Effects of Virtual Clothing and Naturalistic Virtual Environments on Temperature Perception and Thermoregulation

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Thermal perception and regulation are essential for many gameplay experiences. They are primarily influenced by temperature and humidity, but also by visual cues. In particular, stylized avatars and environments that suggest extreme temperatures in virtual reality (VR) games can affect how warm or cold players feel. However, it is unclear whether more naturalistic avatars and environments produce similar effects and how these factors interact. To investigate this, we conducted an online study (N = 100) examining whether an avatar's clothing, body shape, skin tone, age, and the surrounding environment influence anticipated thermal comfort. Most factors showed significant effects. Because environment and clothing had the strongest impact, we examined them further in a second study in VR (N = 24). The results showed measurable effects on skin temperature, thermal sensation, and thermal comfort. These findings indicate that even naturalistic avatars and environments in games can influence players' thermal perception and physiological responses. Game designers can therefore intentionally use visual cues to shape player experience, but they should also be aware of unintended temperature-related effects in VR. Implications for game design and player comfort are discussed.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; • **Applied computing** → *Computer games*.

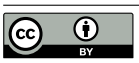
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1 Introduction

Thermal perception and regulation are fundamental for human satisfaction [41], productivity [19, 118], and performance [42, 139]. In human-computer interaction (HCI), thermal feedback has been explored as an additional sensory channel to enrich interaction and immersion. For example,

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thermal devices have been proposed as multisensory interfaces for digital environments [26], head-mounted displays [96, 131], or handheld devices [81]. Particularly in immersive games, thermal experiences are relevant because they can affect player comfort, performance, and engagement. Temperature can also influence the players' productivity in games [11], serve as an atmospheric or informational cue [81], or even an active game element [73]. Thus, thermal stimuli can serve as both functional as well as experiential components in game design.

Immersive thermal gaming experiences become increasingly important for entertainment, and particularly for gaming, virtual reality (VR) as well as VR exergaming [11, 26, 66, 72, 73]. Players often spend extended periods in virtual environments, where thermal comfort, immersion, and performance are closely linked. Unlike physical environments, VR also allows designers to create entirely artificial worlds and to alter players' appearance by embodying them in different *avatars*. That design flexibility enables game developers to intentionally influence players' thermal perception in VR [21, 22, 53]. At the same time, it raises the possibility of unintended thermal effects, where visual elements of a game—such as snowy landscapes, desert levels, or character clothing—may alter players' perceived comfort or physiological responses without the designer's explicit intent. Understanding these effects is therefore important for both player experience and responsible game design.

Previous work demonstrated that virtual environments presenting extreme thermal conditions in VR can alter both perceived warmth and physiological responses [69]. For example, Kocur et al. [69] showed that immersion in a virtual lava environment increased users' perceived warmth, whereas an ice-themed environment led to a decrease in perceived warmth. Similar effects could be found by Weijs et al. [128], who even showed that users' skin conductance was higher in a red room compared to a blue room. While not in immersive VR, Takakura et al. [116] found that watching videos depicting hot or cold environments influences skin temperature. These findings demonstrate that environments visually suggesting different temperatures can not only influence thermal perception but also physiological responses.

Related research further showed that embodying avatars that visually suggest different thermal conditions in VR can also cause perceptual and physiological responses. While embodying virtual fire hands decreases skin temperature, embodying virtual ice hands increases skin temperature during gameplay in VR [69]. While not measuring body temperature or analyzing effects on perceived temperature, Eckhoff et al. [31] found that burning hands, presented through augmented reality glasses, increase skin conductance for participants who perceived increased warmth.

What remains unclear is whether ordinary, naturalistic cues have similar effects. Many applications and studies rely on highly stylized heat or cold metaphors or exaggerated scenes such as in immersive games [32, 68, 69, 129], which makes it difficult to assess whether features in realistic environments carry enough weight to influence thermal perception or even thermoregulation. Wührl et al. [133], for example, immersed users into a highly stylized virtual lava or ice cave while changing the hue of the scene. Similarly, Kocur et al. [69] embodied users into stylized fire or ice avatars to explore thermal effects. In contrast, a larger body of work used more realistic indoor VR scenes by modifying the wall paint of the scene (e.g., blue or red) [20, 79, 80, 100, 128]. However, these studies did not include avatars. Consequently, users were experiencing the virtual world without having a virtual body. As a result, the interplay between a naturalistic avatar and the surrounding virtual environment and their combined influence remains unclear. As many games now feature realistic virtual characters and environments using high-fidelity graphics [103], a clearer understanding of these mechanisms is needed to inform VR game design, avoid unintended thermal effects, and ground theories of embodied thermal perception in realistic scenarios.

One important and naturalistic cue is the clothing of an avatar. To create natural experiences, designers of game characters equip avatars with attire that can be either functional, i.e., an armor

representing certain abilities such as increased power [24], or for aesthetic purposes, e.g., clothes in games that represent a fashion trend [101]. Clothing also plays an important role in commercial VR applications, where virtual characters can depict various thermal conditions. For example, in Skyrim VR [16], an avatar's clothing and armor can be customized and can represent warm or cold conditions. Importantly, prior research has shown that clothing can influence users' self-perception and performance [1, 2]. For example, Guegan et al. [45] found that embodying an avatar wearing a lab coat increased creativity during brainstorming tasks. The authors attribute the effects to the cognitive and professional qualities people commonly associate with scientists and their clothes. As clothing is inherently associated with temperature, it remains unclear whether an avatar's attire can also influence users' thermal perception or even their thermophysiological responses. From a design perspective, however, understanding how virtual clothing shapes these experiences is essential. On one hand, an avatar's clothing could be leveraged to enhance thermal comfort. On the other, designers and researchers must be aware of potential unintended effects that could diminish the user experience. This highlights the need to further investigate how an avatar's clothing affects thermal perception and how these effects interact with the perceived temperature of the virtual environment.

In this paper, we, therefore, investigate how naturalistic avatars and environments influence subjective and physiological thermal experiences. We first conducted an online survey to assess the effects of avatars' clothing, age, body shape, and skin tone, as well as the virtual environment, on participants' assumptions about thermal comfort. Based on these findings, we conducted a study in VR to investigate the effects of avatar clothing and virtual environment on self-reported thermal perception and objective skin temperature. This two-step approach allowed us to examine how an avatar's virtual clothes associated with different temperatures (summer vs. winter) and virtual environments (arctic vs. beach) influence users' temperature perception, skin temperature, and sense of presence and embodiment. We found that naturalistic avatars' clothing and realistic virtual environments influence both subjective thermal perception and skin temperature. Thereby, we show that virtual clothing and environments can be used to shape thermal comfort and physiological response but also discuss potential risks of unintended thermal effects. As a whole, our work highlights how visual embodiment and the environment can shape the experience of temperature in VR, suggesting that VR game designers can leverage avatar clothing and environmental context not only to enhance immersion and presence but also to support well-being, performance, and energy-conscious design.

2 Related Work

Our work builds on research examining human thermoregulation and thermal comfort, as well as the thermal influences of virtual environments and avatars. First, we review foundational work on body temperature regulation, thermal perception, and the wide range of physiological, psychological, and environmental factors that shape thermal comfort. Next, we summarize research investigating how virtual environments and game worlds—through visual, environmental, and multisensory cues—affect perceived temperature and thermophysiological responses. Finally, we outline prior work showing how game characters and avatars influence users' perception, behavior, and embodiment, highlighting emerging evidence on thermal effects and open questions regarding the role of clothing in shaping thermal experience.

2.1 Temperature Regulation and Thermal Comfort

The human body's temperature regulation is essential for maintaining homeostasis, which in turn allows for optimal physiological and psychological functioning [37, 61]. Its importance ranges from optimizing sport performance [42] and controlling blood flow [56] to supporting cognitive

function [108], preventing heat-related illnesses [43], and aging [38]. Thermoregulative mechanisms are deeply integrated into the body's autonomic nervous system and are controlled by the hypothalamus [117]. The thermoregulatory system as a whole can be divided into an autonomic and a behavioral branch, with the autonomic branch being responsible for involuntary responses such as sweating or shivering, and the behavioral branch being responsible for voluntary responses such as relocating oneself or changing clothes [36].

Thermal comfort, defined as "that condition of mind which expresses satisfaction with the thermal environment" [5, 90], is a critical factor influencing occupants' satisfaction [41], energy use [4, 30], productivity [19, 118], and cognitive performance [139]. Empirical evidence highlights these links. Lipczynska et al. [78], for instance, found that productivity rises with greater thermal satisfaction, while other studies show that thermal discomfort lowers academic performance [52] and adequate comfort enhances athletic outcomes [110]. Similarly, Bueno et al. [19] confirmed the strong connection between productivity and thermal comfort.

