Sustained Effects of Avatars on Skin Temperature and Thermal Sensation in Virtual Reality

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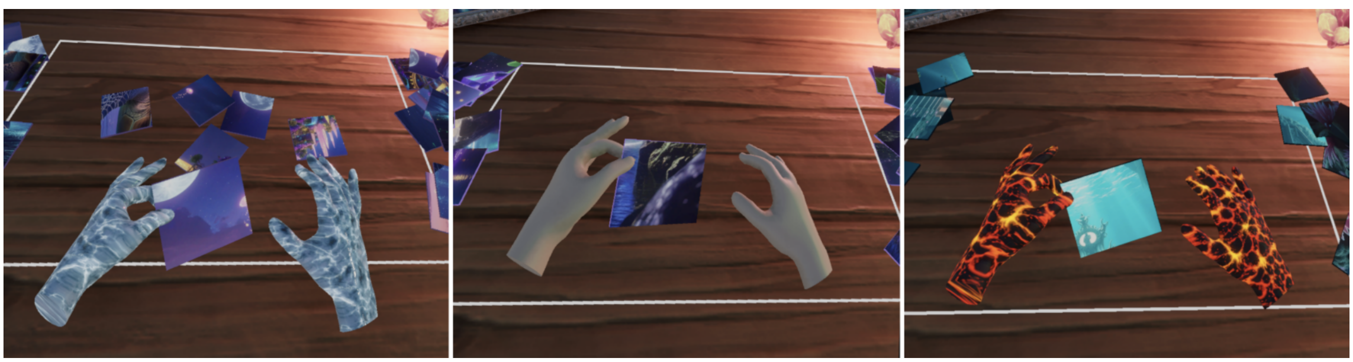

Figure 1: The ice, neutral, and fire virtual hands (from left to right) during the puzzle task in VR.

Abstract

Perceived temperature and thermoregulation are not only influenced by actual temperature but also by visual perception. For instance, the hue-heat hypothesis posits that warm-colored lighting can increase perceived temperature. Recent work indicates that embodying avatars with visual cues suggesting extreme temperatures influences thermal perception and thermoregulation. However, recent work is limited by short exposure times, inconsistent temperature effects, and the absence of a baseline comparison. Thus, we conducted a study where participants embodied ice, neutral, and fire hands in virtual reality for 15 minutes. We show that thermal sensation is significantly higher with fire hands compared to ice hands, but found no consistent effects on skin temperature. As the effects on thermal sensation remain consistent at least over 15 minutes, we conclude that avatars' appearance can be used to systematically influence users' thermal perception.

CCS Concepts

• **Human-centered computing → Virtual reality**.

Keywords

virtual reality, thermal perception, thermal comfort, skin temperature, hue-heat hypothesis

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1 Introduction

A large body of work shows that temperature plays a vital role when performing a large number of tasks. It is, for example, generally agreed that there is a connection between thermoregulation and human performance. In a meta-analysis, Hancock et al. assessed the effect of hot and cold thermal stressors on performance [15]. They revealed that the effect size for heat was comparable to that for cold and that performance degraded, especially for psychomotor and perceptual tasks. Previous work also showed that the room temperature affects office work [39], the environment's temperature affects physical performance [13], and that ambient temperature affects the probability of injuries [32]. Previous work also tried to isolate the effect of subjective temperature perception from the ambient temperature. Ahmed et al. suggests that thermal sensations affects cognitive performance [1] even if the ambient environment remains constant. Inducing different temperature sensations by applying a heating pad to participants' back, Van Cutsem et al. found, that subjective thermal strain is an important and independent mediator of the heat-induced impairment in endurance performance [45].

Already in 1926, Mogensen and English suggested that thermal percepetion is malleable [28] and proposed what was later coined the hue-heat hypothesis [5]. The hypothesis, according to Bennett and Rey, posits that an environment with red lighting feels warm and one with blue lighting feels cool [5]. Although the hue-heat hypothesis has been debated for almost a century [50], work from the last decades consistently confirms it (e.g. [12, 26, 46, 50]). Reviewing 31 experiments, Mayes et al., for example, conclude that visual cues, such as lighting with warm or cold color temperatures, can significantly alter thermal perception [26]. Previous work also revealed effects of the visual environment on humans' physiological response. For instance, te Kulve et al. [43] showed that lighting with a cooler color temperature caused more self-reported shivering. Comparing lighting with three color temperatures, Yasukouchi et al. revealed significant effects of color temperature on skin temperature [49]. Takakora et al. showed videos containing hot, cold, or no scenery to participants and revealed significant effects on skin temperature [40, 41].

