INVESTIGATING THE ABILITY OF IMMERSIVE VIRTUAL ENVIRONMENTS TO FACILITATE OCCUPANT THERMAL STATE DATA COLLECTION INVOLVING FACE MASKS

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ABSTRACT: *This study examines the capability of an immersive virtual environment (IVE–based) experimental protocol to support occupant thermal state (sensation, acceptability, and comfort) data collection when participants wear face masks. Specifically, the goal is to see if there is a change in local thermal states due to face covering and would such a change affect overall thermal states. A between-subject experiment was conducted with fifty-four participants (27 masked; 27 unmasked) who were exposed to three-step temperatures (18.3ºC, 23.8ºC, and 29.4ºC) in a climate chamber under both cooling and heating sequences. In masked IVE experiments, participants donned a face mask and viewed the chamber's virtual model on a head-mounted display. In contrast, in unmasked IVE experiments, participants didn't use a face mask. Skin temperatures and overall/local thermal state responses were collected during the experiments. They were then statistically compared between masked IVE and unmasked IVE experiments. The results suggest that forehead temperature was significantly different under all step temperatures in the cooling sequence, with mean forehead temperature being larger in masked IVE than in unmasked IVE experiments. Furthermore, in masked IVE experiments, thermal sensation in the forehead, neck, and upper-back increased while the thermal acceptability in those same skin sites decreased, but this difference was not statistically significant. Also, in masked IVE experiments, the overall thermal sensation increased, whereas both the overall thermal acceptability and comfort decreased when compared with unmasked IVE experiments. Nonetheless, this difference was not statistically significant. To summarize, wearing a face mask didn't affect the participant's overall and local thermal states in IVEs, although few statistical differences were observed in skin temperatures.*

KEYWORDS: *Immersive virtual environment, thermal sensation, thermal comfort, thermal acceptability, face masks.*

1. INTRODUCTION

Immersive virtual environments (IVEs) are a technology that combines software and hardware systems to produce a virtual or simulated environment that arranges sensory input in a way that makes the user feel as though they are inside the virtual environment. With the help of this sensory input, the user becomes cognitively engaged and interacts with the elements of the virtual environment (Radianti et al., 2020). Head-mounted displays (HMD) are the most popular method to deliver IVEs because they are easy to set up and provide a wide field of stereoscopic vision. In a true 1:1 scaled setting, IVEs generally provide a favorable environment for sophisticated data collection methods, allowing researchers to effectively modify desired variables and test hypotheses at lower costs and shorter experimental times (Alamirah et al., 2022). As a result, IVEs are more frequently employed to research how occupant perception and satisfaction with the tested conditions are affected by changes in ambient conditions (such as lighting settings) (Heydarian et al., 2016). Specifically, IVEs are used to study the occupant's thermal states (thermal sensation, acceptability, and comfort) by incorporating thermal conditions through the use of closed environments like climate chambers (Rentala et al., 2021). Studies have also examined how well IVEs can simulate actual physical settings when evaluating users' comfort (Yeom et al., 2019). Other researchers used IVE to look at how people's perceptions of their indoor environment are influenced by psychological, physiological, and environmental factors (Chinazzo et al., 2020).

The general IVE experimental protocol for studying occupant thermal states usually consists of subjecting the participants to a building design in IVE while simultaneously manipulating environmental conditions such as operative temperatures, humidity, etc., in a test environment (e.g., climate chamber) and collecting their physiological (e.g., skin temperature, heart rate, etc.) and thermal perception responses (e.g., thermal sensation, acceptability, and comfort) (Alamirah et al., 2022). Normally, during these experiments, the participants do not wear any face coverings or face masks. However, there are certain situations where the IVE experiments must be performed with the participants wearing a face covering or a mask for health and safety purposes, such as during the COVID-19 pandemic. This mask-wearing presents new challenges for occupant thermal state experiments using IVEs. Face mask usage affects the respiratory system. It specifically interferes with breathing normally,

