The Effects of Avatar and Environment on Thermal Perception and Skin Temperature in Virtual Reality

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ABSTRACT

Humans' thermal regulation and subjective perception of temperature is highly plastic and depends on the visual appearance of the surrounding environment. Previous work shows that an environment's color temperature affects the experienced temperature. As virtual reality (VR) enables visual immersion, recent work suggests that a VR scene's color temperature also affects experienced temperature. It is, however, unclear if an avatar's appearance also affects users' thermal perception and if a change in thermal perception even influences the body temperature. Therefore, we conducted a study with 32 participants performing a task in an ice or fire world while having ice or fire hands. We show that being in a fire world or having fire hands increases the perceived temperature. We even show that having fire hands decreases the hand temperature compared to having ice hands. We discuss the implications for the design of VR systems and future research directions.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *Haptic devices*; • **Applied computing** → **Computer games**.

KEYWORDS

virtual reality, thermal perception, skin temperature, embodiment

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1 INTRODUCTION

How humans perceive their ambient temperature can be affected by the design and visual appearance of the surrounding environment [27]. The hue-heat hypothesis claims that a cool ambient color leads to a cooler temperature perception and a warm ambient color to a warmer temperature perception [82]. Previous work showed, for example, that aircraft passengers' had warmer thermal sensations in a cabin lit with yellow light compared to blue light [4]. Similarly, there is also evidence that warm-colored objects are perceived as warmer and cold-colored objects as colder [122]. As thermal perception is directly linked to one's thermal comfort—"that condition of mind which expresses satisfaction with the thermal environment" [8]—prior work found that lighting's color temperature can also influence thermal comfort [5, 20, 48]. Interestingly, the visual appearance of an environment is even capable of evoking thermophysiological responses [116]. Takakura et al. [113] found that pictures of a desert reduced participants' body temperature and pictures of snow slightly increased their body temperature. These findings suggest that the mere thermal appearance of an environment does influence body temperature even though the actual ambient temperature is unchanged [85, 127]. As thermal comfort and thermophysiological effects are known to be connected to productivity and performance [78], well-being, and the overall experience and satisfaction of many activities [38], understanding and influencing thermal comfort and body temperature is, therefore, important for designers and researchers of virtual reality (VR) applications.

VR immerses users in a virtual environment (VE) by completely surrounding them with the digital content and creating the sensation of being present in an alternate 3D world. As computer-generated worlds consist of editable shapes and shaders, designers of immersive applications can create any imaginable VE and, therefore, allow users to explore virtual spaces that cannot be experienced in the real world. Commercial VR applications leverage this characteristic to transport users to fascinating locations frequently depicting all kinds of thermal conditions, e.g., Skyrim VR [25], Everest VR [101], or Moon Landing VR [73]. Consequently, VR could potentially also influence thermal comfort and even users' body temperature.

Lauderdale investigated the difference between a virtual snowy blizzard environment and a temperate forest environment [70].

While effects on skin temperature were inconclusive, the environment significantly affected perceived temperature. Similarly, Huang et al. [47] compared four VEs with different colors. They also found that the environment's color does affect the perceived temperature and thermal comfort. While Günther et al. [40] simultaneously investigated the effects of different factors, their results also suggest that visual feedback in VR does affect the perceived temperature.

While VR enables controlling the environment, it does also enable altering the user's body. The user's avatar has a range of effects including effects on attitudes [15], behavior [95], cognitive abilities [16, 64], and physical performance [59]. VR games frequently embody users in avatars that suggest extreme temperatures. There are many examples, including MARVEL Powers United VR [103], Skyrim VR [25], or the Unspoken VR [50], where users embody characters with the two elemental powers fire and ice. However, it is unclear if embodying such avatars affect thermal perception or regulation of the body temperature. While not measuring body temperature or analyzing effects on perceived temperature, Eckhoff et al. [34] found that burning hands, presented through augmented reality (AR) glasses, increase skin conductance for participants who experienced an involuntary heat sensation which indicates that there might also be effects on skin temperature.

Overall, previous work shows that the visual environment can affect thermal comfort [5, 20, 48]. While work on the effects of a VE is sparse [40, 47, 70], it seems likely that effects on thermal comfort also hold for VR. While VR applications frequently place users in VEs or embody them in avatars that suggest extreme temperatures, it is not only unclear if the visual scene affects body temperature but also if avatars' design can affect thermal comfort or even the body temperature. Designers and researchers of VR applications need to understand effects of virtual avatars and environments on users' thermal perception and body temperature. A reduced thermal comfort during the VR experience, for example, could potentially decrease the usage and user retention. In addition, a decreased body and hand temperature could also deteriorate performance as a reduced hand temperature is associated with a reduced dexterity in hands and fingers [29]. Consequently, learning about the effects could provide valuable insights into users' thermoregulation and inform the design of avatars and virtual worlds.

We conducted a study to investigate the effects of a VE and the user's avatar on thermal perception and skin temperature. In a controlled experiment in VR, participants performed a simple task in an ice and a fire world while having either ice or fire hands. We found a significant time × hand interaction effect revealing that over time the hand temperature increases with ice hands and decreases with fire hands. We further found that the hands as well as the environment affect thermal perception in VR. These results suggest that virtual avatars and the surrounding environment indeed affects users' thermal comfort and thermoregulation during the VR experience. Consequently, VR technology can be leveraged to gain a better understanding of humans' thermal regulation. The results, however, also highlight the importance of long-term VR studies to prevent unintentionally induced negative effects on users' experience and thermal perception while transporting them into virtual worlds.

2 RELATED WORK

Our work builds on previous findings about how perceived temperature and body temperature are affected by non-thermal factors in both the real and VE. In the following, we first describe effects on regulating the body temperature. Afterward, we discuss work on the effects on perceived temperature and body temperature in real-world experiments, followed by work on effects in VR. Finally, we give an overview of thermal effects caused by embodiment illusions inside and outside of VR.

2.1 Body Temperature Regulation

A natural ability of humans vital for survival is regulating the body temperature. Much like a thermostat adjusts room temperature, the brain's hypothalamus regulates the body temperature to react to certain internal and external events [115]. The human body aims to maintain a temperature of about 37°C using different mechanisms such as sweating, shivering, or narrowing blood vessels for regulating blood flow [110]. Sweating, for example, acts as a heat-regulatory function to cool the body maintaining a constant body temperature. Particularly when humans physically or mentally exert themselves, the body temperature increases and the autonomic nervous system triggers sweating mechanisms to balance this rise in temperature [13].

While the main factors for changes in body temperature are usually the ambient temperature or physical effort, studies have found that these changes may also occur due to non-thermal factors, such as the stress level [90], experienced motion sickness [79], or season [75]. The biological functioning of the human body can also change its temperature via hormones such as histamine [76] or cortisol [11], which vary, for example, during the circadian and menstruation rhythm, while perceiving stress, and during pregnancy [12, 28, 54, 76]. The circadian rhythm, for example, affects body temperature causing the temperature to be lower during the night than day [94].

Previous work also found that emotions can trigger changes in skin temperature [18]. Kosonogov et al. [67], for example, revealed in an elicitation study that in contrast to neutral pictures, pleasant and unpleasant pictures can influence face temperature. Kosonogov et al. [68] attributes such effects to a reduced blood flow to certain body parts caused by vasoconstrictive reaction narrowing blood vessels due to emotional arousal. Such a reaction is a function of the flight/fear response causing increased muscle irrigation resulting in a higher readiness of muscles, and a decreased skin surface irrigation resulting in reduced effects of injuries.