Body temperature and consequently also thermal comfort are influenced by ambient temperature and humidity as well as by physical and mental exertion [8, 35]. Yet, research showed that further factors also shape thermal perception and regulation. These include stress [94], seasonal variation [82], emotional states [33], and hormonal fluctuations across circadian cycles [7, 35]. Evidence further suggests that even purely cognitive processes, such as mental imagery and meditation, can alter thermal regulation. For example, Kozhevnikov et al. [74] reported that Tibetan tummo meditation can elevate core body temperature into the moderate fever range. Some researchers argue these effects arise from somatic processes (e.g., changes in respiration or muscle activity) rather than cognitive mechanisms (e.g., mental imagery or relaxation) [63, 88], but the underlying causes remain unresolved. Although controversial [27], other studies showed that bodily illusions, such as the experience of inhabiting an artificial rubber hand, can modulate skin temperature through altered thermoregulation [91, 104]. Collectively, these findings show that thermal regulation and perception are shaped by more than exertion and ambient conditions.

Given that vision is the dominant human sense [44], research also identified visual input as an important contributor to thermal experience [23, 119]. Postulated a hundred years ago, the hue-heat hypothesis [14, 89], for example, posits that an environment with red lighting feels warm and one with blue lighting feels cool. While the hue-heat hypothesis has been debated for almost a century [141], recent work concludes that visual cues, such as lighting with warm or cold color temperatures, indeed alter thermal perception [86, 124, 141]. Consequently, the design and visual characteristics of the surrounding environment can affect how people perceive ambient temperature [17].

Recognizing the effects of the visual surroundings on thermal perception, building designers aim to optimize indoor thermal conditions not only for occupant well-being but also to support climate-change mitigation efforts [51]. Strategies range from architectural interventions such as wall design [112, 124] to environmental features like lighting with specific color temperatures that influence thermal comfort [54]. Ultimately, environments that promote positive thermal perception can simultaneously improve human performance and reduce energy consumption in buildings [132].

2.2 Thermal Effects of Virtual Environments and Game Worlds

Immersive technologies are a promising tool to systematically explore thermal perception [95]. For example, Chinazzo et al. [21] observed that colored lighting in VR influenced perceived temperature, even when actual room temperature remained constant. Similarly, Huang et al. [53] found that participants rated red VR rooms as warmer and more comfortable than blue ones, suggesting that lighting conditions can modulate thermal comfort and potentially reduce energy demand.

Subsequent studies have replicated these findings [22, 106], though systematic approaches to influencing both comfort and physiological response remain limited.

Vittori et al. [123] examined how window aspect ratio, sunlight color, and lighting temperature (1800–5000 K) affect perception. Results indicate that larger window ratios and lower color temperatures increased warmth perception, aligning with prior findings that blue rooms feel cooler than red or yellow ones [53]. Similarly, Chinazzo et al. [21] showed that orange lighting at 24 ℃ heightened perceived warmth but reduced comfort.

Beyond lighting, VR allows users to inhabit diverse virtual worlds that imply different thermal conditions. Wu et al. [132] showed that outdoor scenarios were perceived as thermally more pleasant than indoor or laboratory settings. Adding natural elements such as green walls enhanced comfort [112] and reduced stress [94, 126]. Previous work also explored thermophysiological effects caused by virtual worlds. Exposure to visual cues that suggest hot temperature, such as flames or smoke, can alter arousal, skin conductance, and heart rate variability [128, 129]. Similarly, Kocur et al. [69] reported that virtual lava fields increase subjective warmth compared to an icy setting. Collectively, these findings demonstrate that VR can modulate both thermal perception and aspects of thermoregulation even without direct thermal energy input.

Another example of intended thermal effects induced through the visual design of a game environment is the serious game SnowWorld [50]. This virtual reality application deliberately integrates cold-related visual cues—such as snow, ice, and frozen landscapes—to create an immersive perception of coldness. The game is used as an adjunctive pain management tool for burn patients, aiming to reduce their perceived pain during wound care procedures. By visually immersing patients into a cold, snowy environment, SnowWorld leverages cross-modal sensory interactions, where visual stimuli influence thermal perception and pain processing [49].

Non-visual cues have also been explored. For instance, Brooks et al. [18] created a scent-based device that induces warm or cool sensations in VR, while Günther et al. [46] designed a wearable sleeve delivering combined visual and thermal stimuli. Investigating spatial perception, Günther et al. [47] found that participants often mislocalized thermal stimuli in VR despite expressing high confidence in their judgments. To strengthen immersion, various thermo-haptic systems have been developed, including gloves [75], bracelets [15], actuators mounted on headsets [96] or feet [34], and stationary prototypes using Peltier packs to simulate catching snowflakes or getting rained on the hands [125]. More recently, Mazursky et al. [87] demonstrated the use of flexible thermally conductive materials to provide localized heating and cooling feedback during grasping or walking.

2.3 Effects of Virtual Avatars

Avatars in VR games are more than digital representations of users. They can shape behavior, perception, and even physiological responses. Controlling avatars from a first-person perspective with visuo-motor synchrony, users often develop a strong sense of embodiment, feeling as if the virtual body is their own [62, 113]. This sense of embodiment enables the Proteus effect, which describes changes in users' behavior, attitudes, and perception caused by an avatar's characteristics [65, 135].

Research also showed that avatars' characteristics can influence social interaction and cognition. For instance, users embodying taller avatars negotiated more confidently, while those with more attractive avatars maintained closer interpersonal distance and disclosed more personal information [136]. Banakou et al. [10] showed that embodying avatars with the appearance of Albert Einstein improved cognitive task performance, while other work demonstrated that embodying users in athletic avatars can reduce their heart rate [67, 72] and perceived exertion [67, 71].

Previous work also found that embodiment illusions can influence users' thermophysiological responses. Salomon et al. [107] showed that participants exhibited decreased skin temperature across several body locations when experiencing an avatar as their own body. Although not

conducted in VR, Moseley et al. [91] similarly reported a drop in skin temperature in the real hand when participants felt ownership over an artificial rubber hand. However, subsequent attempts to replicate Moseley et al.'s findings have produced inconsistent results (see de Haan et al. [27] for an overview). Drawing on a series of studies, de Haan et al. [27] concluded that hand cooling in the rubber hand illusion is not causally related to changes in body ownership. In contrast, Rohde et al. [104] conducted their own series of experiments while systematically varying the experimental procedures. Their findings suggest that relative hand cooling occurs only during manual, but not automated, stroking, and that this effect is independent of the subjective ownership illusion.

Recent work also systematically explored thermal effects caused by avatars representing extreme thermal conditions. Kocur et al. [69] investigated how fire and ice avatar hands influence thermal perception and thermophysiological responses in a gamified VR experience. Participants felt warmer when embodying fire hands compared to ice hands. In addition, their skin temperature decreased with fire hands compared to ice hands. Hence, results suggest that avatars associated with thermal conditions can induce perceptual and physiological changes. The authors used avatars with superpowers such as the ability to throw fireballs. The effects of more realistic avatars that suggest different thermal conditions are unknown.

2.4 Behavioral and Perceptual Effects of Avatars' Clothes

Clothing not only conveys identity and appearance but also shapes behavior [115]. For instance, wearing a lab coat associated with scientists and doctors can enhance cognitive performance on attention-related tasks [1]. Similarly, professional hockey teams dressed in black jerseys displayed more aggressive behavior and received more penalties than those in lighter uniforms [40]. This phenomenon, termed "enclothed cognition", extends the broader theory of embodied cognition, which suggests that perceptions and behaviors are influenced by the body's physical attributes [6, 130].

Research in digital contexts revealed similar effects of avatars' clothing. For example, sexualized avatars [39] or avatars with non-creative attire [28] can shape users' behavior and self-perception. Importantly, these effects were induced by clothing alone rather than by altering morphological traits such as muscularity [48, 71], age [102], or height [134]. This underscores that the perceived functionality of clothing can independently trigger behavioral and perceptual changes.

Several studies highlight the role of clothing for enhancing or altering performance during virtual embodiment. Previous work demonstrated that participants exposed to avatars that resembled themselves in sportswear engaged in more physical activity than when embodied as strangers in formal attire [92]. Avatars dressed in attire associated with intelligence and creativity increased users' creative output [45]. In contrast, Peña et al. [97] showed that embodying an avatar wearing Ku Klux Klan robes activated aggression-related concepts and inhibited affiliative ones, whereas avatars dressed as doctors promoted less aggressive behavior. Similarly, avatars in dark robes elicited more antisocial behavior than those in white robes.

Clothing in games can also provide perceived protection. For example, embodying virtual arms covered in iron armor reduced pain responses to electrical stimulation compared to unprotected arms [127]. Likewise, avatars equipped with robust, armor-like suits performed better at blocking projectiles than those without protective gear [24]. Oberdörfer et al. [93] found that stride length and hip flexion differed significantly when participants embodied avatars in high heels versus sneakers.