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causing some carbon dioxide to be expelled and some inhaled throughout each breathing cycle (Lazzarino et al., 2020). Moreover, wearing a mask will directly lower the amount of oxygen inhaled by the body and prevent heat transmission between the facial region and the environment (Hu et al., 2022). Also, when wearing an HMD, the participant's face is already covered, which can trap heat and cause discomfort (Mehrfard et al., 2019). Adding a face mask on top of this can exacerbate the heat buildup, affecting a person's overall thermal state. As a result, it is reasonable to assume that using a face mask during IVE experiments may significantly impact how participants' thermal sensation, acceptability, and comfort are evaluated, thereby impacting the validity of IVE experiments. Therefore, it is necessary to investigate the effect of using face masks on participants' thermal states in IVE experiments. In this study, human subject experiments were performed in IVE under three-step temperatures in a climate chamber with participants who wore face masks (referred to as masked IVE experiments) and participants who did not wear face masks (referred as unmasked IVE experiments). Local skin temperatures and both the overall and local thermal state responses were collected. We hypothesize that the local skin temperatures, local thermal states and overall thermal states between the masked IVE and unmasked IVE experiments will differ significantly. The results of this analysis would provide new insights into developing IVE experimental protocols for occupant thermal state research particularly regarding the mask use. That is, whether to modify the experimental protocol to account for mask wearing or continue using the existing one when face masks needed to be used during the experiments.

2. METHODOLOGY

2.1 Participants

This study was approved by the university's Institutional Review Board. A total of fifty-four participants were enlisted for this study. Half of the participants did the masked IVE experiments, and the other half did the unmasked IVE experiments. Participants in both experimental groups are divided roughly equally by gender and age, with 15 men and 12 women participating in masked IVE experiments with a mean age of 21.9 years and 14 men and 13 women participating in unmasked IVE experiments with a mean age of 22.3 years, respectively. This was done to ensure that gender and age would not affect the results when statistically comparing the two groups.

2.2 Immersive Virtual Environment

Both masked and unmasked IVE experiments were carried out inside a climate chamber that was located on the university's campus. An immersive virtual environment of the climate chamber was delivered via an HTC Vive head-mounted display device. The chamber's 3D model was produced with Autodesk 3ds Max. The model, together with the material textures and lightmaps, was loaded into Unreal Engine 4, as shown in Figure 1. The climate chamber offers space heating and cooling in an IVE experiment for measuring occupant thermal states. At the same time, the users observe the virtual world of the chamber interior via a head-mounted display (HMD).

Fig. 1: Climate chamber's virtual environment

2.3 Experiment Procedure

Between-subject experiments were conducted using the procedure outlined in Figure 2. After the participants signed the consent forms, they were given a demographics survey and were asked to arrive at the chamber in a specific set of clothing (clo of 0.5-0.6), which included trousers and a T-shirt or a long-sleeve shirt. After coming to the chamber, the participants were tested for cigarette or alcohol use using the pre-experiment screening survey in the chamber's resting area, where the temperature and relative humidity were set to 75ºF/23.8ºC and 50% RH, respectively. Participants were excluded from the study if they were found to have used cigarettes or alcohol. The screening took about 10 minutes to complete and allowed the participants to adjust to the chamber's temperature and lessen the impact of their previous thermal state. Then, the participants were asked to enter the chamber's testing area and have the skin temperature sensors (Vernier surface temperature sensors; accuracy: ± 0.5 °C, resolution: 0.1 °C) attached to their bodies at eight locations, i.e., forehead, neck, chest, upper back, forearm, hand, calf and foot.