Kocur et al. used virtual reality (VR) to immerse participants in a hot or cold scene while embodying them in a hot or cold avatar [21, 22]. The authors demonstrated that being in a fire world or having fire hands increases the perceived temperature, while being in an ice world or having ice hands decreases it. Results also suggest that having fire hands decreases and ice hands increase the hand temperature. The effects of the embodied avatar are in contrast to previous work. Kocur et al., for example, claim that hot-looking avatars decrease skin temperature but Takakora et al. showed that hot-looking scenes increase skin temperature [40, 41]. Furthermore, previous work suggests that the mere embodiment of artificial limbs, such as a rubber hand [19, 23, 29, 34], can affect skin temperature. Thus, results by Kocur et al. [22] are not only surprising but even if correct, there are alternative explanations that cannot be ruled out due to a lack of a control condition. Embodying any avatar, for example, might affect skin temperature and thermal perception in general independently of the suggested temperature. This change might just be more pronounced for one type of avatar than for the other.

Building on prior work by Kocur et al. [22], we address two open questions: whether thermal effects persist during sustained exposure and how they compare to a neutral control condition. By extending embodiment time to 15 minutes, our study investigates longer-term impacts on thermal perception and thermoregulation, which have not been examined before. Supporting previous work, we found that thermal sensation is significantly higher with fire hands compared to ice hands. However, we found no consistent effects on skin temperature. We conclude that avatars' appearance can be used to systematically influence users' thermal perception. Thus, avatars can be used by designers and developers to influence the perceived temperature without changing the ambient temperature.

2 Related Work

Our work builds on a body of research demonstrating that thermal cues represented by the environment or avatars can influence thermal perception and body temperature regulation. We begin by summarizing previous work on thermal comfort and the mechanisms of body temperature regulation. We then review research on the hue-heat hypothesis, which explores how color temperature affects thermal perception and regulation. Finally, we cover prior work on thermal effects in immersive environments.

2.1 Physiological and Psychological Modulators of Thermoregulation

The human body works like a thermostat that constantly checks how warm or cold we are and then acts to keep us close to 37 °C. Signals from the skin and from deep inside the body travel to temperature-sensitive cells in the brain, which in turn adjust blood flow, sweating, shivering, and heat-making brown fat [42]. Regarding skin blood flow, vessels open wide when we overheat so that extra blood can lose heat at the surface, and they tighten when we cool down to hold heat inside [6]. If this tightening and opening system weakens, because of age or nerve problems, people struggle to remain comfortable. Non-shivering heat comes from brown adipose tissue, a "good fat" that burns calories when we get cold or eat certain spicy foods. Imaging studies show that most adults still have active brown fat and that it helps them warm up without shivering [35].

Internal timing and chemistry also shift body temperature even when the room temperature stays the same. Core temperature follows a 24-hour rhythm. The core temperature is lowest a few hours before waking and peaks late in the afternoon [33]. In women, hormones change the baseline as well—progesterone raises resting temperature by roughly half a degree after ovulation, whereas oestrogen has a mild cooling effect [2]. Strong emotions can push the set-point even more. Some patients develop "psychogenic fever", reaching over 40 °C during intense stress. This rise does not respond to common fever medicine but drops with anti-anxiety drugs, pointing to a brain-driven cause rather than infection [31]. Motion sickness shows the opposite pattern: seasick travellers often look pale, sweat, and actually cool down, a coordinated response that widens vessels and slows heat production [30].

Feelings such as fear, anger, or joy leave rapid fingerprints on skin temperature. Classic lab work found that acting out anger warms the fingertips, while re-living fear cools them—proof that different emotions trigger different nerve patterns, not just "more arousal" [10]. Modern infrared cameras confirm and extend this idea. Within seconds of a stressful event, the nose and area around the eyes cool because sympathetic nerves squeeze small vessels and pleasant engagement can instead warm the cheeks [18]. The size of these changes is not random. People who score high on empathy, for instance, show stronger cooling when they watch someone else in pain [37]. Together, these studies show that skin temperature is a sensitive window into cognitive and emotional state and not just a passive read-out of the thermostat.

2.2 Visual Influences on Thermal Perception

Color is a fast-acting thermal cue. Classic climate-chamber work showed that people sitting under red light preferred a slightly lower thermostat setting than those under blue light, even though the air temperature was identical [12]. Newer studies found larger perceptual shifts: warm-hued LED lighting made a neutral room feel noticeably hotter, whereas cool-blue lighting created an immediate chill [44]. Color can even bias touch. When participants handled cylinders painted red or blue, the "red" cylinders had to be physically warmer to feel the same as the "blue" ones; tinting the participant's own hand flipped the bias, showing that the visual system flexibly combines surface and body color with skin input when judging warmth [16]. Together, this work demonstrates that small, low-energy changes to ambient or object color can raise or lower perceived temperature without touching the thermostat.

Visual content that signals climate pushes the effect further. Participants who watched looping videos of deserts versus snowfields showed measurable changes in both core and skin temperature, mirroring the "story" told by the footage [40, 41]. Social imagery matters too. Simply seeing another person plunge a hand into ice water made viewers feel colder themselves and lowered their own hand temperature—a phenomenon dubbed "temperature contagion" [9]. These findings suggest that the brain uses rich visual context—place, weather, and social cues—to predict thermal state and tune bodily responses before any physical change occurs. Designers can therefore shape comfort by curating the scenes people look at, even on an ordinary screen.

