sensation has been studied as an integrated thermal sensation of the local body area [28–30]. Therefore, the local skin temperature difference between the IE and IVE condition at each overall thermal sensation level was further analyzed.

Table 12 demonstrates the results of two sample T-tests for local skin temperature in the IE and IVE conditions at each overall thermal sensation level. A belly showed clear differences between the IE and IVE condition at every overall thermal sensation level ($P < 0.001$), and the chest and wrist (inner) also revealed significant differences at three overall thermal sensation levels. Every local body segment showed significant temperature differences at OTS level 1, except for the forehead, the wrist (back), chest, belly, waist, and the back, which also showed a significant difference at the neutral OTS level (0).

On the other hand, the forehead did not show any significant difference, considering instrument accuracy (Delta < 0.5), while an arm and the neck demonstrated a significant difference only at the OTS level 1. Additionally, when a participant responded “warm (2)” or “slightly cool (−1)”, only a few local body segments that showed significant differences were the wrist (inner) and belly for “warm (2)” and the wrist (inner), chest, and belly for “slightly cool (−1)”. Therefore, it is evident that most local body skin temperatures are dependable for estimating OTS level 0 and 1 for both IE and IVE conditions. Specific local body skin temperatures are needed, however, to predict OTS levels −1 and −2 for either the IE or IVE condition.

4.3. 10-Fold cross validation analysis

Cross Validation is a technique to evaluate and compare predictive models by dividing the original sample into two sets; one to train and the other to evaluate [31]. To estimate and compare the overall thermal sensation in the IE and IVE condition by local skin temperature, a 10-Fold Cross Validation analysis was conducted.

Table 13 illustrates the estimated OTS accuracy of each factor in the IE and IVE condition in descending order. The waist and back showed the highest accuracy in the IE condition, while the wrist (back) and waist had the greatest influence on the overall thermal sensation in the IVE condition. Gender was the least accurate factor in both the IE and IVE condition. Therefore, it was determined that the accuracy of each factor was different, when predicting the overall thermal sensation and, also, that each factor exercised a different influence in the IE and IVE condition.

Table 14 illustrates the accuracy of the estimates of the overall thermal sensation by different combinations of factors. A combination of the factors (#10) reached the maximum 95.477% accuracy in the IE condition, when local body skin temperatures of the waist, back chest, wrist (front), and wrist (back) were combined. On the other hand, the accuracy reached the maximum at 95.731% in the IVE condition when all of the factors (local body skin temperatures and gender) were combined. However, multiple local skin temperatures may increase the error rate, as well as decrease the consistency. Additionally, the combination of three factors with high accuracy reached 92.883% in the IE condition and 93.746% in the IVE condition. Therefore, this procedure may be more effective than selecting every local skin temperature to measure and control thermal sensation differences in the IE and IVE condition.

5. Conclusions

This study investigated whether an IVE condition affects an occupant's environmental sensations and physiological responses to an ambient condition differently by comparing them to responses for a real environmental condition. It was concluded that there was a significant difference in skin temperature at a core body area (chest, back, and waist) between in the IVE and IE condition, when thermal conditions

Table 14
Cross-Validation results of Estimated OTS Accuracy by combined factors.

	#	Combination of Factors										Accuracy
IE	1	Waist										55.238
	2	Waist	Back									85.434
	3	Waist	Back	Chest								92.883
	4	Waist	Back	Chest	Wrist (Front)							94.546
	5	Waist	Back	Chest	Wrist (Front)	Wrist (Back)						95.477
	6	Waist	Back	Chest	Wrist (Front)	Wrist (Back)	Fore head					94.014
	7	Waist	Back	Chest	Wrist (Front)	Wrist (Back)	Fore head	Arm				95.111
	8	Waist	Back	Chest	Wrist (Front)	Wrist (Back)	Fore head	Arm	Belly			94.114
	9	Waist	Back	Chest	Wrist (Front)	Wrist (Back)	Fore head	Arm	Belly	Neck		94.313
	10	Waist	Back	Chest	Wrist (Front)	Wrist (Back)	Fore head	Arm	Belly	Neck	Gender	95.111
IVE	1	Wrist (Back)										56.221
	2	Wrist (Back)	Waist									90.106
	3	Wrist (Back)	Waist	Wrist (front)								93.746
	4	Wrist (Back)	Waist	Wrist (front)	Neck							94.706
	5	Wrist (Back)	Waist	Wrist (front)	Neck	Belly						95.301
	6	Wrist (Back)	Waist	Wrist (front)	Neck	Belly	Chest					95.301
	7	Wrist (Back)	Waist	Wrist (front)	Neck	Belly	Chest	Back				95.202
	8	Wrist (Back)	Waist	Wrist (front)	Neck	Belly	Chest	Back	Arm			95.698
	9	Wrist (Back)	Waist	Wrist (front)	Neck	Belly	Chest	Back	Arm	Fore head		95.433
	10	Wrist (Back)	Waist	Wrist (front)	Neck	Belly	Chest	Back	Arm	Fore head	Gender	95.731

were consistently maintained. This study also revealed that the overall thermal sensation did not show a statistically significant difference between the IE and IVE condition, and most local thermal sensations were not significantly different either. Also, a different gender generated significant differences in the IE and IVE conditions for the skin temperature and overall/local thermal sensation.

This study also revealed that the indoor temperatures between the IE and IVE conditions were statistically different at each thermal sensation level. Also, certain local body parts had different skin temperatures in the IE and the IVE conditions, depending on the overall thermal sensation level. Based on these findings, it can be concluded that the IVE condition could have an influence on thermal perception, as well as on the physiological responses of the human body, even when thermal conditions are the same. This conclusion is aligned with a few recent studies [32–35], which investigated the impact of a VR device on human psychology and physiology. The findings of this research can be used as technical evidence to create an accurate virtual reality environment, with regard to thermal perception and physiological responses of the human body.

In spite of the significant results of this research, a few limitations may have an effect. The sample sizes in this study should be larger for any future study. Although the 16 sample sizes still gave statistically significant results, larger sample sizes are required to increase the accuracy of the results of this study. Also, two participants reported motion sickness, due to the IVE condition, which would need to be considered in a future study [36]. This research used skin temperature as a physiological response for the ambient indoor temperature, as well as a possible stress index. Even though this study chose skin temperature to measure for estimating the stress of a participant, other physiological factors, such as body mass index (BMI), sweat, and hormone level, may possibly be a stress index, which indicates a need for further study. In addition, this study adopted a thermal range of 20 °C–30 °C as a conventional temperature range in a built environment, based on the previous building study. However, a wider range of thermal conditions (very cold and very hot) could help to verify a more significant pattern of physiological responses. Finally, additional human factors, such as age, ethnicity, thermal preference, and cultural background should be considered, as well as some psychological factors, such as aesthetic quality of the environmental setting and the familiarity to the IVE equipment.

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