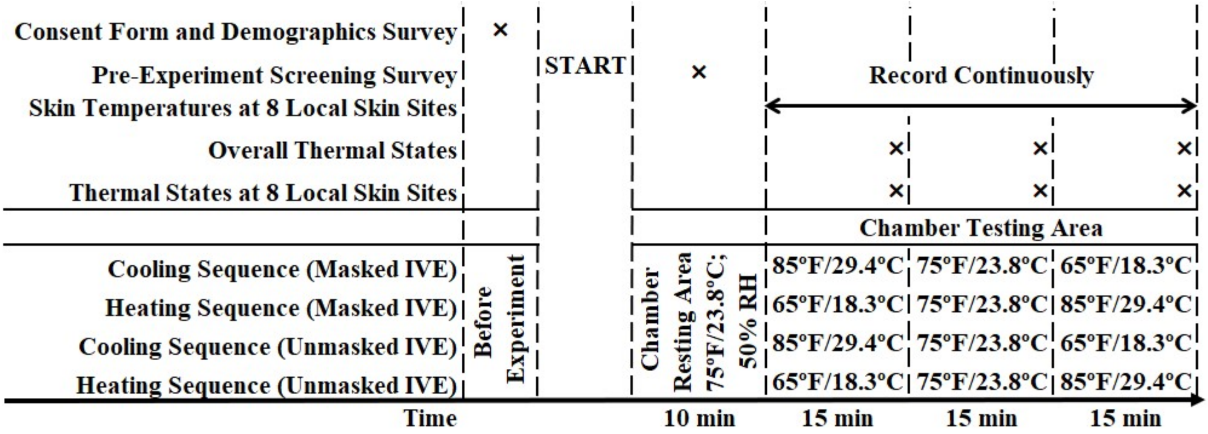

Fig. 2: Experiment procedure

Twenty-seven participants participated in masked IVE experiments, and another twenty-seven participants participated in unmasked IVE experiments. In masked IVE experiments, the participants wore a face mask that entirely covered the mouth and nose area and viewed the chamber's virtual model through the HTC Vive device, as shown in Fig. 3 (left). Whereas in unmasked IVE experiments, the participants only viewed the chamber's virtual model without wearing a face mask (Fig. 3 (right)). Also, both masked and unmasked IVE experiments consisted of cooling and heating sequences that were conducted at least two weeks apart. The cooling sequence had a decrease of three-step temperatures, i.e., 85ºF/29.4ºC –> 75ºF/23.8ºC –> 65ºF/18.3ºC and heating sequence had an increase of three-step temperatures, i.e., 65ºF/18.3ºC –> 75ºF/23.8ºC –> 85ºF/29.4ºC. So, overall there were four experimental sessions, i.e., (1) masked IVE in the cooling sequence, (2) masked IVE in the heating sequence, (3) unmasked IVE in the cooling sequence, (4) unmasked IVE in the heating sequence. The order of the four experimental sessions was random to reduce the order effect and was conducted with a set humidity of 55% RH and a CO_2 limit of 1,000 ppm. From the start of each trial until the end, the indoor control temperature around the participants (sensor placed at the height of 24 inches from the floor (ASHRAE, 2013)) and their skin temperatures were continuously recorded at one-second intervals. Following the stabilization of the indoor control temperature at each step temperature, the participants were subjected to that stabilized temperature for about 5 minutes, and then their overall and local thermal state votes were recorded. The thermal states included responses for thermal sensation, thermal acceptability, and thermal comfort. For local thermal states, only thermal sensation and thermal acceptability were recorded at the exact eight locations where the skin temperatures were sampled from. The ASHRAE Standard 55 Thermal Comfort seven-point scale was used to record overall and local thermal sensation (ASHRAE, 2013). In contrast, six-point scales were used to record the overall thermal comfort and overall/local thermal acceptability (Rentala et al., 2021).

Fig. 3: An experimental session with mask (left) vs. without mask (right).

2.4 Data Processing

After completing the experiments, the mean of the skin temperatures at eight sites and the indoor control temperature for each participant was calculated using the last five-minute data (i.e., data from when the control temperature stabilized to the end of the end thermal state surveys). This 5-minute averaged data was used for all statistical analyses. Furthermore, the mean indoor control temperature was statistically compared between masked IVE and unmasked IVE experiments under all step temperatures in both cooling and heating sequences to ensure that the indoor temperature was properly controlled and remained the same in both sets of experiments. A two-tailed independent sample T-test was used for comparisons. The tests revealed that the p-values in all the cases were not statistically significant ($p > 0.05$), indicating that the control temperature in the masked IVE experiments was comparable with unmasked IVE experiments.