2.3 Thermal Effects in Virtual Reality

Researchers and designers can leverage VR technology to learn more about the cognitive process underlying thermal perception and thermoregulation. Chinazzo et al. [7] showed that the presence of colored light in a virtual room influenced thermal perception despite a constant environmental temperature. Huang et al. [17] revealed that a red room in VR was perceived as warmer and more comfortable compared to a blue room. Hence, The authors conclude that ambient lighting showing warm or cold colors can influence thermal comfort. Similar findings could be replicated in other studies [8, 36] showing effects of lighting conditions on thermal assessments. While not investigating thermal effects, previous work also found effects of sweating avatars on users' perception of effort [20] and physiological responses [14] during physical activity.

Kocur et al. [22] showed that a virtual environment presenting extreme thermal conditions influences thermal comfort. The authors found that users felt warmer while being immersed in a fire world compared to an ice world. Findings also suggest that it is not only the virtual environment that influences thermal perception. Kocur et al. [22] also found that embodying a fire avatar make participants feel warmer than an ice avatar. Interestingly, fire avatars also decrease skin temperature compared to an ice avatar that resulted in elevated skin temperature responses. Those findings are in line with Takakura et al. [40] who also showed body temperature changes by exposing participants to video images presenting different thermal environments. Accordingly, prior research showed that being exposed to a perceived warm environment or elements like flame and smoke overlay [48] can change skin conductance, heart rate, and heart rate variability [47].

While findings suggest that thermal cues presented by a virtual environment or the avatar can not only influence thermal perception but also a body's thermoregulation, little is known about how to systematically influence thermal comfort and users' physiological response using VR. Considering the effects from previous work, particularly the effects on skin temperature appeared to increase throughout the exposure time. Kocur et al. [22], for example, could show effects while embodying the avatar for five minutes in total. While it seems likely that the effects continue to increase beyond the used exposure time, it is unknown how they evolve over a longer period of embodiment time.

2.4 Summary

Previous work showed that the visual appearance of the environment influences thermal perception and thermoregulation [40, 41, 47, 48]. Recent investigations also show that virtual avatars representing extreme thermal conditions, e.g., fire or ice avatars [22], or avatars displaying different emotions [25], affect users' thermal perception and skin temperature while embodying them in VR. While it is not only important to aim to replicate the findings to learn more about the robustness of the effects, Kocur et al. [22] only embodied participants in those avatars for five minutes in total. Due to this short exposure time and the lack of a control condition, it is unknown how the thermal effects evolve over longer periods of embodiment time. Understanding longer-term effects and compare it to a control condition is important for designers and researchers of avatars and immersive applications to learn if and how thermal cues can be leveraged for improving thermal comfort and the general user experience.

3 Method

According to previous work, it is unclear how users' skin temperature and subjective temperature perception develop when embodying avatars that suggest different temperatures for more than five minutes. More importantly, the effects compared to a control condition is also unclear. Thus, we conducted a study to investigate the longer-term effects of virtual hands on thermoregulation and thermal perception compared to a control condition.

Figure 2: Participant (left), the virtual environment (center), and the *neutral* hands while interacting with the VAS scale for assessing thermal perception (right).

3.1 Study Design

We conducted a controlled experiment using a within-participants design with the independent variable Hands consisting of three levels: *ice*, *neutral*, and *fire*. Hence, participants embodied avatar hands in VR that consisted of a ice or fire shader or were simply colored grey (see Figure 1). The shaders and textures for these ice[1] and fire[2] hands were procured from the Unity Asset Store. To eliminate potential sequence or carryover effects, the order of the three conditions was counterbalanced using a balanced Latin-square design.

3.2 Measures

During the study, we took multiple dependent variables. We measured participants' skin temperature on the back of their hands, their subjective thermal perception, and the level of presence. Additionally, we controlled for participants' head movements, performance, and the room temperature.

3.2.1 Skin Temperature. In line with previous work [22], we continuously recorded participants' skin temperature (°C) every second on the back of their left and right hand using two type-t thermocouple sensors on each hand. We averaged the four temperature values (two per hand) at each time point to yield a single temperature value per participant. To control for individual baselines, each participant's first temperature reading, at the start of each condition, was subtracted from the subsequent values.

3.2.2 Thermal Sensation and Comfort. To assess participants' thermal perception, we measured subjective thermal sensation and thermal comfort. To assess subjective thermal comfort, we used the Bedford Thermal Scale [3, 4]. Participants were asked to rate their thermal comfort on a 7-point Likert scale ranging from "much too cold" (-3) to "much too warm" (+3). Participants provided their assessments of thermal comfort on paper once per condition, immediately after leaving the virtual environment.

To assess subjective thermal sensation, we used the thermal sensation scale [24]. The scale consists of a single item ("How do you feel at this time?") with responses on the visual analogue scale (VAS) ranging from very cold to very hot (see Figure 2). Thermal sensation was measured every five minutes within the virtual environment.