Overall, work in physiology and psychology showed that thermal regulation is not only affected by ambient temperature and physical exertion but also by a wide range of additional factors. Example factors include stress [90], motion sickness [79], and emotions [18, 67]. As interacting with computing systems can have effects on these factors, it is likely that this also affects thermal regulation.

2.2 Effects of Color Temperature on Thermal Comfort and Body Temperature

Thermal comfort has been defined as "that condition of mind which expresses satisfaction with the thermal environment" [8, 84]. Research found that thermal comfort is relevant for building occupants' satisfaction [38, 84], working productivity [78], and energy consumption [6]. Due to its importance, building designers optimize for thermal comfort to create satisfactory environments and tackle climate change [46].

Already in 1926, Mogensen and English [82] investigated if an object's color affects the perceived warmth of the object. The underlying assumption of the conducted study has later been coined the hue-heat hypothesis [22], which postulates that the higher the light temperature the colder an object is perceived. As Mogensen and English [82] did not find systematic effects, they initially rejected the hypothesis. Multiple studies followed Mogensen and English [82] but also did not reveal systematic effects [22, 24]. Fanger et al. [36] revealed an effect of the light temperature on the preferred ambient temperature but with a difference of 0.4°C, they considered the effect to be too small to have practical significance .

In recent years, an increasing number of studies started to support the hue-heat hypothesis [4, 43, 80, 121]. Alfano et al. [5], for example, exposed participants to warm and cold light. They conclude that warm light results in a warmer thermal sensation with the potential to improve thermal comfort. Similarly, Huebner et al. [48] found that under warmer lighting, participants not only felt warmer but in a second study they also revealed that participants were putting on more clothing under cold light than under warm light. Furthermore, previous work showed, for example, that aircraft passengers' had warmer thermal sensations in a cabin lit with yellow light compared to blue light [4]. The authors argue that such effects, if systematically applied on a large scale, can indeed affect energy consumption and cost due to the impact of lighting on temperature perception and thermal comfort.

In line with the hue-heat hypothesis [83], Wang et al. [121] confirmed that colors affect temperature perception. Walls with cold colors decreased subjective thermal sensation and walls with warm colors increased thermal sensation. Additionally, warm colors were perceived as more comfortable in cold environments and cold colors in warm environments. Ziat et al. [129] and Balcer et al. [14] showed that objects with warm and cold colors affected behavioral responses based on the anticipated temperature. A hot vessel colored blue and a cold vessel colored red was held longer than vessels with colors consistent with the temperature of the content [129]. Similarly, Szocs [112] coined the color-temperature effect postulating that beverages in a red cup were perceived as warmer while beverages in a blue cup as cooler. While the associations between temperature and colors, and even emotions are applied in a variety of domains, e.g., advertising [93], energy consumption design [6], or interior design [77], the results imply that visual information interacts with one's thermal sensation illustrating the dominance of vision even for thermal perception. This indicates the plasticity of thermal sensations and that humans' thermal comfort can be shaped through visual cues.

Previous work showed that what humans see not only affects the perceived temperature but also their body temperature. Takakura et al. [113] found that pictures of a desert reduced participants' body temperature and pictures of snow slightly increased their body temperature. Such thermophysiological responses are also in line with the hue-heat hypothesis postulating that reddish colors are related to warmth and blueish to coldness [83]. While other explanations cannot be dismissed [81], Takakura et al. [113] mentioned classical conditioning as a potential cause of such changes in body temperature. Seeing images showing a hot desert could activate imagery associations of how it would feel to be in such a place. This mental process could, in turn, activate thermoregulatory mechanisms in a very attenuated but similar way as if one would actually experience a hot and dry environment causing a drop in temperature to maintain homeostasis. This is in line with Takakura et al. [114] who revealed that video footage showing "cold" and "hot" images can affect heart rate and blood pressure.

In a systematic review, Wang et al. [122] identified 18 studies investigating the effects of light temperature. They found significant associations between light temperature and psychological (e.g., thermal sensation, preferred temperature) as well as physiological measures (e.g., proximal skin temperature, heart rate variability). In conclusion, recent work consistently confirmed the hue-heat hypothesis. Under warmer light humans feel warmer and have a lower body temperature. Such results imply that the thermoregulatory system responds to visual information representing certain thermal conditions even when actual thermal energy is missing. While research provides possible theories for psychological thermoregulation [33, 113, 114, 125], e.g., social thermoregulation through an increase in body temperature to warm other fellows [49], a final explanation of why such effects occur remains unclear so the precise mechanisms need to be investigated further.

2.3 Thermal Perception in Mixed Reality

Due to the advancement in immersive technology in recent years, designers and researchers can leverage VR and AR to gain an understanding of the cognitive processes underlying thermal perception. Huang et al. [47] aimed at learning about the thermal sensation of humans to inform the design of energy-efficient buildings. They investigated the effects of VR rooms with different ambient light conditions on thermal comfort and found that the temperature in a red room was perceived as warmer and more comfortable than in a blue room. Similarly, Chinazzo et al. [30] found that colored light in a VR room affected thermal evaluations while the actual environmental temperature was controlled. Such findings potentially indicate that the effects of the hue heat hypothesis can be transferred into VR. While non-VR applications also use environments and avatars with different colors and thermal conditions, e.g., in video games, the sense of presence and immersion induced by immersive VR changes how users perceive the virtual world and intensifies the experience [71, 120]. Hence, the knowledge that applies for non-immersive digital worlds cannot be automatically translated into immersive VR.

While studies revealing effects of the environment on thermal perception were replicated in further studies [31, 100], other researchers used the plasticity of thermal sensations to induce certain effects. Hoffman et al. [44] immersed patients with burn injuries into an ice world where they experienced a snowy canyon in VR. Results indicate that the VR exposure relieved pain sensations during wound cleaning. Gutiérrez-Maldonado et al. [41] put participants into a cold-pressor filled with water having a temperature of 6°C. Results suggest that the pain threshold was increased when participants experienced VR and interacted with a VE.

As users' body parts can be rendered in any desired style in VR and AR, researchers and designers can also induce thermal effects by changing the visual appearance of users' body representation. Eckhoff et al. [35] found that burning hands in AR affect heat-induced pain thresholds and temperature detection thresholds. Similarly, Weir et al. [123] reported that some participants who perceived flames on their hands using AR goggles reported a warming sensation. While these results suggest that the visual appearance of avatars could affect users' thermal perception, the interplay between the effects of the environment and the effects of the virtual body on users still remains unclear.

2.4 Thermal Effects of Embodiment Illusions

To provide users with a virtual body and create lifelike and embodied VR experiences, designers and researchers typically use avatars (c.f. [64, 99]). The term avatar is derived from the Hindu term "avatara" which refers to the descent of a god on earth in terrestrial shapes [91]. Metaphorically, in VR users descent into the VE by taking on digital bodies in terms of avatars [17]. Hence, an avatar acts as the digital self-representation of users that is under their control during the VR experience [56, 69, 89]. Accordingly, Bailenson and Blascovich [10] defined an avatar as "a perceptible digital representation whose behaviors reflect those executed, typically in real time, by a specific human being".