3. RESULTS

Several statistical tests were performed to test the hypothesis that the local skin temperatures, local thermal states, and overall thermal states were significantly different between masked IVE and unmasked IVE experiments under all the step temperatures in both cooling and heating sequences. Independent sample T-tests were used to compare the skin temperatures collected at eight local sites. Wilcoxon Rank Sum tests were used to compare the local and overall thermal state responses. All statistical tests were performed at the significance threshold of 0.05.

3.1 Skin Temperature

Table 1 shows the results where the mean forehead temperature significantly differed ($p < 0.05$) between masked and unmasked IVE experiments under all step temperatures in the cooling sequence. Also, in the cooling sequence, the forehead temperature was higher in masked IVE than in unmasked IVE by an average of 0.5°C under all step temperatures. However, no significant differences in the forehead temperature were observed in the heating sequence under all the step temperatures, even though the forehead temperature under all step temperatures was higher in masked IVE than in unmasked IVE by an average of 1.06°C in the heating sequence. In addition, no significant differences were observed in skin temperatures at other sites (i.e., neck, chest, upper back, forearm, hand, calf, foot) between masked and unmasked IVE experiments under all step temperatures in both cooling and heating sequences. However, like forehead temperature, the neck, chest, upper back, forearm, hand, calf, and foot temperatures were higher in masked IVE than in unmasked IVE experiments by an average of 0.55°C, 0.57°C, 0.49°C, 0.66°C, 0.52°C, 0.48°C, 0.69°C under all step temperatures in both sequences.

Table 1: Independent sample T-test results of skin temperatures

Experiment sequences	Step Temperature	Skin Sites	Masked IVE		Unmasked IVE		p
			Mean (ºC)	SD	Mean (ºC)	SD	
Cooling	65 ºF/18.3 ºC	Forehead	36.75	0.43	36.13	0.71	0.001
	75 ºF/23.8 ºC	Forehead	36.7	0.45	36.17	0.58	0.001
	85 ºF/29.4 ºC	Forehead	36.49	0.41	35.99	0.49	0.001

3.2 Overall Thermal States

The mean overall thermal sensation votes were higher in masked IVE experiments than in unmasked IVE experiments by 0.44, 0.36, 0.4, 0.46, 0.27, and 0.38 (with an average of 0.38) in all step temperatures under both cooling and heating sequences (Fig. 4). This indicates that wearing a mask increases the overall sensation. Still, this increase was not statistically significant ($p > 0.05$) in all conditions. This result is corroborated by an earlier study in a climate chamber that did not use IVE (Yoshihara et al., 2021). On the other hand, in masked IVE experiments compared to unmasked IVE experiments, the mean overall thermal acceptability votes were lower by 0.28, 0.96, 0.72, 0.26, 0.58, and 0.04 (with an average of 0.47) across all step temperatures during both cooling and heating sequences (Fig. 5). Similarly, the mean overall thermal comfort votes were lower by 0.08, 1, 0.44, 0, 0.75, and 0.87 (with an average of 0.52) in masked IVE experiments when compared with unmasked IVE experiments across all step temperatures during both cooling and heating sequences (Fig. 6). These findings indicate that wearing a mask reduces the overall thermal acceptability and overall thermal comfort. However, similar to the results observed for overall thermal sensation, the decrease in overall thermal acceptability and thermal comfort was not statistically significant in all conditions. These results are consistent with an earlier study conducted in a non-IVE climate chamber (Zhang et al., 2021).