[1]https://assetstore.unity.com/packages/vfx/shaders/ice-world-83543
[2]https://assetstore.unity.com/packages/2d/textures-materials/stylized-lavamaterials-180943

3.2.3 Presence. We utilized the Igroup Presence Questionnaire (IPQ) [38] to determine the subjective experience of presence in the virtual environment. The questionnaire consists of the dimensions general presence, spatial presence, involvement, and experienced realism. The dimension of general presence measures the overall experience of presence in the virtual world. Spatial presence, on the other hand, is defined as the sensation of being physically present in the virtual environment and the ability to interact with it. The dimension of involvement describes the level of attention and cognitive engagement a person experiences in the virtual world. Finally, the last dimension, experienced realism, refers to the subjective perception of the realism of the virtual environment. Participants filled out the IPQ questionnaire on paper after each condition.

3.2.4 Control Measures. In line with previous work [22], we determined participants' head movements to assess and control for behavioral changes induced by the visual appearance of the avatars. Thus, we recorded participants' head movement using the 3D position and rotation of the VR headset. We calculated the total x, y and z translation, as well as the total pitch, yaw, and roll rotation of the VR headset by summing up all translations and rotations.

We determined participants performance when completing the puzzle to ensure that task performance is similar throughout the three conditions. To ensure that the temperature of the room also does not influence the results, we continuously determined the room temperature. We used the same type-t thermocouple sensors as for the skin temperature.

3.3 Task

When designing the task, our goal was to create an immersive experience that engages the participants during the 15-minute session per condition. The task should also encourage participants to look at their hands, and their physical activity should remain low to avoid confounding influences of physical activity. Thus, we designed a puzzle task to keep participants engaged in the virtual environment throughout the three conditions. Puzzle games are a common type of VR game[3,4].

During the study, participants were placed in a virtual room in front of a table on which the puzzle pieces were randomly distributed (see Figure 1). On the front left of the table was a picture in a frame that displayed the completed puzzle as a preview image. This

[3]https://www.meta.com/en-gb/experiences/jigsaw-360/3612759222125528/
[4]https://horizon.meta.com/world/10159399877996502

served as an aid for the participants by illustrating how the puzzle pieces should be placed. In the middle of the table was a frame in which the puzzle pieces had to be correctly rotated and positioned. The puzzle pieces were picked up and rotated using a pinch gesture. When a puzzle piece was successfully placed, it snapped into place in the frame. After completing a puzzle, a fireworks animation appeared, and the next puzzle started automatically.

We used hand tracking to make the interaction more natural compared to using controllers. We used no sounds or background music to reduce possible confounders. The puzzles featured fantasy motifs to fit the fantasy-style virtual environment. We created 19 images using Leonardo.Ai4[5], an AI-based image generation tool. Participants solved the puzzles in the same fixed sequence. Because the three experimental conditions were counterbalanced across participants, any potential influence of specific puzzle images was evenly distributed across conditions.

To assess whether image color temperature could have influenced the results, we computed the correlated color temperature (CCT) from the average linear RGB color of each image after masking dark, clipped, and highly saturated pixels. CIE 1931 chromaticities were derived and converted to CCT using McCamy's cubic approximation [27]. Across all puzzle images, we obtained $M = 7387$ K, $SD = 3570.95$ K. The high variance in CCT values indicates that both warm and cool images were present in all conditions, suggesting that any potential influence of image color temperature on the results was likely balanced across groups.

3.4 Apparatus

We conducted the study in our VR laboratory. During the experiment, participants were seated on an office chair at a table (see Figure 2). To display the VR scene, we used a Meta Quest 3 headset. The headset possesses a horizontal field of view measuring 110°, accompanied by a resolution of 2064x2208 pixels per eye and a refresh rate of 120 Hz. We used the headset's hand-tracking to enable participants to interact in the VR environment.

We implemented the game using the Unity game engine (version 6000.0.26f1). We created the fantasy-themed virtual environment using the Alchemy Lab Props package 5[6] from the Unity Asset Store, ensured that burning and icy hands do not appear out of place. We used the same 3D models and shaders for the virtual hands that were used in previous work by Kocur et al. [22]. The scene was designed using global illumination and anti-aliasing. The target frame rate was set at 90 frames per second to ensure a smooth and consistent experience. To characterize the visual appearance of the virtual environment, we also assessed its average color temperature using the same analysis procedure applied to the puzzle images. Across three representative screenshots, the mean correlated color temperature was 3574.33 K, indicating a comparatively warm overall color tone. The values varied only slightly across views.

We measured participants' skin temperature using a professional thermometer module (TC-08 8-Channel USB Thermocouple Data Acquisition Module, Omega Engineering, USA). The device channels were connected to the five thermocouples (insulated thermocouple with connectors: 5SRTC-TT-TI-20-2M, Omega, USA). We attached two thermocouples to each of the participants' left and right hands using medical tape. We used an additional thermocouple to record the room temperature during the experiment.