When users perceive the VE from a first-person perspective and their motion is mapped onto the avatar, they experience a visuomotor synchrony resulting in the sensation of embodying the avatar and its integration into the own body schema [55, 59, 108]. This illusion of embodying artificial bodies can invoke psychological and physiological changes [97], such as an increased heart rate [23, 107], skin conductance response [7], or even thermoregulation [45, 51, 61, 87, 102].

Salomon et al. [102] found that participants had a decreased skin temperature across different body locations while experiencing an avatar as their own body. To induce this illusory sensation of embodying the avatar, users experienced a visuo-tactile synchrony—a synchrony between tactile and visual perception. Participants were stroked on different body parts and could see the stroking in synchrony on their virtual bodies. Interestingly, the drop in skin temperature did not occur during asynchronous stroking, which is known to destroy embodiment sensations. As a drop in temperature is one symptom of certain neurological disorders, e.g., patients suffering from somatoparaphrenia have the sensation that their affected limbs belong to someone else [119], researchers assume that such effects are linked to a disownership of the real hand [86].

Similar effects could also be shown in real-world experiments. Moseley et al. [87] revealed that participants' skin temperature decreased while experiencing the rubber hand illusion (RHI). The RHI is a form of body ownership illusion in which a human can experience an artificial limb (represented by a rubber hand) as if it was their own hand [26]. This illusion is created by hiding the participants' real hand from their view and stroking the visible rubber hand and the real hand synchronously with a brush. Moseley et al. [87] found that the drop in skin temperature was associated with the extent of the experienced embodiment illusion as asynchronous stroking had no effect on skin temperature. While some studies could confirm such observations [45, 52, 61], other studies could not consistently reproduce effects on skin temperature [32, 98]. Due to these ambiguous results, thermal effects on users caused by embodying avatars still remain unclear and require further investigation.

2.5 Summary

Thermal comfort is important for one's productivity and performance [78] and the overall satisfaction and experience of many activities [38]. Related work indicates that a human's body temperature and thermal comfort are highly dynamic and are affected by a wide variety of thermal and non-thermal factors [75, 79]. Experiments in the real world showed that perceived temperature and even thermoregulation is affected by the environment's color temperature [85, 127]. While experiments in VR showed that a VE's color temperature also influences the perceived temperature [30, 47], it is unclear if VEs can also affect the body temperature. Embodying avatars with burning hands has effects related to thermoregulation [35] and there is anecdotal evidence for an effect on perceived temperature [123]. While we know that embodying avatars can even have effects on body temperature [102], it is unclear if avatars suggesting different temperatures have effects on perceived temperature or body temperature. Designers and researchers of VR applications need to understand how VEs and embodied avatars affect perceived temperature and body temperature, as the thermal comfort and body temperature can have an impact on the overall VR experience. In addition, it would deepen our understanding of the interplay between environmental and body-related effects on users' thermoregulation and thermal perception.

3 METHOD

To understand the effects of avatars and VEs on the users' thermal perception, skin temperature, and VR experience, we designed an immersive VR first-person shooting game. Players either embodied ice or fire hands while being immersed in an ice- or fire-styled game world (see Figure 1).

3.1 Study Design

We conducted a controlled experiment using a within-subjects design with the two independent variables AVATAR and ENVIRONMENT both consisting of two levels *fire* and *ice*. For all temperature-related measures, we also included TIME as independent variable as we hypothesized that temperatures change during the experimental conditions. To rule out any sequence effects, we counter-balanced the order of conditions using a balanced Latin square design. Figure 1 shows the study's four conditions.

3.2 Measures

To assess the effects of both independent variables we took objective and subjective measures. We continuously measured the

Figure 1: The *fire* (top) and the *ice* world (bottom) and the *fire* and *ice* avatars resulting in four experimental conditions.

participants' skin temperature on both hands and the room temperature. We repetitively assessed participants' perceived thermal comfort using the Bedford Thermal Scale [19] and the thermal sensation scale as proposed by Lee et al. Lee et al. [72]. Furthermore, we used the Igroup Presence Questionnaire (IPQ) [104] to evaluate the participants' sense of presence during the VR experience. In line with Schwind et al. [105], all questionnaires were filled in VR for not interrupting the VR experience by removing the headset. To control for behavioral changes possibly modulating the thermal responses, we also tracked participants' head movement during the VR experience.

3.2.1 Skin Temperature. We continuously recorded the participants' skin temperature on both hands during the course of the study. As both hands were virtually replaced by the same 3D hand model, we calculated the average skin temperature of both hands for the statistical analysis. In line with Moseley et al. [87], we transformed the skin temperature data by subtracting the first skin temperature observation from every value of each observation per participant to center the variable at zero. We hypothesized that the avatar hands affect participants' skin temperature during the experimental conditions.

3.2.2 Thermal Sensation and Comfort. We assessed participants' perceived thermal sensation using the thermal sensation scale by Lee et al. [72] during the VR experience. This scale is a visual analog scale consisting of one item with the question "How do you feel at this time". The continuous scale ranges from "very cold" to "very hot" without discrete value and assessed using a continuous slider ranging from 0 to 1. To analyze the change in thermal perception across time, we repetitively surveyed the participants after 90, 180, and 270 seconds within the gaming experience while embodying the respective avatar hand condition.

Additionally, we measured the thermal comfort using the Bedford Thermal Scale [19]. This scale consisted of a 7-point Likert item ranging from 1 to 7 "How would you rate your thermal comfort during the last scene?" ranging from "much too cool" to "much too hot". As this questionnaire is typically administered after the experience and assesses the thermal comfort in retrospect, participants were surveyed in a neutral VE while embodying neutral virtual hands after the respective condition. We hypothesized that the avatar and environment affect participants' thermal sensations and comfort.

3.2.3 IPQ. We assessed presence using the IPQ. The IPQ consists of fourteen 7-point Likert items ranging from 1 to 7, which reflect different dimensions of presence: *general presence*, *spatial presence*, *involvement* and *realism*. The dimension *general presence* consists of one item "In the computer generated world I had a sense of being there". *Spatial presence* includes items that assess the participant's sense of being actually present in the virtual world rather than operating a VR device. The dimension *involvement* assesses how much the participants were absorbed into the virtual world and forgot about the real world around them. Lastly, the dimension *realism* includes items assessing how "real" the virtual world was compared to the real world.

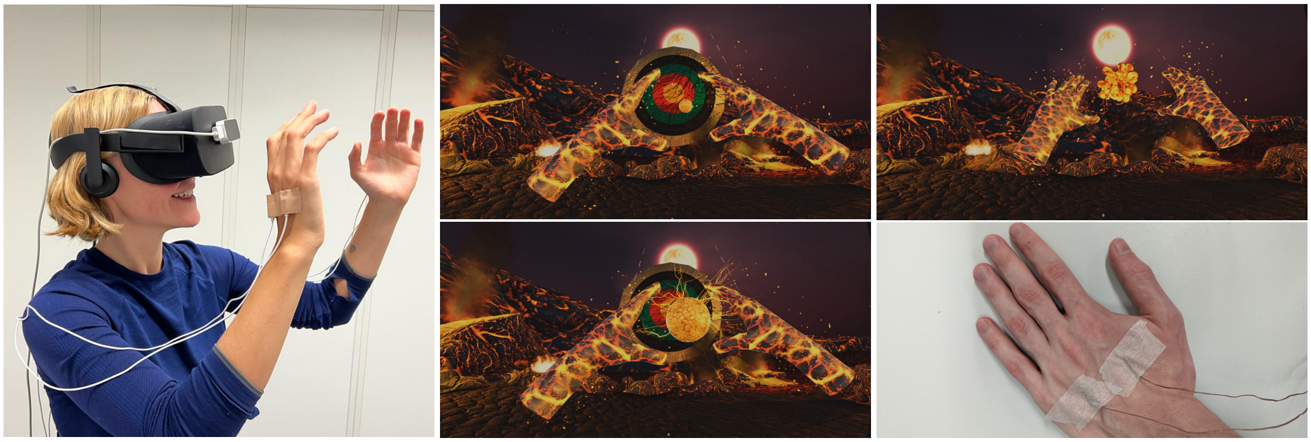

Figure 2: User (left) charging and shooting a projectile by performing the "charging gesture" (middle and top right), and the thermocouples attached to participants' hands for continuously assessing the skin temperature (bottom right).