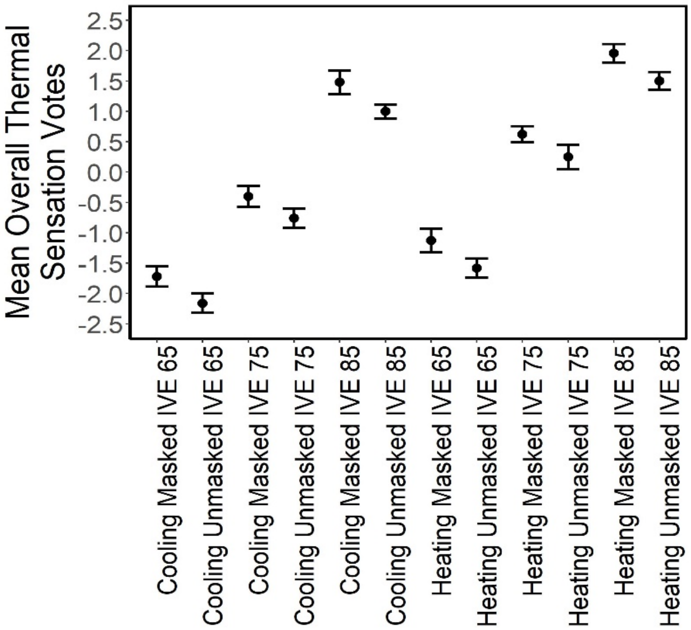

Fig. 4: Mean overall thermal sensation votes.

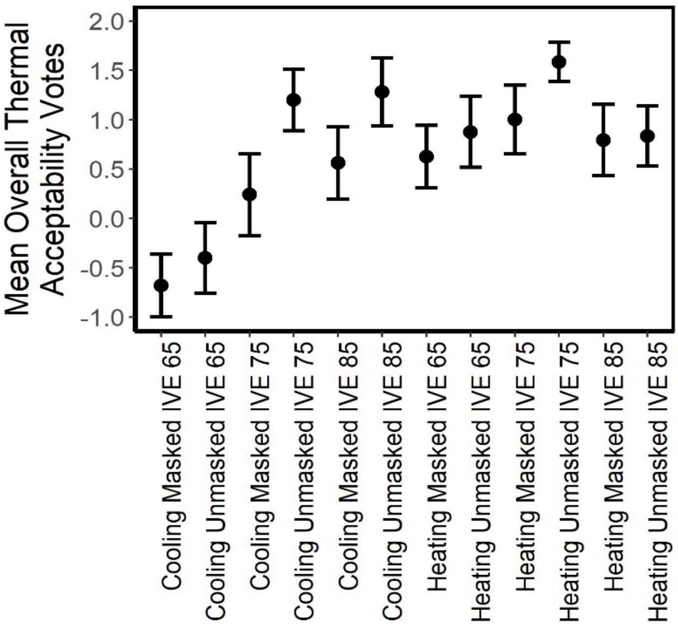

Fig. 5: Mean overall thermal acceptability votes.

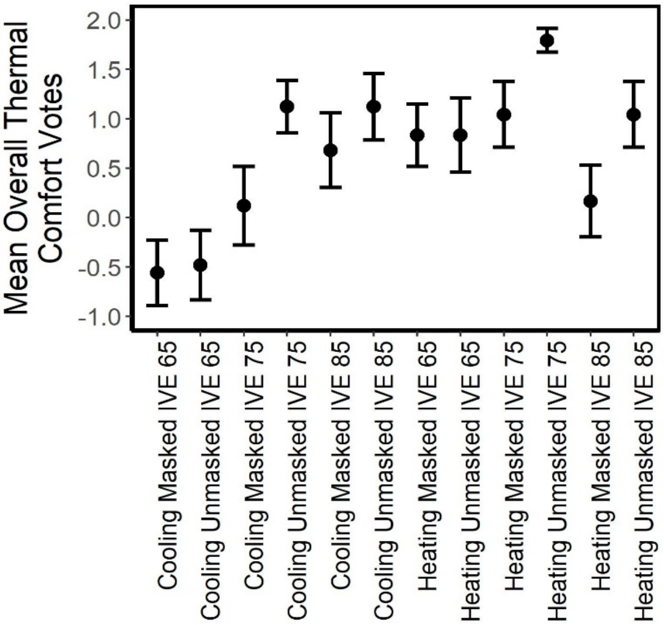

Fig. 6: Mean overall thermal comfort votes.