In this vein, previous work showed that aligning the virtual environment with an avatar's visual appearance can enhance both behavioral and perceptual plausibility [84, 85]. Mal et al. [85], for example, investigated if users' physical performance was influenced by a congruent or incongruent avatar-environment relationship, i.e., either embodying an avatar in sports or business wear in

either a gym or office environment. As the authors found that congruence can help to increase users' perceived plausibility, it is reasonable to assume that congruence between an avatar's clothing and the surrounding virtual environment may further amplify the effects elicited by both the avatar and the environment. While avatars wearing certain clothes are known to influence users' perception and behavior [65, 137], thermal effects caused by the avatars' clothes and the interaction with the environment remain unclear.

2.5 Summary

Previous studies showed that human perception of warmth and cold is shaped by visual cues. For example, cooler lighting is perceived as cold, whereas warmer lighting is perceived as warm [3, 4, 89]. Building on this, recent work used playful VR environments to immerse participants in environments suggesting extreme thermal conditions, replicating earlier findings. Players reported feeling warmer in fire-themed worlds and colder in ice-themed ones [69]. Interestingly, embodying avatars associated with specific thermal states can modulate perception and physiology. For instance, embodying avatars with fire hands led to a decrease in skin temperature, whereas ice hands increased it, despite the absence of actual thermal stimuli. However, these studies relied mainly on superhuman-like avatars (e.g., fire or ice hands) or extreme environments (fire vs. ice worlds). Although a larger body of work has employed more realistic indoor VR settings by altering environmental features such as wall color (e.g., blue or red) [20, 79, 80, 100, 128], these studies did not use avatars to provide users with a virtual body in VR. To enhance realism and ecological validity, however, naturalistic stimuli, such as avatars dressed in seasonally appropriate clothing (e.g., winter attire vs. summer attire) and virtual environments resembling everyday warm (e.g., beach) or cold (e.g., arctic) settings, are needed. Yet, it is unknown how such realistic cues influence thermal perception and physiological responses, and how a virtual environment's thermal cues interact with an avatar's thermal cues.

3 Exploring Effects on Anticipated Thermal Comfort

We conducted a controlled experiment to explore which characteristics of an avatar influence anticipated thermal comfort. To explore multiple factors, we systematically varied the environment and four different avatar characteristics in an online survey.

3.1 Method

To achieve high statistical power, we used the online platform Prolific to recruit a homogeneous sample of 104 participants. They completed the study using LimeSurvey.

3.1.1 Design. We conducted the study using a full-factorial design with five within-participant factors and one between-participant factor. We derived the five binary within-participant factors (environment, clothing, body shape, skin tone, and age) that vary the avatars' characteristics from previous work (see section 3.1.2). We assumed that the avatars' characteristics might be differently perceived in different environments. For example, a person in warm clothes shown in a neutral environment might suggest that the environment is cold and, consequently, the person also feels cold despite wearing warm clothes. Therefore, we used the environment as an additional binary within-participant factor. Finally, previous work showed that gender affects thermal comfort [57, 59]. Consequently, we used gender as a between-participant factor and showed female participants female-gendered avatars and male participants male-gendered avatars.

Combining the five binary within-participant factors and the between-participant factor gender resulted in 64 stimuli across 32 within-participant conditions (see Figure 1 as well as Figures 10 and 11 in the appendix). For each of the 32 variations of the within-participant factors, we asked

participants two questions to assess the assumed thermal comfort and the realism of the scene. We derived the question regarding thermal comfort from the Bedford Thermal Scale [13] by asking "Imagine you are this person in this place. How would you rate your thermal comfort?". The seven-point item ranged from "much too cold" to "much too warm". In addition, we derived a single item from the IPQ presence questionnaire [109] to assess the realism of the presented scene by asking "How real does this scene seem to you?". The seven-point item ranged from "Not real at all" to "Completely real".

3.1.2 Stimuli. We systematically developed 64 stimuli by crossing gender as well as the five binary factors we derived from previous work. Each of the five factors was defined at two categorical levels, typically aligned with either "warm" or "cold" semantic cues, to preserve factorial balance and ensure interpretability. To identify the factors that may influence users' thermal responses, we reviewed prior work in environmental ergonomics and psychology, particularly research on thermal perception and comfort. In the following section, we outline how these factors were derived from the studies and literature.

While research still investigates the nuances [138, 140], clothing obviously affects thermal comfort and thermoregulation. Thus, we varied the avatars' clothing by either dressing them in a light summer outfit or in warm winter clothes. In line with the hue-heat hypothesis suggesting that warm colors (e.g., reddish colors) are associated with warmer temperatures compared to cold colors (e.g., bluish colors) with colder temperatures [89, 141], we used black clothes to isolate the effects of the avatars' clothes from the effects caused by its displayed hue.

Lipczynska et al. [77] found that individuals with higher BMI consistently prefer cooler temperatures, especially under moderate ambient conditions. This aligns with the assumption that a larger body size is associated with greater thermal insulation and heat retention. Supporting this, Rupp et al. [105] observed that individuals with a higher weight reported greater discomfort in warm indoor environments. Accordingly, broader avatars may visually cue a warmer thermal impression. Thus, we manipulated body shape by rendering avatars with either slim or broad morphologies.

Ziat et al. [141] showed that participants exposed to thermal stimuli paired with congruent colors (red–hot, blue–cold) rated the sensations as more intense. This suggests a reliable cross-modal mapping between visual color and temperature. Subtle differences in facial coloration may bias thermal perception in a predictable direction. Thus, we varied skin tone by adjusting facial hue toward a warmer, browner tone or a cooler, paler tone.

Inoue et al. [55] demonstrated that older individuals exhibit diminished thermal sensitivity to warm and cold stimuli, a phenomenon attributed to age-related decline in peripheral thermal receptors. These physiological changes can lead to the perception that older adults are less thermally robust. While Collins et al. [25] observed no large difference in preferred temperature across age groups, older adults showed reduced responsiveness to ambient fluctuations. Beach et al. [12] concluded that age affects thermal perception and reduces thermal sensitivity. Thus, we varied the avatar age by presenting an either younger or older adult representation to investigate whether the perceived age of the avatar modulates users' anticipated thermal perception, such that the warm environment is rated as less warm and the cold environment as less cold.

Previous work found that the visual environments can induce thermoregulatory shifts. Takakura et al. [116] showed that participants' core body temperature changed in response to viewing videos of hot or cold locations. In support, Wu et al. [132] found that immersive VR nature scenes significantly altered users' thermal comfort ratings. Thus, we varied the environment by either showing a snow-covered landscape or a sunlit beach.

In addition to the five within-participant factors, we included gender as a further factor, as there is robust evidence for gender-related differences in thermal sensitivity. Reviewing findings from



Fig. 1. Exemplary male-gendered (top row) and female-gendered avatars (bottom row). The avatars on the left represent the winter clothes, younger, slim body, and darker skin color conditions, located in the snow-covered environment. The avatars on the right represent the summer clothes, older, broad body, and lighter skin color conditions, located in the beach environment.

over forty studies, Karjalainen [59] concluded that women consistently report greater thermal discomfort than men under identical indoor conditions, a pattern linked to physiological traits such as lower skin temperature and attenuated vasoconstriction. Supporting this, Jowkar et al. [57] found that female students in naturally ventilated classrooms reported colder sensations than their male peers despite wearing warmer clothing. Thus, we presented female-gendered avatars to female participants and male-gendered avatars to male participants. We ensured that the five within-participant factors are consistent across both considered genders.

3.1.3 Implementation. We created all avatars with DAZ Studio 4.22 and rendered them from a fixed first-person camera. To balance embodiment with self-awareness, the camera was positioned to simulate taking a 'selfie' with a smartphone, allowing participants to see both the virtual body (the avatar) and the surrounding environment simultaneously. A first-person perspective was chosen because it strengthens body ownership and enhances the realism of self-representation [29], making it particularly suitable for evaluating visual influences on thermal perception.

To increase reproducibility and ease implementation, we retrieved all assets, including clothing and environments, from the DAZ 3D Asset Store. We used the Genesis 8 female and male base figures together with their corresponding Body Morph Kits[1]. We varied age, body shape, and skin tone using morph sliders[2]. Clothing was depicted using a light summer outfit (T-shirt for male

[1]female: https://www.daz3d.com/body-morph-kit-for-genesis-8-female, male: https://www.daz3d.com/body-morph-kit-for-genesis-8-male

[2]https://www.daz3d.com/aging-morphs-bundle-for-genesis-8-female-s-and-male-s

avatars, tank top for female avatars) or a heavy winter outfit[3]. All color settings were kept constant (black) to avoid perceptual biases. A beach environment[4] was used as the warm condition and a snow-covered landscape[5] as the cold condition.

3.1.4 Procedure. We recruited participants using the online platform Prolific. They completed the study using the survey website LimeSurvey. Participants were first informed about the purpose and procedure of the study. Afterwards, we asked them to provide informed consent according to our institution's ethical regulations and data protection policies. After providing informed consent, participants were asked to complete a demographic questionnaire, covering age, gender, color-vision status, used device type, and current thermal comfort. Afterwards, the 32 first-person avatar images were presented one after another in randomized order.