3.5 Procedure

After welcoming the participants, we explained the general procedure of the study. Afterwards, they were asked to read and sign the informed consent form and complete a demographic questionnaire. Because outdoor temperatures were relatively low during data collection, participants were asked to wash their hands with warm water to ensure acclimation before starting the VR conditions. We cleaned the backs of participants' hands with disinfectant and attached two thermocouples to each hand with medical tape. We introduced participants to the system and the gameplay. They were then able to test the game mechanics in a short tutorial. The puzzle of the tutorial consisted of only four puzzle pieces. The same picture was always used for the tutorial. Participants were asked to grasp, rotate, and place individual puzzle pieces. They were also asked to practice grabbing different puzzle pieces from a distance. After completing the puzzle, the remaining questions were clarified, and the participant was informed that the study would then begin.

After completing the tutorial, participants went through the three conditions in a counterbalanced order. In each condition, participants were asked to solve puzzles comprising 40 pieces, each featuring a distinct motif. When a puzzle was completed, a new puzzle was automatically displayed, and participants were asked to continue. They were shown the question of the Thermal Sensation Scale [24] three times after every 5 minutes (see Figure 2). At the end of the 15 minutes and the last questionnaire, the participants were asked to take off the VR glasses via a dialog in the virtual world. They then completed the Bedford Thermal Scale [3] and the IPQ [38] on paper. We ensured that participants had a 5-minute break between conditions and used this time to check on their well-being and that the thermometers were still attached correctly. In total, participation in the study took about 75 minutes.

3.6 Participants

We recruited a total of 26 participants for the study. As the temperature measurement was incomplete for two participants, their data were excluded from the analysis. We ensured that the 24 remaining participants (14 female, 10 male) fulfilled the balanced Latin Square Design for the sequence of hand conditions. Participants were recruited through a call on our institution's forum for recruiting participants and through personal networks. The 24 participants were between 20 and 30 years old ($M = 24.52$, $SD = 2.92$); 22 were students, and two were not enrolled in a university. Two were left-handed, 22 right-handed.

Participants rated their experience with VR applications on a scale from 1 (very inexperienced) to 7 (very experienced). Eight participants rated their experience as 1, seven as 2, four as 3, two as 4, two as 5, and one as 7. Regarding medication use, 21 participants reported taking no medication before the study, while three indicated taking medication unrelated to the study. Eight participants

[5]https://leonardo.ai/

[6]https://assetstore.unity.com/packages/3d/props/furniture/alchemy-lab-props-41758

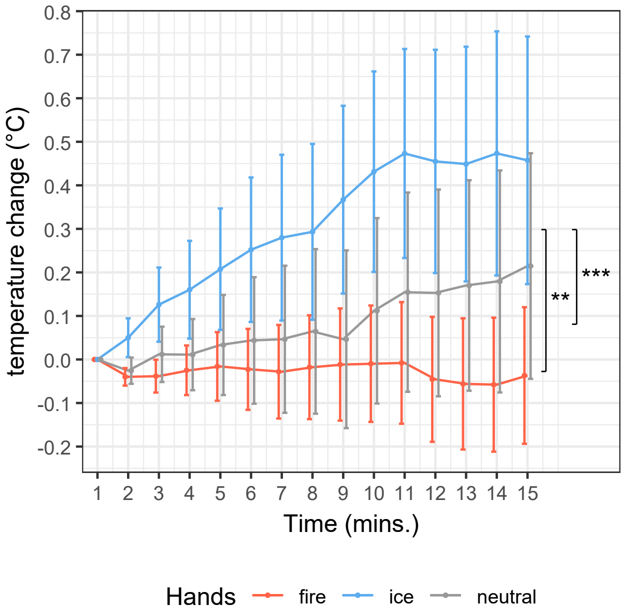

Figure 3: Line plot of the mean temperature change for each HANDS condition, with error bars representing the standard error (SE) of the mean.

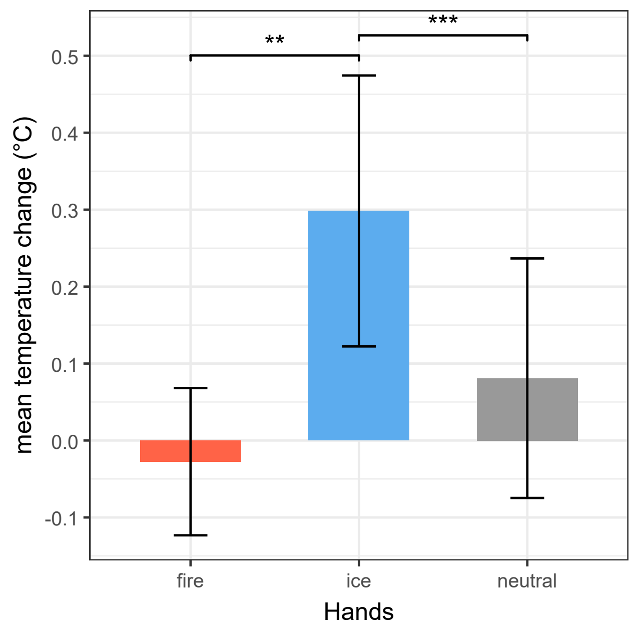

Figure 4: The bar chart summarizes mean hand temperature changes aggregated over all time points. Error bars show the SE of the mean.

received course credits as compensation, while the rest participated voluntarily. Participants were informed that they could withdraw from the study at any time without consequences.