3.3 Local Thermal States

The thermal sensation and thermal acceptability at the eight local skin sites were also analyzed. The mean thermal sensation on the upper body, specifically at the forehead, neck, and upper back, increased by an average of 0.5, 0.18, and 0.24, respectively, in masked IVE when compared with unmasked IVE under all step temperatures in both cooling and heating sequences (Fig. 7). This finding is partially supported by a prior non-IVE study where they reported higher mean thermal sensations at only forehead and upper back (Tang et al., 2022). Also, the reason for the thermal sensation increase is that mask use can affect the frequency of breathing, leading to heat buildup around the face and neck area, causing the participants to feel warmer (Zhang et al., 2021). On the contrary, the thermal acceptability at those same three skin sites decreased by an average of 0.62, 0.23, and 0.16, respectively, in masked IVE when compared with unmasked IVE, under all step temperatures in both cooling and heating sequences (Fig. 8). However, the increase in thermal sensation and decrease in thermal acceptability at those three skin sites were not statistically significant ($p > 0.05$) in all step temperatures under both cooling and heating sequence even though the forehead temperature was statistically significant in the cooling sequence (Table 1). Similarly, thermal sensation and thermal acceptability at other skin sites (chest, forearm, hand, calf, and foot) were also not statistically significant ($p > 0.05$) between masked IVE and unmasked IVE experiments.

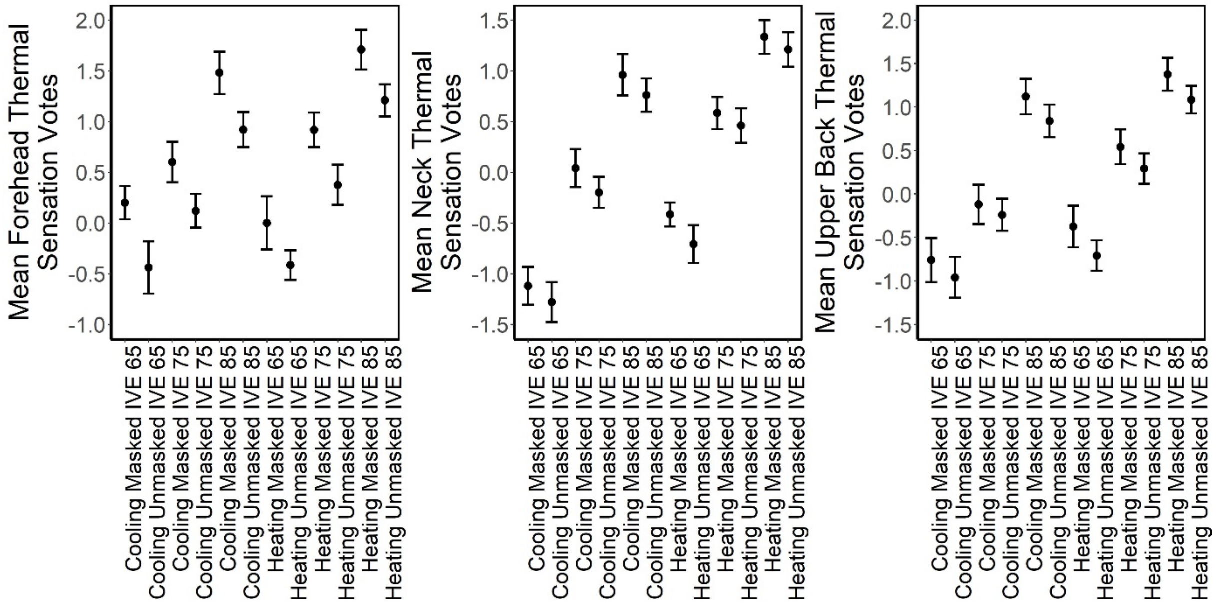

Fig. 7: (Left to right) Mean forehead, neck and upper back thermal sensation votes.