Each participant saw only avatars matching their gender, while the other factors were systematically varied. For each image, anticipated thermal comfort and perceived realism were rated as described above (see also Figure 2). Once all 32 images were assessed, we guided participants back to the Prolific website. Based on a pre-study, we assumed a completion time of less than 12 minutes. In line with Prolific's fair-pay policy, participants were accordingly compensated with £1.80, an hourly rate of £9.00.

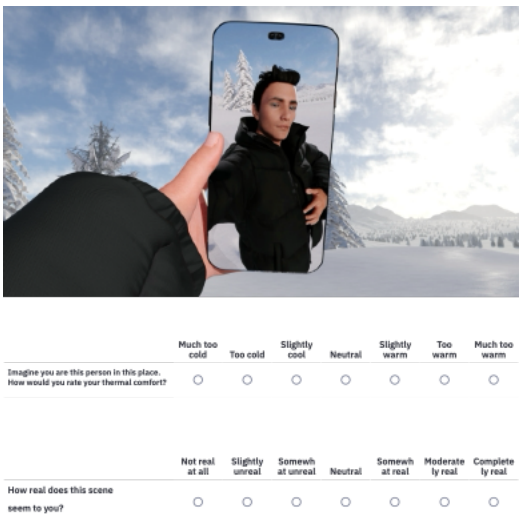


Fig. 2. Screenshot from the survey with the image of the scene on top and the two questions below.

3.1.5 Participants. We restricted participation to desktop and laptop users through Prolific's filters to ensure a consistent stimulus size. In addition, we restricted participation to participants fluent in English to ensure that they understand the consent form, the instructions, and the questions. Furthermore, we limited participation to people from the United Kingdom to ensure that they come from a region with a similar thermal environment. Finally, we ensured that half of the participants self-identified as female and half self-identified as male to achieve an equal gender split.

[3]The same winter outfit was worn by male and female avatars: the jacket is from https://www.daz3d.com/su-winter-outfit-for-genesis-9-81-and-8-female, and the beanie and gloves are from the dForce Winter Snow Outfit (https://www.daz3d.com/dforce-winter-snow-outfit-for-genesis-8-males-and-females).
[4]https://www.daz3d.com/the-beach
[5]https://www.daz3d.com/easy-environments-winter-ii

We asked participants if they had any color deficiency in the demographic questionnaire. Four respondents who reported a form of color deficiency were excluded from the analysis, resulting in a final sample of 100 participants. The age of the participants ranged from 19 to 78 years ($M = 43.48$, $SD = 13.68$). Completing the study took 7.6 minutes on average. Thus, participants were compensated with an average effective hourly rate of £14.22.

3.2 Results

All analyses were conducted in R (v. 4.4.1). As the dependent variable was measured on a 7-point ordinal scale and the data contained repeated observations as well as between-subject variables, we used a cumulative link mixed model (CLMM) implemented in the `ordinal` package[6] using logit link to examine how the visual characteristics and user-related variables influenced anticipated thermal comfort and realism. The CLMM accounts for the non-independence of repeated measurements using random intercepts for participants. Fixed effects included Clothing, Environment, Body, Skin, Age, and Gender.

3.2.1 Thermal Comfort. Effect size analysis showed that the strongest predictor of thermal comfort was Environment. Snow scenes strongly shifted ratings toward colder categories, $\beta = -5.04$, $SE = 0.13$, $z = -37.67$, $p < .001$. Clothing also exerted a substantial influence, with winter clothing increasing the likelihood of warmer ratings, $\beta = 1.72$, $SE = 0.10$, $z = 17.33$, $p < .001$. Moreover, Environment and Clothing interacted such that winter clothing partially attenuated the anticipated coldness of the snowy environment, $\beta = 0.58$, $SE = 0.15$, $z = 4.02$, $p < .001$. Avatar-related characteristics also contributed to anticipated thermal comfort. Warmer or darker Skin tones increased the probability of warmer ratings, $\beta = 0.33$, $SE = 0.06$, $z = 5.11$, $p < .001$, while slim Body shapes decreased it, $\beta = -0.27$, $SE = 0.06$, $z = -4.10$, $p < .001$. Participants identifying as male reported warmer sensations than female participants, $\beta = 0.56$, $SE = 0.13$, $z = 4.45$, $p < .001$. A follow-up linear mixed-effects model additionally revealed a significant Gender × Clothing interaction, $\chi^2(1) = 75.97$, $p < .001$, indicating that winter clothing increased anticipated warmth more strongly for male than for female participants. In contrast, Age of the avatar showed no meaningful effect on thermal comfort ratings, $\beta = -0.01$, $SE = 0.06$, $z = -0.14$, $p = .887$. Figure 3 shows the thermal comfort ratings for each factor.

3.2.2 Realism. The strongest predictor of the subjective realism ratings was Environment. Snow scenes were judged as less realistic than beach scenes, $\beta = -2.50$, $SE = 0.11$, $z = -23.76$, $p < .001$. Clothing also influenced realism, with winter clothing reducing perceived realism across scenes, $\beta = -1.74$, $SE = 0.10$, $z = -17.60$, $p < .001$. None of the avatar characteristics meaningfully affected realism judgments: the effects of Age, Body, and Skin were small and non-significant (all $p > .10$). Participants identifying as male tended to provide slightly higher realism ratings than female participants, although this trend did not reach conventional significance, $\beta = 0.87$, $SE = 0.47$, $z = 1.86$, $p = .063$. A strong interaction emerged between Environment and Clothing. Realism ratings increased markedly when winter clothing was presented in the snowy environment, reflected in a large positive interaction effect, $\beta = 4.06$, $SE = 0.15$, $z = 26.92$, $p < .001$. This pattern suggests that realism judgments are highest when visual cues in the scene are semantically congruent. Figure 4 shows the perceived realism rating for each factor.

3.3 Summary

In the first study, we identified visual factors that influence anticipated thermal comfort and subjective realism in virtual scenes in an online survey. The strongest effects were driven by

[6]https://cran.r-project.org/package=ordinal

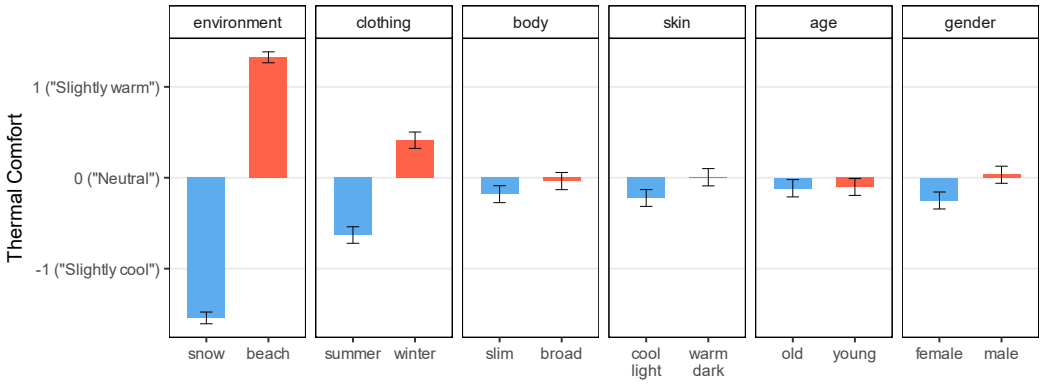


Fig. 3. Thermal comfort (–3 = "much too cold" to 3 = "much too warm") for each factor level. Error bars show 95% confidence intervals.

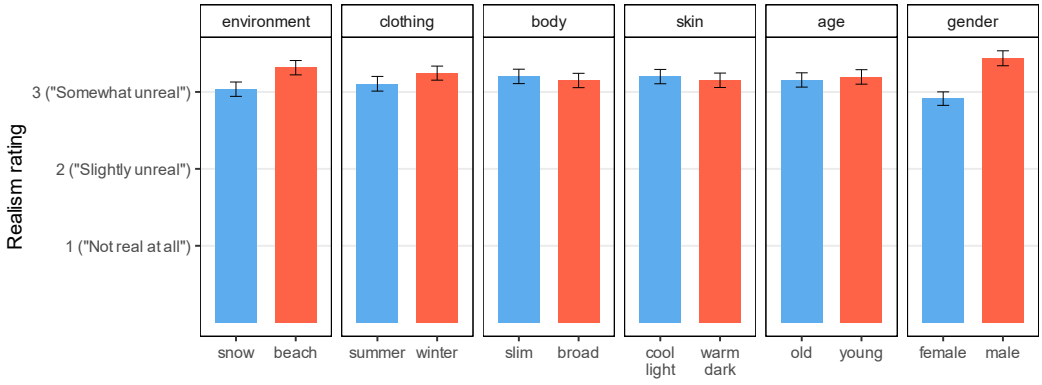


Fig. 4. Perceived realism (1 = "Not real at all" to 7 = "Completely real") for each factor level. Error bars show 95% confidence intervals.