3.2.4 Head Movement. To control for behavioral changes caused by the visual appearance of the virtual world and the avatar [58, 60, 62, 65], we determined the head movement using the x, y, and z-position and rotation of the HMD based on the left-handed coordinate system of the game engine Unity. We, therefore, subtracted the value of one frame from the value of the previous frame to calculate the average total translation for x, y, and z, and the average total rotation (pitch, yaw, and roll) of the head-mounted display (HMD).

3.3 Apparatus

We used the Oculus Rift VR Headset (Meta) with a resolution of 1080×1200 pixels per eye displayed at 90 Hz and a field of view of 110°. We attached a LeapMotion controller (LeapMotion) with a 3D-printed case and velcro strips to the front of the HMD. The controllers of the Oculus Rift headset were not used during the experiment. We defined a tracking area (width: 2 m, length: 3 m) in our VR laboratory. The game engine Unity (version 2020.3.22f1) was used to develop the VR application. We designed a single world containing a rocky and stylized landscape using different sets of 3D-Models. This world was then used as a basis for our *fire*- and *ice*-like virtual worlds. Both worlds comprised of the same 3D meshes, terrains, and landscape elements, however, we used different materials for creating the *fire* and *ice* world. Hence, we can dismiss that other factors than the mere visual appearance in terms of *fire* and *ice* characteristics affected our dependent variables. We used a neutral VE with neutral virtual hands extracted from the Leap Motion SDK to administer the Bedford Thermal Scale (see Figure 3). The target frame rate of the application was 90 frames per second (fps) while global illumination and antialiasing were enabled. To ensure a high hand-tracking quality, the hand interaction with the VE, which consisted of shooting targets and completing questionnaires, was designed to be within the field of view of the LeapMotion controller (see Figure 2 and 3).

To measure participants' skin temperature, we used a professional thermometer module with multiple channels, a sampling rate of 4 Hz, and a resolution of 20 bit (TC-08 8-Channel USB Thermocouple Data Acquisition Module, Omega Engineering, USA). We used five T-thermocouples (fast response insulated thermocouple with connectors: 5SRTC-TT-TI-20-2M, Omega, USA) to assess the skin temperature on each hand. To increase measurement accuracy and compensate for a potential malfunction of a thermocouple, we attached two thermocouples to the participant's left hand and another two to their right hand using adhesive tape. One thermocouple was fixed at the center of a table to measure the room temperature.

3.4 Stimuli

Our hand models are based on the 'Ghost Hands' models from the LeapMotion - Unity plugin [118]. The *fire*[1] and *ice*[2] hands were equipped with stylized shaders and textures from the Unity Asset store representing red-hot glowing and blueish frozen virtual hands (see Figure 1). Additionally, we added particle systems to each hand condition as special effect visually highlighting the virtual temperature. The neutral hand model for interactions between the conditions were white cylinders as bones and gray spheres as joints as provided by LeapMotion plugin (see Figure 3). Each hand model has an identical mesh, size, and skeleton with a total of 20 bones animating the skin. The participants experienced our VR application from a first-person perspective. The VR application ran on a desktop PC (Windows 10, Intel i7-5820K CPU, 16GB RAM, NVIDIA GeFore GTX 980Ti GPU).

3.5 Gameplay and Tasks

In the VR game, participants had to aim and shoot at targets. The application has been developed to engage participants in VR and to utilize both virtual hands as game controllers for the interaction. Every five seconds a target randomly spawned in one of twelve predetermined positions in the game world. Only one target was active at a time. To reduce the participants' physical activity the targets' spawn locations were limited to the frontal 180° of the participants' field of view, so that participants did not need to turn

[1]https://assetstore.unity.com/packages/2d/textures-materials/stylized-lava-materials-180943

[2]https://assetstore.unity.com/packages/vfx/shaders/ice-world-83543

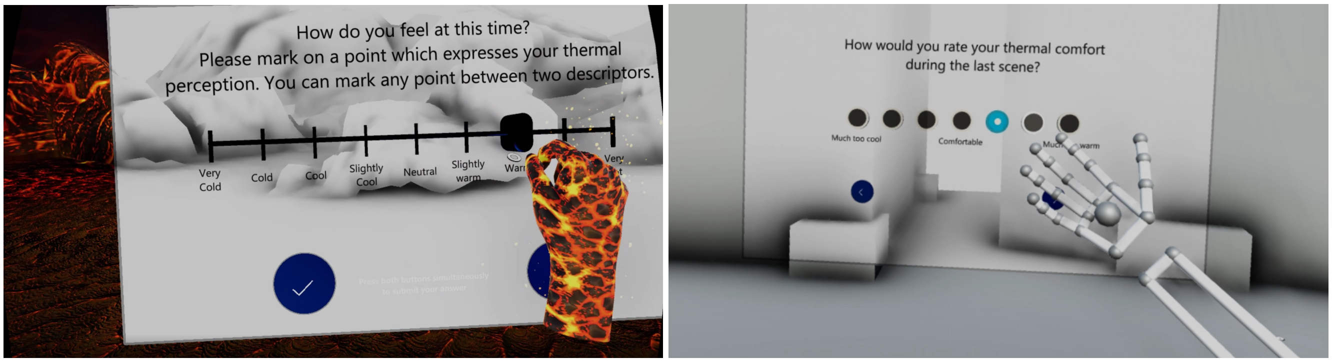

Figure 3: Models of the thermal sensation scale [72] during the *fire* hand and *fire* environment condition (left), and the neutral environment for assessing the Bedford Thermal Scale [19] and IPQ [104] (right).

their body while searching for the targets. Hence, we aimed at reducing sweating to avoid confounding thermal responses caused by skin respiration.

Participants could shoot a target by charging a projectile between their virtual hands (see Figure 2). To foster embodiment of the avatar and draw participants' attention to their virtual hands, a charging gesture had to be performed directly in front of their view before shooting. While the projectile was charging, it steadily grew in size between the hands for three seconds. Afterward, participants could shoot the projectile by rotating and releasing the charging gesture. When the projectile hit its target, the target exploded and a new target was spawned after five seconds. We did not include any background sound to reduce interference caused by audio.