4 Results

The collected measures were subjected to a normality check using the Shapiro-Wilk test. In cases of significant deviation from normality ($p < .05$), variables meeting the assumption of normality were analyzed with a parametric repeated measures analysis of variance (RM-ANOVA). For variables violating normality, a non-parametric ANOVA based on the Aligned Rank Transform (ART) was conducted using the `ARTool`[7] package for R [11].

4.1 Skin Temperature

Hand temperature measures significantly deviated from normality across all conditions ($p < .001$). While the distribution for the *fire* condition remained approximately normal across all time points ($p > .15$), both the *ice* and *neutral* conditions showed strong and consistent violations from minute 2 onwards. An ART-based RM-ANOVA revealed a significant main effect of HANDS, $F(2, 943) = 18.182$, $p < .001$, indicating that hand temperature differed between the avatar temperature conditions. Neither the main effect of TIME, $F(13, 943) = 0.11$, $p = .999$, nor the interaction between HANDS and TIME, $F(26, 943) = 0.391$, $p = .998$, reached significance. These results suggest that while avatar condition had a consistent influence on participants' hand temperature, this effect did not vary across the 15-minute exposure period. Additional pairwise Wilcoxon signed-rank tests (Bonferroni corrected) confirmed these results. Hand temperature was significantly higher in the *ice* condition compared to the *fire* condition ($p = .003$) and the *neutral* condition ($p < .001$), whereas no significant difference was found between *fire* and *neutral* ($p = 1.000$). To assess the relationship between *room* and *hand temperature*, a Spearman rank correlation was computed. Although the correlation between the variables was statistically significant ($\rho = .162$, $p < .001$), the effect size was small, indicating only a weak positive association between the two temperature measures. Given the large number of observations, even weak associations may reach significance without representing a meaningful relationship. Figure 3 shows the participants mean temperature over time. Aggregated hand temperature changes are shown in Figure 4.

4.2 Thermal Sensation

To assess the effect of virtual hand condition and exposure duration on participants' thermal sensation, we conducted a two-way repeated-measures ANOVA with the within-subject factors HANDS (*fire*, *ice*, *neutral*) and TIME (5, 10, 15 minutes). Mauchly's test indicated that the assumption of sphericity was met for the main effects of HANDS ($W = 0.959$, $p = .634$) and TIME ($W = 0.945$, $p = .535$), but violated for the interaction term ($W = 0.227$, $p < .001$). Therefore, Greenhouse–Geisser corrected values were used for the interaction. The analysis revealed a significant main effect of HANDS, $F(2, 46) = 5.50$, $p = .007$, $\eta_p^2 = .193$. There was also a significant main effect of TIME, $F(2, 46) = 4.18$, $p = .021$, $\eta_p^2 = .154$, suggesting a change in perceived temperature over time. The interaction between HANDS and TIME was not significant, $F(2.60, 59.85) = 0.13$,

[7] https://cran.r-project.org/package=ART

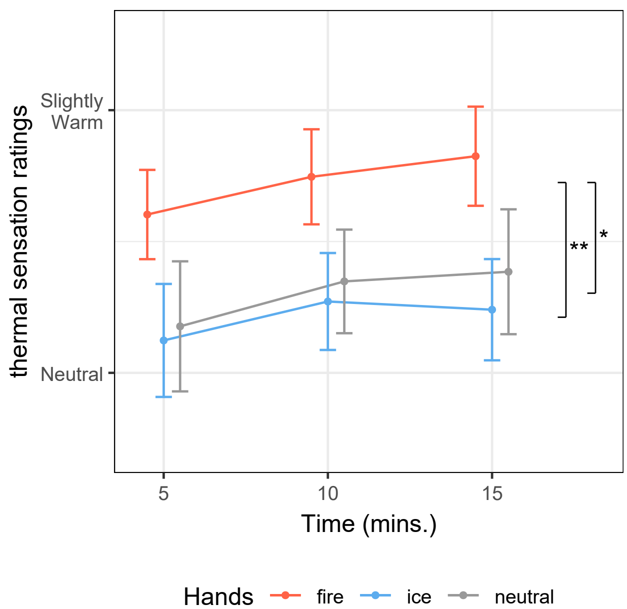

Figure 5: Mean thermal sensation ratings across time for each hand condition. The *fire* condition shows consistently higher ratings than the *neutral* and *ice* conditions, indicating increased thermal perception. Ratings in the *ice* condition remain lowest and relatively stable across all time points despite a main effect of TIME. All error bars represent the SE of the mean.