Environment and Clothing. Snow environments produced markedly colder impressions than beach scenes, and winter clothing increased anticipated warmth compared to summer clothing. These effects align with previous work showing that viewing cold or warm environments can shift thermoregulatory perception [69, 116]. Smaller but reliable contributions came from Body shape and Skin tone, consistent with prior findings on visual and physiological cues to temperature [77, 105, 141]. Age of the avatar showed no effect, and Gender produced a small but systematic shift in thermal comfort ratings.

The only strong determinant of perceived realism was the interaction between Environment and Clothing. Snow scenes appeared less realistic overall, and winter clothing appeared less realistic in general. However, realism sharply increased when both cues matched, indicating that consistency between environmental and bodily information drives perceived plausibility. Avatar-related features such as Body, Skin, and Age had no meaningful influence on realism.

Because participants evaluated static images and imagined how they might feel in each situation, the results indicate—but do not confirm—thermal regulatory effects yet. Still, the pattern reveals which cues have the strongest potential to elicit robust and interpretable thermal responses in

immersive settings. Based on these findings, we selected the beach and arctic environments—the arctic scene corresponding to the snow-covered environment used in the survey—and the summer and winter clothing conditions as primary thermal cues for the subsequent VR study.

4 Effects of Avatar Clothing and Virtual Environments

Based on the findings of the initial study, we investigated whether the environment and the clothing of realistic avatars affect thermal perception and thermoregulation in a playful VR experience. Overall, previous work shows that exaggerated visual designs in virtual environments and avatars can influence thermal perception and thermoregulation, e.g., being in a fire world or embodying hands with fire superpowers [69]. However, it remains unclear whether and how ordinary, naturalistic cues (e.g., warm or cold clothing, or environments such as a beach or an arctic landscape) produce similar effects and how both factors interact with each other. Thus, we pose the following hypotheses:

- H1: A virtual beach increases perceived temperature and skin temperature compared to a virtual arctic environment.
- H2: Summer clothing decreases perceived temperature and skin temperature compared to winter clothing.
- H3: Effects of the virtual environment and clothing interact. Virtual clothes presented in incongruent environments, i.e., winter clothes in a beach environment and summer clothes in an arctic environment, influence perceived temperature and skin temperature differently than in congruent environments.

4.1 Method

We conducted a controlled VR experiment to determine the effects of avatars' clothing and the virtual environment on thermal perception and skin temperature. Thus, we developed a playful VR experience that featured realistic avatars dressed in either summer or winter clothing. Participants played a simple color sorting game in VR while being immersed in two virtual environments, a sunny beach and an arctic landscape, using video-based hand tracking, allowing natural object manipulation and questionnaire completion without removing the VR headset [111]. Each condition lasted for five minutes, providing sufficient time for both subjective and physiological responses to emerge.

4.1.1 Study Design. We conducted a within-participant experiment with a 2×2 full-factorial design. The study included two independent variables: Avatar Clothing (with the levels *summer* and *winter*) and Environment (with the levels *beach* and *arctic*). This resulted in four conditions: *summer-beach*, *summer-arctic*, *winter-beach*, and *winter-arctic*. Time was included as a repeated-measures factor for skin temperature (tested after *minute 1, 2, 3, 4, and 5*) and thermal sensation (tested after *90*, *180*, *270 seconds*). We took objective and subjective measures to determine the effects of the independent variables.

4.1.2 Measures. In line with previous work [69, 70, 133], we continuously measured skin temperature using a TC-08 data logger and five Type T thermocouples (Pico Technology). Two sensors were attached to the back of each hand with medical tape, and a fifth sensor monitored ambient room temperature, all sampling at 1 Hz. Subjective measures included thermal sensation [76], thermal comfort [13], sense of presence [109], and body ownership [9]. Thermal sensation was rated three times per condition using a continuous visual analogue scale (VAS) slider from *very cold* to *very warm*, after an initial 30-second acclimatization period and at 90-second intervals. Thermal comfort was assessed once at the end of each condition using a 7-point item ranging from *much too cool* to

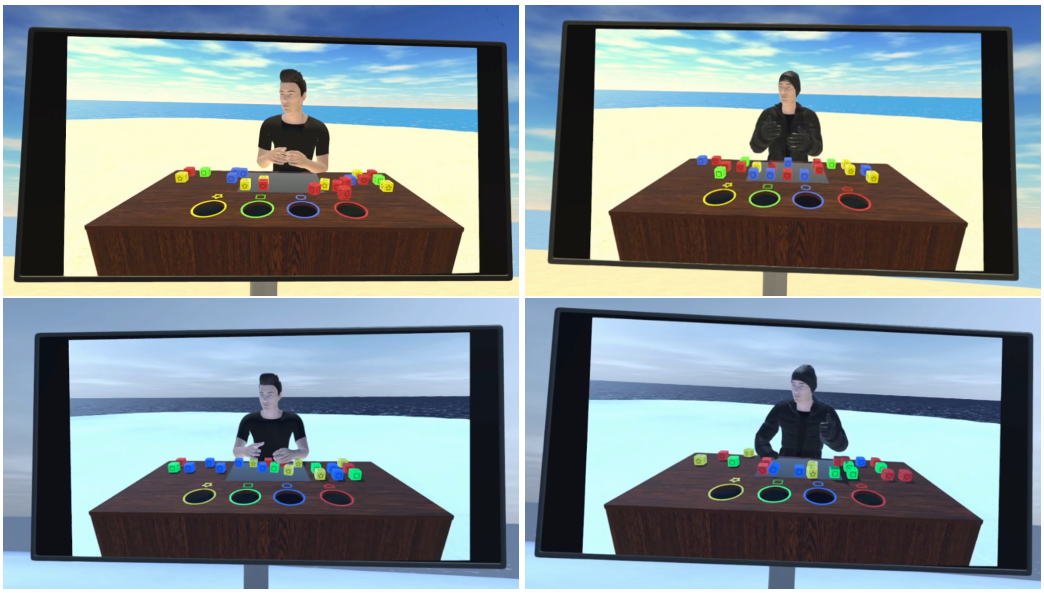


Fig. 5. First-person views of the male avatar in the four conditions: (top-left) *summer clothing - beach environment*, (top-right) *winter clothing - beach environment*, (bottom-left) *summer clothing - arctic environment*, and (bottom-right) *winter clothing - arctic environment*. The virtual mirror was used to support visual identification with the avatar.

much too warm. Sense of presence was measured with the igroup presence questionnaire (IPQ) [109], which includes 14 items across the subscales *Spatial Presence*, *Involvement*, *Experienced Realism*, and *General Presence*. To quantify the induced body ownership, we used the body representation questionnaire (BRQ) [9, 10] with the single-item subscales *Body Ownership* ("I felt that the virtual body I saw when looking down at myself was my own body"), *Mirror Recognition* ("I felt that the virtual body I saw when looking at myself in the mirror was my own body"), *Visual Features* ("I felt that the virtual body resembled my own real body in terms of shape, skin tone or other visual features"), *Two Bodies* ("I felt as if I had two bodies"), and *Agency* ("I felt that the movements of the virtual body were caused by my own movements"). All questionnaires were presented within the VR environment to facilitate continuous immersion.

4.1.3 Avatars and Environments. Participants were represented by realistic full-body avatars, created using DAZ Studio 4.22 and exported via the DAZ to Unity Bridge. Two base avatars (male and female) were generated from Genesis 8.1 models and featured light skin tones and neutral body proportions. In line with the avatars' clothing used in the first study, different clothing was depicted using a light summer outfit (T-shirt and shorts) or a heavy winter outfit (jacket, beanie, gloves, snow pants, and boots). All color settings were kept constant (black) to avoid perceptual biases. To avoid potential gender mismatches and enhance embodiment, participants were assigned an avatar matching their self-identified gender.

The virtual environments consisted of two visually distinct scenes: one warm (beach), one cold (arctic). Both scenes shared identical terrain geometry, created using Unity's Terrain Tools. Differences in lighting, textures, and skyboxes were used to simulate temperature. High-resolution textures (4096×4096 px) for sand, snow, and water were sourced from the Unity Asset Store, and



Fig. 6. Participant equipped with headset and skin temperature sensors interacting in VR.

environmental temperature was visually reinforced through lighting post-processing (e.g., color temperature: +30 for beach, -35 for arctic).

A neutral startup scene introduced the task and confirmed the participant's readiness. Each scene included a virtual wooden table adjusted to match the real-world table height for tactile alignment. All avatars were rendered from a first-person perspective, with a virtual mirror included in each scene to support visual identification and body ownership.

4.1.4 Task. To keep participants engaged during each condition without inducing performance pressure or stress, we implemented a simple cube-sorting game. Participants were instructed that they could sort colored cubes into matching holes on the virtual table, but were not required to do so. The open-ended game aimed to maintain a baseline level of interaction without distracting from the study's focus on embodiment and thermal perception. Cubes appeared in randomized positions on the virtual table. Four cube types were used (red, green, blue, yellow), each associated with a corresponding hole marked by both color and symbol to accommodate potential color deficiencies. Cubes placed correctly were removed from the scene. When all twenty cubes were sorted, a new set automatically spawned. Incorrectly placed or dropped cubes reappeared after one second, ensuring continuous interaction without interruption.