3.6 Procedure

After welcoming the participants, they were asked to sign an informed consent form. Then, they completed a demographic questionnaire consisting of additional questions about their previous VR experience. The participant received a short introduction about the used VR hardware and functionality of the system. The experimenter then attached the thermocouples to the participants' hands. Participants were helped to put on the VR headset and to adjust it to their head. We started the VR experience using a short tutorial. The participants were asked to look around to familiarize themselves with the VR system, the environment, and hands. The experimenter then explained that targets will appear randomly throughout the world, which can be shot via projectiles. The participants further completed some steps explaining the basic game mechanics, particularly the charging gesture. All participants were informed that it does not matter how fast the targets are being hit to prevent them from overly exerting themselves. To continue, participants had to create and shoot a projectile using the charging gesture as shown in Figure 2. Afterward, a questionnaire appeared that could be answered by using a slider and confirmation of the input.

After completing the tutorial phase, the first of four experimental conditions started. Thus, every participant played the game four times and experienced each hand pair once. Participants shot at targets for a total of five minutes per condition. During each condition, they were asked to report their current thermal comfort three times (after 90, 180, and 270 seconds) using the thermal sensation scale [72]. The questionnaire automatically spawned in front of the center of the participant's view to allow a quick and easy completion After each condition, participants were virtually situated in the neutral environment, where they were asked to answer the Bedford Thermal Scale [19] and the IPQ (see Figure 3). We used the neutral environment as part of a three-minutes resting period. Hence, each participant spent three minutes in the neutral environment while completing the questionnaires to ensure similar resting times for all participants. All participants managed to complete the questionnaires within three minutes and experienced the same duration of the experimental trial. The four experimental conditions automatically continued and took exactly 32 minutes in total for all participants – excluding the variable amount of time spent in the tutorial phase at the beginning of the experiment.

3.7 Participants

The study received ethical clearance according to the guidelines and hygienic instructions of our institution. Due to the COVID-19 pandemic during the time of the experiment, participants were required to provide a proof of vaccination before participating. We recruited 32 participants (15 female, 13 male, 4 preferred not to answer) through forwarding a message about the study through several student and work group chats, as well as through the mailing lists of IT-related courses of our institution. The participants' age ranged from 21 to 35 years ($M = 26.41$, $SD = 3.52$). When asked to rate their previous experience with VR applications on a scale from one (no experience at all) to five (very experienced), 17 of the participants answered one, 9 answered two, 5 answered three, and 1 answered four. None of the participants was taking any medications at the point of the study. All participants felt healthy to complete the study. 17 participants were students and were compensated with one credit point for their study course. All participants were informed that they can withdraw from the experiment at any point without penalty.

4 RESULTS

Our measures consist of parametric and non-parametric data. We used Shapiro-Wilk tests to assess the assumption normality of all measures. Results show violations for certain conditions of the thermal sensation and thermal comfort scale, the IPQ, head movement,

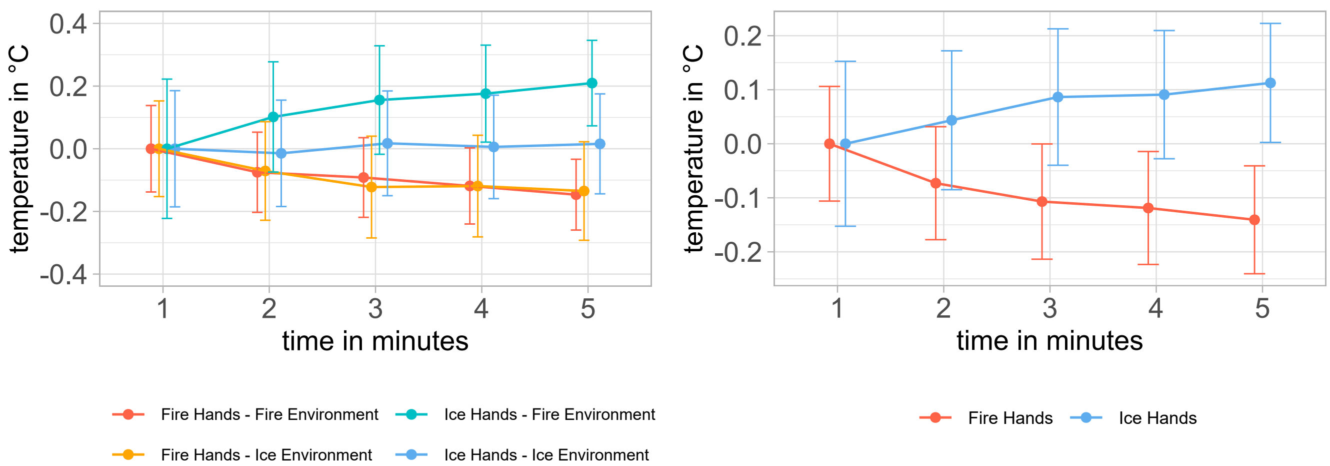

Figure 4: Mean skin temperature per minute centered at zero for the hands and environment (left) and the skin temperature per minute centered at zero for the hands aggregated for both environments (right). The error bars show the standard error.

and the skin and room temperature. As skin temperature was continuously measured, we additionally used q-q plots to assess the distribution of skin temperature data. A visual inspection of the q-q plots indicated normal distribution. For hypothesis testing of non-parametric data, we used the ARTool package for R by Wobbrock et al. [126] to apply an aligned rank transform (ART) analysis of variance (ANOVA). To ensure that the room temperature is not a confounder, we tested whether there were differences between the Avatar and the Environment conditions and found no statistically significant differences (all $p > .137$).

4.1 Skin Temperature

A 2(Hands: *fire* vs. *ice*) x 2(Environment: *fire* vs. *ice*) x 5(Time: *1* vs *2* vs *3* vs *4* vs *5*) ANOVA on the skin temperature across time did not show a significant effect of Hands, $F(1,31) = 0.396$, $p = .533$, $\eta_p^2 = .012$. There was also no significant effect of Environment, $F(1,31) = 0.440$, $p = .511$, $\eta_p^2 = .014$, and of Time, $F(4,124) = 0.084$, $p = .987$, $\eta_p^2 = .003$. However, we found a significant interaction effect of Hands × Time, $F(4,124) = 5.834$, $p < .001$, $\eta_p^2 = .158$, indicating that the skin temperature across time was affected by the virtual hands participants were embodying in VR. Over time, participants' hand temperature decreased with *fire* hands compared to *ice* hands. All other interaction effects were not significant (all $p > .05$). Figure 4 depicts the average relative skin temperature across time.

4.2 Thermal Sensation

A 2(Hands: *fire* vs. *ice*) x 2(Environment: *fire* vs. *ice*) x 3(Time: *90s* vs *180s* vs *270s*) ART ANOVA on the thermal sensation scale showed a significant main effect of Hands, $F(1,31) = 13.770$, $p < .001$, $\eta_p^2 = .308$. There was also a significant effect of Environment, $F(1,31) = 45.945$, $p < .001$, $\eta_p^2 = .597$. There was no significant effect of Time, $F(2,62) = 0.856$, $p = .423$, $\eta_p^2 = .027$. We found a significant interaction effect of Environment × Time, $F(2,62) = 11.555$, $p < .001$, $\eta_p^2 = .272$. All other interaction effects were not significant (all $p > .05$). Thus, participants felt warmer with *fire* hands compared to *ice* hands. Additionally, they felt warmer in the *fire* world than in the *ice* world and this difference increased over time. Figure 5 depicts the average thermal sensation score at 90, 180, and 270 seconds for all conditions.