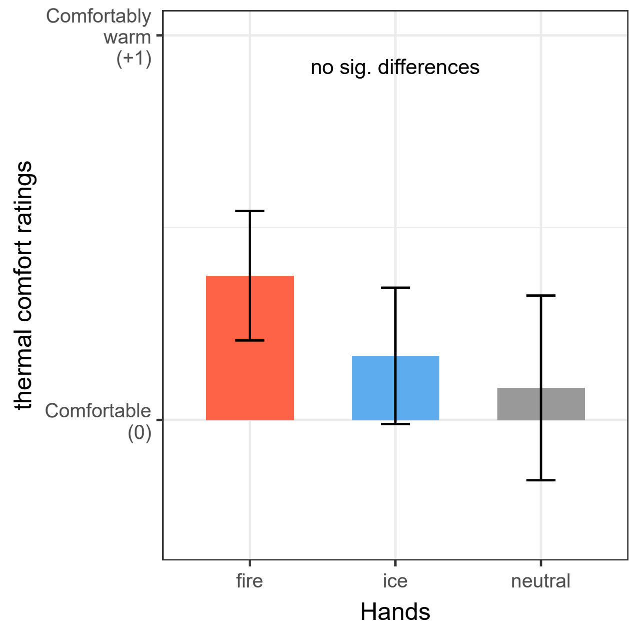

Figure 6: Mean thermal comfort ratings after 15 minutes of exposure for each condition ranged from very uncomfortable (−3) to very comfortable (+3). While the *neutral* condition appears numerically slightly more negative than *ice* or *fire*, statistical tests revealed no significant differences. All error bars represent the SE of the mean.

$p = .926$, $\eta_p^2 = .005$. Post hoc pairwise comparisons (Bonferroni corrected) showed that participants reported significantly higher thermal sensation in the *fire* condition compared to the *ice* condition ($p = .006$) and the *neutral* condition ($p = .033$), whereas the difference between *ice* and *neutral* was not significant ($p = 1.000$). No significant pairwise differences were observed between time points (all $p > .280$). Overall, participants felt warmer when embodying the *fire* hands compared to both the *neutral* and *ice* conditions, and this effect remained basically stable over the 15-minute period. Figure 5 shows the mean and standard errors of the thermal sensation ratings over time.

4.3 Thermal Comfort

Participants rated their overall thermal comfort at the end of each condition. Shapiro–Wilk tests indicated deviations from normality for all hand conditions ($p < .021$). Therefore, a non-parametric Friedman test was conducted to examine the effect of HANDS. The analysis revealed no significant effect, $\chi^2(2) = 2.23$, $p = .327$. Pairwise Wilcoxon signed-rank tests with Bonferroni correction confirmed that none of the pairwise comparisons were significant (all $p > .528$). Means and standard errors of the thermal comfort ratings are shown in Figure 6.

4.4 Task Performance

To evaluate task performance, we analyzed participants' median response times across hand conditions. Shapiro–Wilk tests indicated that the data did not deviate from normality for any condition (*fire*: $W = 0.937$, $p = .138$; *ice*: $W = 0.958$, $p = .401$; *neutral*: $W = 0.956$, $p = .357$). An RM-ANOVA with HANDS revealed no significant effect, $F(2, 46) = 0.661$, $p = .521$, $pes = .028$. Bonferroni-corrected pairwise comparisons confirmed that none of the differences were significant (all $p > .858$).

4.5 Headset Movements

To test for potential confounds due to head movements, we analyzed the translational and rotational differences extracted from the VR headset. For translational head movement, no violation of normality was found (all $p > .24$). A RM-ANOVA revealed no significant effect of HANDS, $F(2, 46) = 0.95$, $p = .394$, $\eta_p^2 = .040$. No significant differences were found for angular head movements, $F(2, 46) = 0.36$, $p = .697$, $\eta_p^2 = .016$. All pairwise comparisons were non-significant ($p > .771$). Overall, headset movement did not differ meaningfully between hand conditions, suggesting that head motion cannot explain any of the effects reported above.

4.6 Presence

We analyzed the overall IPQ presence score and its three subscales: *spatial presence*, *involvement*, and *realism*. There were no significant differences between the hand conditions in any of the scores. For the overall presence score, an RM-ANOVA revealed no significant effect, $F(2, 40) = 0.75$, $p = .478$, $\eta_p^2 = .036$. The same pattern held for the subscales. For *spatial presence*, the ANOVA showed no effect, $F(2, 40) = 0.43$, $p = .656$, $\eta_p^2 = .021$. For *involvement*, we found $F(2, 40) = 0.94$, $p = .400$, $\eta_p^2 = .045$. For *realism*, the result was $F(2, 40) = 0.14$, $p = .868$, $\eta_p^2 = .007$. None of the Bonferroni-corrected pairwise comparisons reached significance ($p > .41$). These results suggest that the hand conditions had no measurable effect on presence or any of its subdimensions.

5 Discussion

The aim of this study was to investigate how visual thermal stimulation of virtual hands in VR affects objective and subjective responses in a virtual environment during an interaction of 15 minutes per condition. In line with previous work, skin temperature changes differed significantly across the *fire*, *ice*, and *neutral* conditions, confirming the effectiveness of the thermal manipulation [22]. These changes were also reflected in participants' thermal sensation ratings, with the *fire* condition leading to stronger perceived warmth compared to the *ice* and *neutral* conditions. Interestingly, the *ice* condition did not produce a significant perceptual contrast to the *neutral* condition, despite physiological differences in skin temperature.