4.1.5 Apparatus. To measure the hands' skin temperature, we used a TC-08 Thermocouple Data Acquisition System (Pico Technology) with five T-thermocouples, as it is commonly employed to measure skin temperature [83]. The sensor provides a high noise-free resolution of 16.25 bits and 0.025 ℃ that is particularly important to detect relative skin temperature changes. Two thermocouples were attached to each hand with breathable tape. We averaged the measurements from the four thermocouples to further reduce potential sensor noise. A fifth sensor monitored ambient room temperature. We implemented the VR application using Unity (2022.3.36f1) and deployed it on a Meta Quest 3 head-mounted display (HMD). The Unity project used the Universal Render Pipeline (URP) optimized for mobile VR. Native hand tracking was implemented to allow controller-free interaction. The software was built using Meta's XR SDKs for interaction and hand tracking. Thus, participants interacted without controllers with the objects and responded to the series of questionnaires via virtual panels embedded in the VR scene. The virtual avatars were full-body models that dynamically adjusted to participants' height, shoulder width, and arm length, using real-time tracking data from the headset to enhance embodiment and realism. The application source code is available on GitHub[7].

[7]https://github.com/Zeyku/MoreHeat_MA

4.1.6 Procedure. After welcoming participants, we explained the study's procedure, equipment, and VR task. After signing the informed consent, they completed a demographic questionnaire on a laptop. This questionnaire included age, gender, education level, current occupation, currently worn clothing, mode of transportation to the lab, prior VR experience, and average time spent in VR. During this time, participants also acclimated to the room temperature ($M = 24.02$ ℃, $SD = 0.85$). Then, the experimenter measured each participant's body height to calibrate the virtual avatar's proportions. Participants were then seated at a real table (see Figure 6), which was adjusted to their preferred height for ergonomic alignment.

Thermocouples were attached to the backs of both hands using skin-friendly medical tape and secured at the forearm to prevent slippage. The sensors were connected to a data logger via long cables, allowing free movement. Participants then put on the Meta Quest 3 headset and adjusted it to their comfort. After starting the VR application, participants entered the neutral startup scene and initiated the first condition. Conditions were counterbalanced using a balanced Latin square design to avoid sequence effects. Each condition lasted five minutes and began with a 30-second acclimatization phase. Participants then rated their thermal sensation three times at 90-second intervals using the VAS slider. After the third rating, additional questionnaires, including thermal comfort [13], the IPQ [109], and the BRQ [9] appeared on a virtual touchscreen embedded in the table. This sequence was repeated for all four conditions. After completing the final condition, participants removed the headset, and the thermocouples were detached. The study concluded with a short debriefing and an opportunity to ask final questions. The complete experimental procedure lasted approximately 45 minutes.

4.1.7 Participants. An a-priori power analysis using G*Power indicated that, to detect an effect of size partial $\eta_p^2 = .06$ (based on medium effects on thermophysiological responses observed in preliminary work [69]) with a significance level of $\alpha = .05$, a total sample size of N = 24 would be required to achieve 80% power ($1 - \beta = .80$). Hence, we recruited a total of 24 participants (18 male, 6 female). Age ranged from 22 to 35 years (M = 26.63, SD = 2.83). Recruitment was conducted via forums, mailing lists, and student groups at our institution. Participants were instructed to wear comfortable clothing and to avoid jackets, coats, or long sleeves to minimize thermal interference during skin temperature measurements. Regarding prior experience with VR, 19 participants reported previous exposure, primarily in academic or study-related contexts. Only six reported using VR for entertainment, and just four indicated using VR for more than one hour per week on average.

4.2 Results

Linear mixed-effects models (LMMs) were used to account for time-related trends and repeated measures, while Aligned Rank Transform (ART) was used for analysis of variance (ANOVA) outcomes that violated normality assumptions. Avatar Clothing and Environment were treated as fixed factors in all analyses, with Time included as a numeric predictor in the mixed models to capture changes over the exposure period. Gender and Room Temperature were included as covariates where appropriate. We used R to analyze the data (version 4.4.1).

4.2.1 Skin Temperature. We averaged temperature data at minute-wise intervals. Minute 0 served as an individualized baseline and was excluded from the model. Random intercepts and slopes for Time were specified for each participant. To determine whether a non-parametric analysis is needed, residual diagnostics were conducted. The analysis indicated temporal autocorrelation

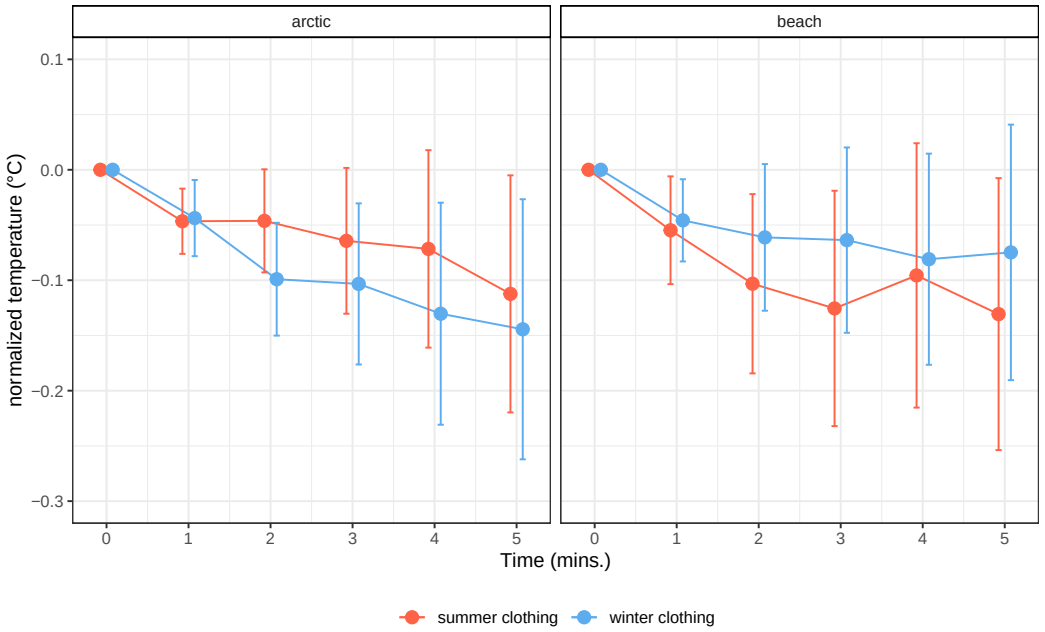


Fig. 7. Mean normalized temperatures over time, plotted separately by Avatar Clothing (*summer* and *winter*) and Environment (*beach* and *arctic*). Both measures are shown on the same normalized scale to allow direct visual comparison of their trends. Error bars indicate standard errors (SEs) across participants ($N = 24$).

($\phi = 0.93$, all factors $p > .75$) and Shapiro-Wilk test revealed significant violations of normality ($p < .001$). Hence, we used robust LMM (`robustlmm`[8]) for the analysis.

Robust LMM revealed significant main effects of Avatar Clothing, $b = -0.080$, $SE = 0.030$, $z = -2.625$, $p = .009$, and Environment, $b = -0.067$, $SE = 0.030$, $z = -2.204$, $p = .028$. The Avatar Clothing × Environment interaction was also significant, $b = 0.099$, $SE = 0.043$, $z = 2.325$, $p = .020$, indicating a stronger clothing effect in the arctic environment. Time was not significant, $b = -0.009$, $SE = 0.019$, $z = -0.492$, $p = .623$, and no higher-order interactions were statistically significant: Avatar Clothing × Time, $b = -0.032$, $SE = 0.021$, $z = -1.503$, $p = .133$; Environment × Time, $b = -0.019$, $SE = 0.021$, $z = -0.893$, $p = .372$; Avatar Clothing × Environment × Time, $b = 0.039$, $SE = 0.030$, $z = 1.281$, $p = .200$. A post-hoc Tukey test confirmed the clothing effect in the arctic condition ($z = 2.63$, $p = .043$); all other contrasts were not significant. Effects of the covariates Room Temperature, $b = -0.075$, $SE = 0.065$, $z = -1.153$, $p = .249$, and Gender, $b = 0.058$, $SE = 0.064$, $z = 0.902$, $p = .367$, were not statistically significant.

Descriptively, normalized hand temperature changed by −0.112 ℃ ($SD = 0.526$) in *summer clothing–arctic*, −0.131 ℃ ($SD = 0.603$) in *summer clothing–beach*, −0.144 ℃ ($SD = 0.577$) in *winter clothing–arctic*, and −0.075 ℃ ($SD = 0.567$) in *winter clothing–beach*. These descriptive patterns correspond to the modelled interaction. Figure 7 shows the trajectories across conditions.