4.3 Thermal Comfort

A 2(Hands: *fire* vs. *ice*) x 2(Environment: *fire* vs. *ice*) ART ANOVA on the thermal comfort scale showed no significant main effect of Hands, $F(1,31) = 2.229$, $p = .145$, $\eta_p^2 = .067$. There was a significant effect of Environment, $F(1,31) = 5.288$, $p = .028$, $\eta_p^2 = .146$. However, there was no significant interaction effect of Hands × Environment, $F(1,31) = 2.481$, $p = .125$, $\eta_p^2 = .074$. Thus, participants had a higher thermal comfort in the *ice* world than in the *fire* world. Figure 5 shows the average thermal comfort score for each condition.

4.4 IPQ

A 2(Hands: *fire* vs. *ice*) x 2(Environment: *fire* vs. *ice*) ART ANOVA on the dimensions of the IPQ. We did not find a significant effect of Hands, $F(1,31) = 0.019$, $p = .890$, $\eta_p^2 = .000$, and of Environment, $F(1,31) = 0.515$, $p = .478$, $\eta_p^2 = .016$, on the dimension *general presence*. We also did not find a significant interaction effect of Hands × Environment, $F(1,31) = 0.019$, $p = .890$, $\eta_p^2 = .000$.

We did not find a significant effect of Hands, $F(1,31) = 0.037$, $p = .848$, $\eta_p^2 = .001$, on the dimension *involvement*. However, we found a significant main effect of Environment, $F(1,31) = 6.147$, $p = .019$, $\eta_p^2 = .165$. We also found a significant interaction effect of Hands × Environment, $F(1,31) = 5.998$, $p = .020$, $\eta_p^2 = .162$.

We found a significant effect of Hands, $F(1,31) = 5.517$, $p = .025$, $\eta_p^2 = .151$, on the dimension *realness*. However, we did not find a significant effect of Environment, $F(1,31) = 1.344$, $p =$

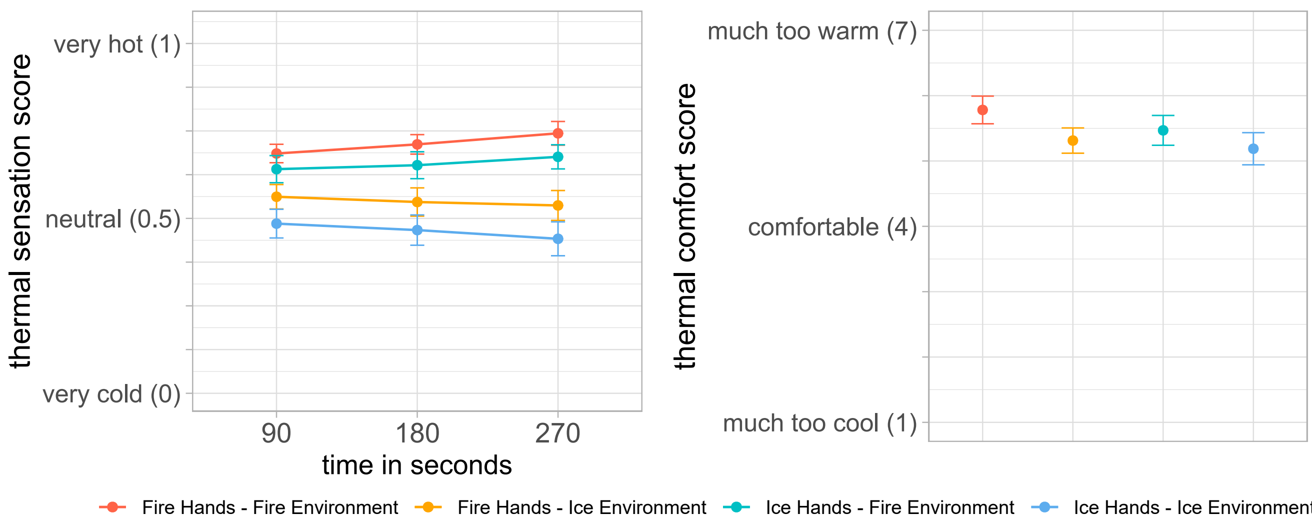

Figure 5: Average thermal sensation scores using a continuous visual analog scale ranging from 0 to 1 (left) and the thermal comfort scores using a 7-point Likert item ranging from 1 to 7 (right). The error bars show the 95% confidence interval.

.255, $\eta_p^2 = .041$. We also found a significant interaction effect of Hands × Environment, $F(1, 31) = 5.930$, $p = .021$, $\eta_p^2 = .161$.

We found a significant effect of Hands, $F(1, 31) = 10.763$, $p = .003$, $\eta_p^2 = .258$, and of Environment, $F(1, 31) = 10.654$, $p = .003$, $\eta_p^2 = .256$, on the dimension *spatial presence*. We did not find a significant interaction effect of Hands × Environment, $F(1, 31) = 0.460$, $p = .503$, $\eta_p^2 = .015$. Figure 6 shows the dimensions of the IPQ for each condition.

4.5 Head Movement

A 2(Hands: *fire* vs. *ice*) x 2(Environment: *fire* vs. *ice*) ART ANOVA on the total translation of the HMD showed a significant effect of Hands, $F(1, 31) = 8.277$, $p = .007$, $\eta_p^2 = .210$. However, we could not find a significant effect of Environment, $F(1, 31) = 3.170$, $p = .085$, $\eta_p^2 = .093$. There was a significant interaction effect of Hands × Environment, $F(1, 31) = 10.019$, $p = .003$, $\eta_p^2 = .244$.

A 2(Hands: *fire* vs. *ice*) x 2(Environment: *fire* vs. *ice*) ART ANOVA on the total rotation of the HMD showed a significant effect of Hands, $F(1, 31) = 8.837$, $p = .006$, $\eta_p^2 = .222$, and of Environment, $F(1, 31) = 16.686$, $p < .001$, $\eta_p^2 = .349$. There was no significant interaction effect of Hands × Environment, $F(1, 31) = 2.933$, $p = .097$, $\eta_p^2 = .086$.

Results indicate that participants moved and rotated their head more in the *fire* hands and *fire* environment compared to the other environments (see Figure 7).

4.6 Correlation Analyses

To test whether there is a relationship between the skin temperature and the sense of presence, the head movement, and the thermal comfort and sensation, Spearman's rank correlations between the skin temperature in the last minute (the fifth minute) and the other measures were computed. We found a significant correlation between the total translation of the HMD and the skin temperature, $r_s = .44, p < .001$, as well as the total rotation of the HMD and the skin temperature, $r_s = .35, p < .001$. This indicates that the skin temperature increased the more participants moved their heads while experiencing VR. The correlation between the skin temperature and all other measures were not significant (all $p > .05$).

We also performed correlation analyses between the room temperature and each measure to understand their relationship. Spearman's rank correlations revealed a significant negative correlation between the dimension *involvement* of the IPQ and the room temperature, $r = -.021$, $p = .017$. Furthermore, we found a significant positive correlation between the total head translation and the room temperature, $r = .33$, $p < .001$. A Pearson correlation analysis also showed a significant correlation between the hand temperature and room temperature, $r = .53$, $p < .001$. All other correlations were not significant ($p > .05$).

5 DISCUSSION

The study revealed significant effects of avatar and environment on objective and subjective measures. Thus, we discuss the effects in relation to previous work, highlight the implications, and outline important future work.