However, one unexpected finding was the lack of interaction effects between Time and Hand of the physiological thermal response. While thermal stimulation clearly altered perception, the trajectory of ratings over time did not vary substantially between conditions. In other words, differences between conditions emerged early and then remained roughly stable throughout the 15-minute exposure.

This is particularly interesting given the observable trends in the data. For example, the *ice* condition showed a relatively steady increase in thermal sensation, peaking around minute 10, while the *fire* condition showed only a modest upward drift with more fluctuation. The *neutral* condition initially decreased in sensation ratings before slowly recovering. These divergent temporal profiles might suggest an interaction, yet no significant effect was detected statistically. One plausible explanation is that inter-individual variability and overlapping standard deviations masked these temporal differences. Additionally, the trends in some conditions (e.g., a rise followed by a drop) may have canceled each other out in the interaction term of the model, especially when tested with conservative corrections.

These results imply that the onset of thermal perception occurs rapidly and stabilizes afterward, potentially due to early sensory adaptation or cognitive recalibration. It is also possible that participants relied on an initial impression of thermal change, and subsequent input failed to shift their perception further. In contrast to the clear physiological and perceptual effects, we found no evidence that thermal stimulation affected task performance, head movement, or presence. Participants completed the task with similar speed across all conditions, and presence scores—including spatial presence, involvement, and realism—remained unaffected. This suggests that thermal hand stimulation, while perceptually salient, does not translate into measurable differences in user behavior or presence within a virtual environment, at least in the context of this task and exposure duration.

5.1 Implications

The results in this experiment highlight the dissociation between physiological and subjective thermal changes and their impact on cognitive performance or presence. This is particularly relevant for VR designers aiming to increase immersion or evoke specific affective states via thermal cues. While thermal feedback can clearly manipulate low-level sensations, its effect on complex psychological constructs such as presence may require stronger or more targeted stimulation, or may be dependent on context, such as the nature of the task or narrative. The absence of changes in task performance or presence is encouraging from a usability perspective: mild thermal manipulations do not introduce distractions or performance impairments. In scenarios where thermally responsive wearables are used (e.g., for medical monitoring or biofeedback), designers may be less concerned about unintended side effects on user engagement or task performance.

5.2 Limitations

Several limitations must be considered. First, the thermal stimuli were relatively moderate in intensity and applied only to the hands. It is possible that broader or more intense stimulation (e.g., whole-body cooling) would have resulted in stronger effects on comfort, performance, or presence. Second, the task used in this study was relatively simple and repetitive. More demanding or emotionally charged tasks might be more sensitive to thermal influences. Furthermore, presence was measured using standardized self-report scales, which may not capture subtle experiential shifts. Incorporating behavioral or physiological proxies of presence (e.g., galvanic skin response, postural sway) could provide a more nuanced view. Finally, all participants were exposed to the same sequence of conditions, which may have introduced order effects despite the counterbalancing. Although we controlled for obvious confounds like head movement, other uncontrolled factors (e.g., fatigue, adaptation) may have played a role. The weak correlation between room and body temperature indicates that the body affects the surrounding temperature. Although the relationship was statistically significant ($\rho = .19$, $p < .001$), the effect size was minimal and likely driven by the large number of repeated measures. Still, room temperature could have interacted with the body's thermal state in a saturating manner, potentially dampening or overriding skin responses over time, particularly in the more temperature-sensitive conditions such as *ice*. Moreover, thermal sensation was sampled only at 5-minute intervals, which may have limited the detection of transient perceptual changes. Future work should employ higher-frequency sampling to better capture such short-term effects.

5.3 Future Work

Future studies should explore how thermal stimulation interacts with emotional or narrative content in VR. For instance, applying warmth in socially positive scenarios, or cold in threatening contexts, may enhance immersion through affective congruence. Another promising direction is adaptive thermal feedback, where the system responds in real time to user state or behavior. Moreover, combining thermal cues with other sensory modalities (e.g., haptics, audio, scent) may amplify their impact. Understanding these multisensory interactions could lead to more effective and engaging VR experiences. Finally, research should investigate individual differences in thermal perception and sensitivity to better tailor feedback systems to user profiles.

6 Conclusion

In this paper, we investigated effects of embodying avatars representing thermal cues on users' thermal perception and thermoregulation. Hence, we conducted a study with 24 participants who were embodied in a ice, fire, or neutral avatar serving as a control condition to obtain a baseline comparison. To learn about how the thermal effects evolve over a time, participants had to perform a puzzle task for 15 minutes per condition while being embodied in the respective avatar. Results show that thermal sensation was systematically influenced by the avatar hands so that participants felt warmer while embodying the fire hands compared to the ice hands. Over time, the effects on thermal perception appear to remain stable. Results also show effects on skin temperature. Participants had higher skin temperature changes while embodying the ice hand compared to the fire hand. However, there were no effects over time. Hence, the skin temperature differences between conditions emerged early and then remained roughly stable throughout the 15-minute exposure. Our findings indicate that virtual hands conveying extreme thermal cues can systematically influence thermal perception. Although future research should examine even longer exposure durations to better understand long-term effects, our results suggest that these thermal effects intensify initially but stabilize after reaching a peak over time.

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