4.2.2 Thermal Sensation. Shapiro-Wilk tests indicated no significant deviations from normality on condition level (all $p > .27$) of the subjective ratings of thermal sensation. Thus, a regular LMM was fitted to the ratings with Avatar Clothing, Environment, and Time (90 s, 180 s, 270 s) as

[8]https://cran.r-project.org/package=robustlmm

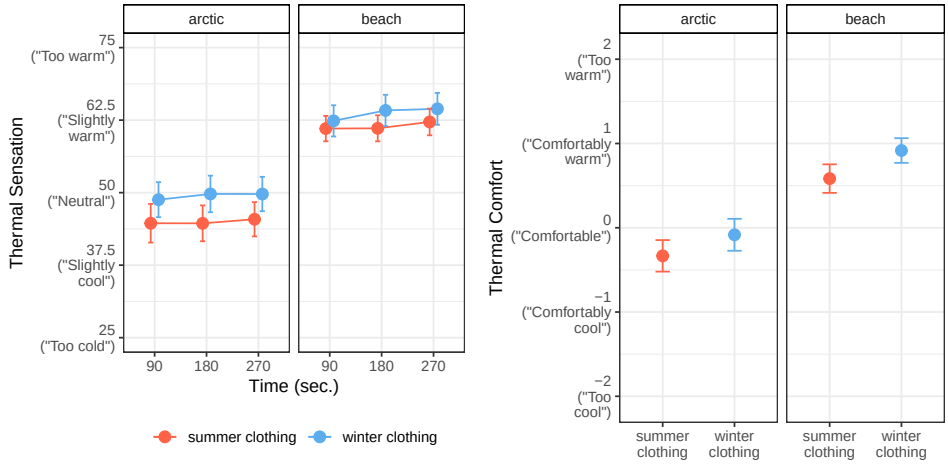


Fig. 8. Thermal sensation and thermal comfort rating for each condition. Thermal sensation was asked each 90 seconds. Ratings are plotted for Avatar Clothing (color) and split by Environment (facets). Error bars show SE.

fixed factors. Gender (male vs. female) and the normalized Room Temperature were treated as covariates.

The analysis revealed significant main effects of Environment, $F(1, 24.043) = 19.134$, $p < .001$, $\eta_p^2 = .443$, and Avatar Clothing, $F(1, 240.081) = 15.369$, $p < .001$, $\eta_p^2 = .060$. No significant effects were observed over Time, $F(2, 239.970) = 0.745$, $p = .476$. None of the interactions was significant ($p > .271$). Effects of the covariates Room Temperature, $F(1, 252.697) = 1.211$, $p = .272$, and Gender, $F(1, 23.998) = 0.008$, $p = .929$, were also not significant. Thus, participants consistently reported significantly higher thermal sensation in the *beach* environment ($M = 62.6$) compared to the *arctic* environment ($M = 47.3$). They also reported higher warmth when viewing avatars wearing *winter clothing* ($M = 56.6$) compared to *summer clothing* ($M = 53.3$). The results are shown in Figure 8.

4.2.3 Thermal Comfort. Thermal comfort ratings were analyzed using an ART-ANOVA due to violations of the normality assumption in the experimental conditions (all $p < .01$). The analysis revealed a significant main effect of Environment, $F(1, 92) = 30.807$, $p < .001$, $\eta_p^2 = .251$, indicating that participants felt differently depending on whether they were in the beach or arctic environment. However, the main effect of Avatar Clothing was not significant, $F(1, 92) = 1.275$, $p = .262$, $\eta_p^2 = .014$, nor was the interaction between Avatar Clothing and Environment, $F(1, 92) < 0.001$, $p = .988$, $\eta_p^2 < .001$.

4.2.4 Presence (IPQ). An ART-ANOVA revealed no significant main effects of Avatar Clothing on any of the IPQ subscales ($p > .05$). A significant main effect of Environment was found for the *Spatial Presence* subscale, $F(1, 92) = 4.135$, $p = .045$, $\eta_p^2 = .043$, indicating that the virtual environment influenced participants' spatial presence. No other environment-related effect was significant: *Involvement*, $F(1, 92) = 0.310$, $p = .579$, $\eta_p^2 = .003$; *Experienced Realism*, $F(1, 92) = 0.015$, $p = .903$, $\eta_p^2 = .000$; *General Presence*, $F(1, 92) = 0.241$, $p = .625$, $\eta_p^2 = .003$. The interaction between Avatar Clothing and Environment was not significant for any subscale ($p > .79$). Descriptively, participants reported higher spatial presence in the beach environment (summer

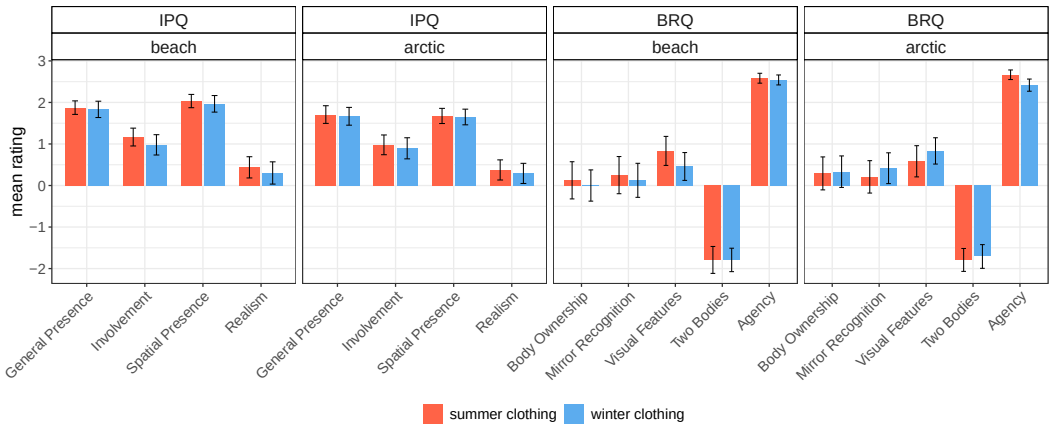


Fig. 9. Mean scores of IPQ and BRQ subscales by Avatar Clothing and Environment. Error bars represent standard errors. Spatial presence was significantly higher in the *beach* environment compared to the *arctic*, while other IPQ subscales (involvement, experienced realism, general presence) showed no significant effects. Body ownership subscales remained statistically unaffected by the experimental conditions. Descriptively, highest ratings were found for the *Agency* subscale, while *Two Bodies* showed consistently negative scores. The *Body Ownership* and *Mirror Recognition* subscales yielded near-zero mean values, suggesting overall neutrality in these aspects.

clothing: $M = 2.033$, $SE = 0.160$) compared to the arctic setting (summer clothing: $M = 1.675$, $SE = 0.183$). Other subscales showed smaller and non-significant differences (e.g., *General Presence* under summer clothing: beach $M = 1.875$, $SE = 0.163$; arctic $M = 1.708$, $SE = 0.213$). These findings suggest that perceived spatial presence is modulated by the virtual environment, while avatar clothing has a negligible influence on any of the measured aspects of presence.

4.2.5 Body Ownership (BRQ). An ART-ANOVA revealed no significant main effects of Avatar Clothing or Environment on any of the BRQ subscales ($p > .05$). No significant interaction effects between Avatar Clothing and Environment were found either ($p = .36$). Descriptive statistics also indicate that responses do not vary meaningfully between conditions. For example, *Agency* showed the highest overall scores (e.g., summer clothing in beach environment: $M = 2.583$, $SE = 0.119$), while *Two Bodies* consistently showed negative mean values (e.g., winter clothing in arctic environment: $M = -1.708$, $SE = 0.285$), reflecting a low sense of dual embodiment. Ratings on subscales such as *Body Ownership* and *Mirror Recognition* were close to zero across all conditions, suggesting neutral responses (see Figure 9). These results suggest that neither the avatar's clothing nor the virtual environment significantly influenced body ownership experiences in the study. Observed differences were minor and not systematically modulated by the experimental manipulations.

4.3 Summary

This study investigates how avatar clothing and the virtual environment jointly shape objective skin temperature and subjective thermal perception in an immersive VR setting. Using a controlled full-factorial 2 × 2 within-participant design, we manipulated Avatar Clothing (*summer* vs. *winter*) and Environment (*beach* vs. *arctic*) to test whether virtual representations of clothing and environment influence users' skin temperature, thermal sensation, thermal comfort, and sense of embodiment. We summarize the main findings of the study as follows:

Normalized skin temperature declined over time across all conditions. LMM showed that this decline was significantly modulated by the interaction between Avatar Clothing and Environment. Hence, we can confirm H3 for skin temperature responses. In the *arctic* condition, participants with *winter clothing* exhibited a steeper temperature drop compared to those wearing *summer clothing*. In contrast, in the *beach* condition, *summer clothing* led to a stronger decline than *winter clothing*. This pattern suggests that the congruence or mismatch between clothing and perceived ambient temperature cues shaped the physiological thermoregulatory response. Specifically, mismatched combinations of clothing (e.g., winter clothing in warm environments or summer clothing in cold environments) appeared to elicit attenuated thermoregulatory adaptation, whereas congruent combinations led to stronger cooling effects over time. The observed effects on skin temperature are small but statistically significant. Because the effects ran counter to the hypothesized direction, we cannot confirm H1 and H2 for skin temperature responses.