5.1 Effects on Skin Temperature, Thermal Sensation, and Comfort

We found that virtual *fire* hands decreased and virtual *ice* hands increased skin temperature of participants' hands across time (see Figure 4). Interestingly, the VE had no effect on skin temperature indicating that the embodiment of virtual hands with thermal characteristics such as being "very hot" or "very cold" affect the actual skin temperature across time. While the room temperature and the hand temperature positively correlated, which is not surprising, we

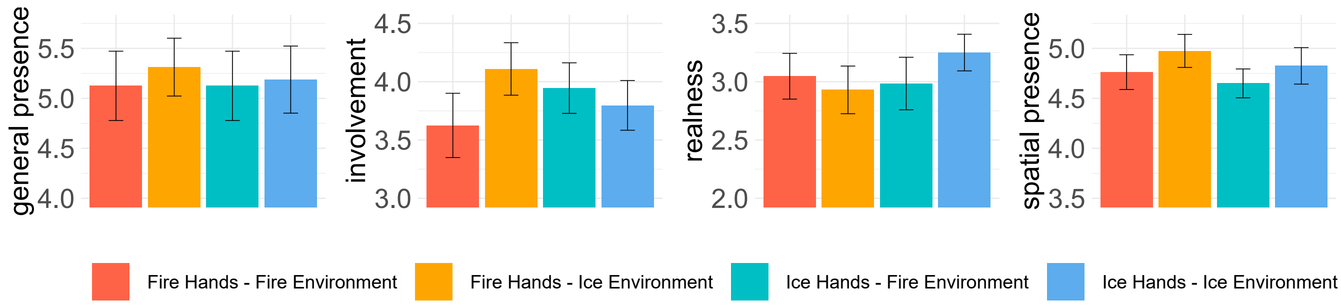

Figure 6: Mean scores of each dimension of the IPQ. The error bars show the 95% confidence interval.

can dismiss that the room temperature was a confounder as there were no significant differences of the room temperature between conditions. Results of the thermal sensation scale indicate that the environment and the visual appearance of the virtual hands affected participants' thermal sensations. Participants felt warmer in the *fire* environment while having *fire* hands and colder while embodying *ice* hands in the *ice* environment. We also found that the environment affected participants' thermal comfort. Participants had a higher thermal comfort in the *ice* world compared to the *fire* world. Hence, we could increase or decrease participants' perception of temperature by changing the virtual avatar and environment. We also replicated findings from previous work showing that in general participants experienced a warmer temperature sensation while being in the *fire* compared to the *ice* environment. The significant interaction of Environment × Time suggests a systematic increase (*fire* world) or decrease (*ice* world) of the thermal sensation across time (see Figure 5).

To explain the findings, we refer to previous work showing thermophysiological effects induced by visual characteristics representing certain thermal conditions. The effects on skin temperature and thermal comfort are in line with Takakura et al. [113], who found that images showing a hot desert could decrease body temperature while images depicting snow increased temperature. Our results even extend these findings, as we found that not only environmental characteristics but also the avatar's visual appearance can induce thermophysiological reactions. Takakura et al. [114] proposed conditioning as a potential explanation for such effects. The authors assume that seeing extreme thermal conditions can activate mental imagery and associations how it would feel to experience such conditions.

In line with self-perception theory [21], the embodiment of avatars in terms of virtual hands that represent fire and ice activate cognitive concepts that are associated with such thermal conditions. Hence, thermoregulative mechanisms could be triggered to counteract the rise or fall of temperature that is displayed by the avatar. In contrast to Eckhoff et al. [35], we explicitly stylized our virtual hands instead of realistically animating fire or ice effects to create the feeling of embodying a superhero's hand to prevent negative effects such as pain sensations from occurring. Results of the thermal sensation and comfort scales show that our stylized hands could trigger cognitive concepts such as *heat* associated with *fire* or *cold* associated with *ice*. In line with embodied cognition theories postulating a strong bond between physiological and psychological processes [9, 124], we assume that such top-down cognitive mechanisms could affect thermoregulation resulting in an increased or decreased skin temperature.

5.2 Implications

Our findings have implications for designers and researchers of VR applications. As thermal regulation, sensitivity, and even immersion, can change due to virtual content, the users' discomfort and, therefore, likely their VR experience can also be affected.

As designers and developers of VR applications frequently transport users to virtual places with different environmental colors or even thermal conditions to create interesting VR experiences, they, therefore, have to be aware of the effects caused by the environment on users' thermal perception and comfort. We showed, for example, that a virtual world suggesting extreme heat can reduce the thermal comfort during the exposure. This could, in turn, potentially decrease the usage and even the user retention on a long term, which could cause detrimental effects for commercial applications. Hence, we argue that designers of VR applications have to consider that a prolonged exposure to a virtual world inducing the sensation of an increased temperature could have negative effects on the overall VR experience. When designers need to create environments that suggest certain temperatures, for whatever reason, our findings suggest that the design of avatars could potentially counteract a sensation of an increased or decreased temperature to maintain a balance. However, more research is needed to substantiate our findings and better understand how users' thermal perception is affected by the visual appearance of virtual worlds and avatars to inform the design of VR applications.

Similar applies to the embodiment of the virtual avatar. While the fire avatar caused participants to feel warmer and the ice avatar made them feel colder, our findings even show that avatars are even able to change users' skin temperature. These findings are important for researchers who investigate avatar embodiment. They have to understand how and whether avatars that suggest different thermal conditions influence the basal skin temperature as such effects may confound physiological measurements [106], e.g., galvanic skin response is connected with skin temperature and sweating mechanisms [74].

Our findings also indicate that the effects can be leveraged in certain circumstances. When aiming at creating a virtual scenario

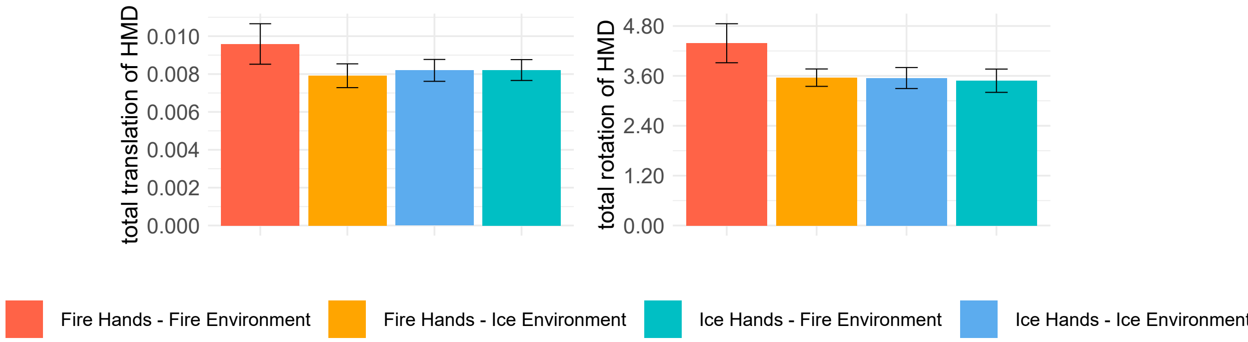

Figure 7: Average total translation (left) and rotation (right) of the HMD using its x,y, and z-position and rotation per frame based on the coordinate system of the game engine Unity.

that should depict heat, e.g., for VR simulations that should raise awareness for global warming, we argue that depicting extreme temperatures in VR using avatars and the VE can reduce the thermal comfort and contribute to the efficacy of such interventions. As users also feel warmer and experience the ambient temperature to be higher during the VR exposure, such "negative" effects could potentially contribute to raising awareness for environmental issues. While exposing users to negative consequences of certain behavioral patterns is a fundamental aspect of exposure therapies and interventions, e.g., experiencing ocean acidification [3], the process of becoming homeless [42], or cutting down large trees to raise awareness for environmental issues [2], future research could further investigate whether the design of VEs that reduce thermal comfort could contribute to the efficacy of VR interventions related to environmental issues.