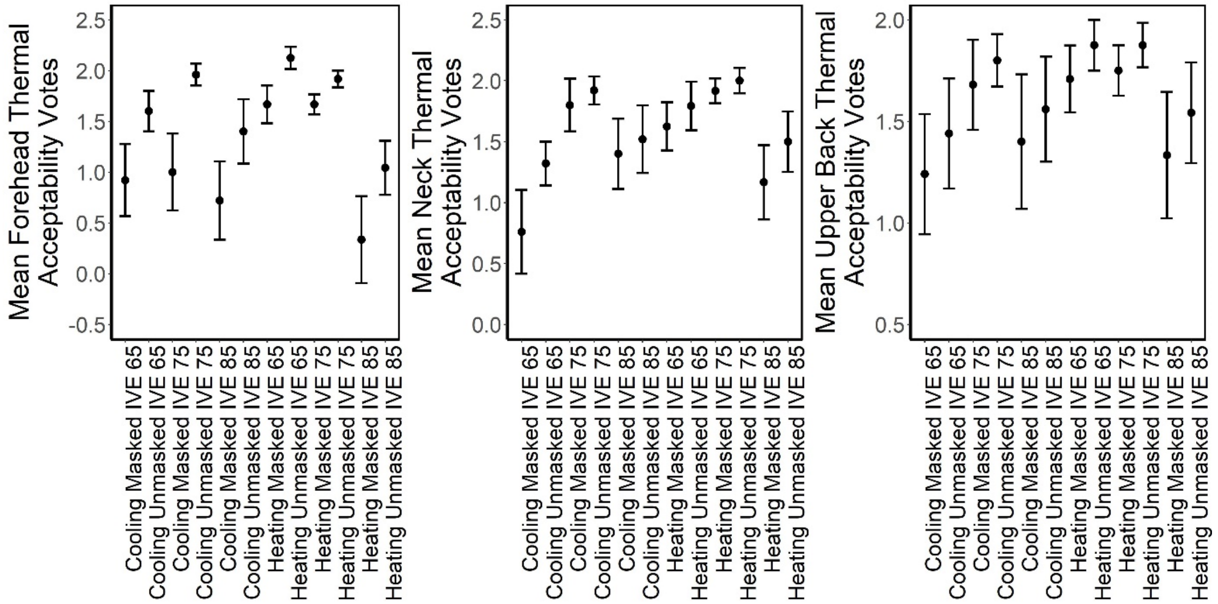

Fig. 8: (Left to right) Mean forehead, neck and upper back thermal acceptability votes.

4. CONCLUSIONS AND FUTURE STUDIES

The study shows that wearing a face covering or mask while performing IVE experiments did not significantly affect the participants' overall thermal states as well as their local thermal sensation and acceptability at the eight skin sites. In other words, an appropriately designed experimental approach can support IVE experiments involving face masks. This approach should include precisely regulating the indoor test environment (e.g., temperature and humidity), offering an adequately designed virtual environment that induces high immersion with minimal motion sickness, and closely monitoring the participants throughout the experiment to make sure the masks are fitted correctly and do not interfere with the experimental apparatus (e.g., sensors). Even though the results were not statistically significant, small differences were observed in the mean votes, such as higher overall thermal sensation and lower overall thermal acceptability and comfort in masked IVE compared to unmasked IVE experiments. Higher thermal sensation and lower thermal acceptability were observed at the forehead, neck, and upper back in masked IVE compared to unmasked IVE experiments. Furthermore, higher temperatures were observed at all eight skin sites in masked IVE than in unmasked IVE under all step temperatures in both sequences. But these results were not statistically significant except at the forehead in the cooling sequence. Also, the increase in forehead temperature did not affect the forehead sensation, acceptability, or overall thermal states. While the results are noteworthy, they may be affected by some limitations. Firstly, the sample size within both the masked and unmasked groups was relatively small (n = 27). Therefore, the lack of statistical significance in the results could be attributed to the small sample size. Future investigations should aim to explore the impact of face masks on the validity of the IVE experimental protocol using a larger sample size. Secondly, this study only accounted for indoor air temperature and skin temperature, and future research may extend its scope to incorporate other environmental and physiological factors, such as the impact of relative humidity, air velocity, skin electrodermal activity, and heart rates. Finally, future studies may test the validity of the IVE experimental protocol involving mask use in different outdoor temperature conditions or seasons.

5. ACKNOWLEDGEMENT

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