5.3 Limitations

There are multiple potential limitations, which we discuss in the following. As we found effects on the dimensions involvement, realness, and spatial presence of the IPQ, we cannot rule out that experiential characteristics of the VR conditions modulated body temperature and thermal comfort. For example, participants could experience a higher presence and involvement in one of the conditions and, therefore, be more physically active resulting in effects on skin temperature, e.g., due to sweating. As we found effects of the virtual hands and environment on participants' head movement (see Figure 7), one could assume that such induced behavioral changes could therefore modulate thermal responses.

While participants were more physically active while embodying *fire* hands in the *fire* environment, their skin temperature decreased across time during this condition. A higher physical activity, however, should result in an increased skin temperature across time [39], which was not the case. Hence, we assume that the effects on skin temperature do not originate from participants' higher physical activity. In line with research from the Proteus effect describing behavioral changes caused by the visual appearance of avatars [57, 59, 64, 128], future work should further explore how avatars representing certain thermal conditions affect users' behavior and activity in VR. In this vein, it could be investigated whether a fire or ice appearance of the avatar increases or decreases physical activity due to the connected associations with both elemental powers [1], e.g., fire could be connected with energy and assertiveness whereas ice with inactivity and motionlessness due to freezing.

Our study design did not involve a neutral condition to understand how participants would behave and react with avatar hands with an appearance that does not provide any thermal cues, e.g., virtual hands with a neutral appearance (for example, see Fig. 3 or more realistic humanoid virtual hands using skin tone matching). Future studies could use a baseline to understand users' "normal" thermophysiological responses in such a setting. This could provide further insights into whether the fire hands indeed decreased or the ice hands increased the skin temperature compared to a baseline.

While we assessed essential VR qualia such as the sense of presence, future studies could also measure the experienced limb ownership of the virtual hands to investigate its moderating influence on the effects on thermoregulation and thermal comfort. Limb ownership is known to be mainly driven by bottom-up factors such as visuo-tactile and visuo-motor synchrony [117] and not by top-down factors such as the visual appearance of avatars [55]. As we used avatars with an identical configuration of bones and, therefore, ensured a constant framerate and tracking in all conditions, we did not assess the experienced limb ownership. Previous work suggests that our conditions should induce similar ownership sensations of the avatars and should, thereby, not moderate our effects found on thermoregulation and thermal comfort. Nonetheless, future studies could investigate the effects of limb ownership by modulating it using visuo-motor asynchrony to create a delay between users' motion and the displayed avatar's motion [15, 66].

Similarly, motion sickness and other effects caused by VR can modulate users' behavioral and physiological responses [88]. To reduce motion sickness, we set our target frame rate to 90 fps to create a smooth and low-latency VR experience [37]. Additionally, we only changed the mere visual appearance of the avatars and the VE by using different shaders and materials. We therefore do not assume that the conditions induced different levels of motion sickness. However, future work could control for effects caused by motion sickness, e.g., using physiological measurements such as galvanic skin response, to further isolate thermophysiological and psychological impact of avatars and the VE from possible confounders.

5.4 Future Work

In our study, participants embodied virtual fire or ice hands while being immersed in a fire or ice world for a maximum of 5 minutes per condition. To sustainably increase one's thermal comfort and decrease energy consumption, we argue that longer exposure is required to amplify the effects. While research on long-term effects of VR in general [109] and avatar embodiment, in particular, is sparse [53, 63, 96], future studies should address the time facets of VR expositions to deepen our understanding of thermophysiological effects and inform the design of avatars and VEs to leverage such effects.

Great care should also be paid to negative effects due to prolonged exposure to VR content that causes changes in users' thermoregulation. Manipulating thermoregulative mechanisms through a visual discrepancy between the anticipated temperature provided by visual information and the actual temperature of the environment could be harmful for the neuroendocrine system in case of prolonged exposure. In line with Takakura et al. [114], who argued that it is not useful for the body to adapt the body temperature to cues that do not contain thermal energy, such disturbance of human homeostasis could have negative consequences that need to be investigated in future studies, e.g., maladaptive thermoregulation that incorrectly responds to actual thermal energy [113, 114].

From a game design perspective, future work could also address the effects of different avatar hands and VEs on the player performance. It could be explored whether ice hands in a fire environment causes player to perform worse since ice hands may appear at a disadvantage in a fire environment compared to fire hands in an ice environment. Peña and Kim [92], for example, postulated the "give up hypothesis". The authors showed that participants performed worse when playing tennis on a WiiFit with avatars the authors dubbed obese against NPCs with a more athletic appearance, as they thought they have a physical disadvantage compared to their opponents. In our study, we did not assess task performance to avoid creating a competitive scenario causing participants to be physically engaged at a higher level due to the pressure of competition, which, in turn, could skew the thermophysiological responses and temperature perception. However, future work could investigate the "give up hypothesis" building upon our study without focusing on thermoregulation but instead addressing the player performance and overall game experience.

Our work also provides insights to research aiming at modulating thermal comfort without changing the ambient temperature (e.g. [5, 47, 122]). Changing the ambient temperature through air conditions or heating increases energy consumption. Approaches to modulate thermal comfort without changing the ambient temperature can therefore decrease energy consumption. Optimizing energy consumption through the design of the VE is certainly limited by the use case. For office work, it could be as subtle as changing the environment's color temperature. Less constrained experiences, such as social VR, could happen in VEs providing more prominent temperature cues. In games, the whole experience, including the environment and the avatar, could be adapted. Players could, for example, play Marvel's Human Torch during cold weather or Marvel's Iceman during warm temperatures. Game publishers could also develop expansions for their games that counteract the season's temperature and release, for example, an ice world in summer and a hot desert world in winter. While the effects are likely small, increasing the temperature in an air-conditioned room by just 1°C could reduce the energy consumption by over 10% [111]. Future studies could further elaborate on reducing energy consumption using different VEs and avatars.

6 CONCLUSION

In this paper, we investigate the effects of avatars and the VE on thermal perception and skin temperature. In a controlled experiment, 32 participants performed a simple task in a fire or ice world while embodying fire or ice hands. We found that fire hands decreased skin temperature over time. In contrast, ice hands increased participants' skin temperature over time. Additionally, participants' thermal sensation was affected by the virtual hands and the environment. Participants felt warmer while being immersed in the fire environment having fire hands compared to the ice environment having ice hands. Their thermal comfort was also affected by the environment. They had a lower thermal comfort in the fire environment compared to the ice environment.

Overall, we showed that virtual avatars and environments representing extreme thermal conditions can not only affect thermal perception but even thermoregulative mechanisms as indicated by changes in skin temperature. Hence, our paper extends prior research by showing that both virtual worlds as well as avatars affect how users perceive their ambient temperature while experiencing VR. Future studies can build upon our work to explore further aspects such as long-term effects or behavioral changes to deepen our understanding of humans' thermoregulation and temperature perception and inform the design of VEs and avatars.

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