Thermal sensation was influenced by both Avatar Clothing and Environment, with no evidence of an interaction. Hence, we confirm H1 and H2 but reject H3 for thermal sensation. Participants consistently reported higher thermal sensation in the beach environment compared to the arctic one, regardless of their virtual clothing. Likewise, winter clothing elicited higher thermal sensation than summer clothing for both environments. This suggests additive effects: both the virtual environment and virtual clothing contributed separately to the subjective thermal experience, with the environment exerting a stronger overall influence.

Only the virtual environment, but not clothing, had significant effects on thermal comfort and spatial presence. Hence, we can confirm H1 for thermal comfort. This suggests an interplay between visual cues and thermal experience: While physiological responses (the skin temperature) appear to be sensitive to the interaction between bodily and environmental visual cues, perceptual judgments (e.g., thermal sensation) rely on parallel, additive integration of those cues. Thus, higher-level cognitive evaluations such as comfort and presence are shaped predominantly by environmental context, with a smaller influence from the visual representation of one's own body.

5 General Discussion

We conducted two studies to learn whether and how an avatar's characteristics and the virtual environment influence users' thermal perception and regulation. In the first study, we identified which visual factors had the strongest potential to shape anticipated thermal comfort. Based on these results, we then conducted a VR study focusing on avatar clothing and virtual environment, as these two factors showed the strongest and most interpretable effects. To understand the effects of these factors on users' thermal responses during a VR experience, we conducted a second study in VR using a 2 × 2 repeated measures design that systematically changed the virtual Environment (*arctic* vs. *beach*) and the Avatar's Clothing (*summer* vs. *winter clothing*).

5.1 Thermal Effects of Avatar Clothing and Environment

The significant interaction between Avatar Clothing and Environment on skin temperature in the playful VR experience supports the notion that users' physiological thermoregulation is not solely driven by physical stimuli, but can be shaped by cognitive expectations derived from visual input. We can confirm H3 for thermophysiological responses. In the arctic environment, participants wearing winter clothing exhibited a stronger decline in hand temperature compared to wearing summer clothing, while the inverse pattern was observed in the beach environment. As the ambient room temperature remained stable throughout the experiment, the crossover interaction cannot be explained by room temperature. Instead, our findings suggest that congruency between clothing and environmental context influences a player's thermoregulation differently than incongruent cues (see Figure 7). Embodying an avatar wearing summer clothing resulted in a higher skin temperature

over time compared to an avatar wearing winter clothing while being in the arctic environment. However, the effects reversed in the beach environment. Participants had a lower skin temperature over time when embodying the avatar wearing summer clothing compared to winter clothing. Hence, the effects do not reflect a simple "warm clothes = warmer body" relationship or vice versa.

Compared to previous work revealing effects in the magnitude of approximately 0.2 ℃ after five minutes [69] (using fire and ice avatars) and 0.2 ℃ after five and ten minutes [133] (using a fire and ice environment), our effects on skin temperature are relatively small (within a range of 0.07 ℃). While a systematic comparison between naturalistic and highly stylized thermal cues is still missing, our findings suggest that the observed differences in effect size potentially stem from the visual design and the intensity of the anticipated thermal condition. For example, fire- and ice-themed avatars or virtual environments may be immediately associated with extreme temperatures, whereas clothing is more commonly linked to moderate thermal conditions. More work is therefore needed to investigate how visual design can maximize these effects and whether varying degrees of depicted warmth or coldness produce gradual changes in thermal perception, e.g., by increasing the size or intensity of flames in a virtual fireplace.

In contrast to skin temperature, subjective thermal sensation showed no interaction effect. Instead, both Avatar Clothing and Environment contributed independently to perceived warmth. Hence, we can confirm H1 and H2 for thermal sensation. Participants reported higher thermal sensation when wearing winter clothing, independent of the environment, and likewise reported higher thermal sensation in the beach environment, regardless of clothing. This dissociation suggests that users cognitively separate bodily and environmental thermal sources in their perceptual model, treating the avatar's clothing and the surrounding environment as parallel but additive cues. The absence of an interaction effect implies that thermal perception may operate on a dual-pathway system: one that integrates embodied appearance (e.g., clothing) and one that tracks environmental features (e.g., sky, snow, sun). Unlike thermoregulation, which responds to the alignment of cues, thermal sensation appears to reflect a more linear integration of visual inputs. Hence, we cannot confirm H3 for thermal sensation.

Thermal comfort ratings were primarily shaped by the virtual Environment and showed no significant sensitivity to Avatar Clothing. Participants felt warmer in the *beach* environment, irrespective of whether they wore *summer* or *winter clothing*. Hence, we can confirm H1, and reject H2 and H3 for thermal comfort. This pattern suggests that judgments of comfort—unlike sensation or thermoregulation—may rely more heavily on external scene cues than on self-representation. Comfort, as a construct, often integrates affective and contextual dimensions, which may explain its strong alignment with environmental features. Similarly, spatial presence, as measured by the IPQ, was higher in beach settings but unaffected by avatar clothing. These results align with established presence models that emphasize environmental realism, spatial layout, and interactivity as dominant predictors of immersion. That clothing had no detectable effect on presence suggests that even highly visible self-representations do not disrupt the place illusion, at least in the absence of strong haptic or incongruent multisensory cues.

The illusion of body ownership remained stable across all conditions. We found no significant effects of Avatar Clothing and Environment on any of the BRQ dimensions. Participants consistently reported a moderate sense of ownership over their virtual body, independent of its clothing or the environmental context. This finding contrasts with prior research on embodiment in VR, which showed that users can experience different levels of ownership over diverse body types, sizes, and features [9, 10, 69, 70, 72]. The results suggest that virtual clothing does not significantly alter body ownership, even when clothing type contrasts with environmental context. In our setup, movement was accurately tracked via hand tracking, and perspective remained stable throughout the interaction, factors that likely contributed to the robustness of the embodiment experience.

The same applies to the sense of presence. Participants only reported a slightly higher spatial presence in the beach environment (summer clothing: $M = 2.033$, $SE = 0.160$) compared to the arctic setting (summer clothing: $M = 1.675$, $SE = 0.183$). Our findings, therefore, suggest that the effects on thermal perception and skin temperature are unlikely to be caused by differences in perceived body ownership and sense of presence. Consequently, we attribute the effects to the visual thermal cues represented by the avatar and the virtual environment. To learn about the modulatory effects of perceived embodiment and presence, future work could systematically explore how different degrees of embodiment (e.g., using visuomotor synchrony and asynchrony to modulate embodiment [9, 62]) or presence (e.g., modulating the realism of the scene by changing the number of polygons [111]) influence thermal effects.

The results echo earlier findings in embodied cognition, where visual stimuli have been shown to affect physiological processes. For example, Kocur et al. [69] demonstrated that embodying virtual fire hands caused a measurable decrease in real hand temperature, even in the absence of actual heat. Tieri et al. [120] found that visually coherent virtual limbs modulated skin temperature as a function of embodiment strength. However, both our experiment and the one by Kocur et al. [69] suggest that embodiment alone does not account for these thermal changes. The observed physiological responses may be interpreted as being consistent with anticipatory mechanisms shaped by cognitive expectations and contextual congruency, suggesting that coherent sensory input could contribute to top-down thermoregulatory modulation. Thus, our findings are rather consistent with the hue-heat hypothesis, suggesting that visually induced expectations can modulate thermal perception and even physiological responses [64, 141]. The precise relationship between, and respective roles of, top-down and bottom-up processes has to be conclusively determined in future work.

Another possible explanation for the thermal effects could be behavioral changes caused by the avatar's visual appearance. In line with previous work [69], we intentionally used a non-competitive task to isolate thermal effects from effects caused by performance pressure or stress. It is, however, imaginable that participants moved faster with summer clothes, for example, than with winter clothes. While one might assume that such changes in physical activity may influence physiological responses, they do not explain the interaction effect between the environment and the avatar, i.e., embodying an avatar with summer clothing resulted in a higher skin temperature in the arctic environment but a lower skin temperature in the beach environment. In line with research on the Proteus effect [134], future work should further explore how an avatar representing hot or cold thermal cues influences user's behavior and physical activity in VR and how those changes depend on the surrounding environment. This is in accordance with Mal et al. [84, 85], who suggest that the plausibility of the virtual experience can modulate behavioral changes caused by the avatar and environment. In this vein, we rule out effects of different levels of fatigue as a causal explanation for the variance in physiological and perceptual responses. We employed a repeated-measures design to minimize unsystematic variance arising from individual differences. To mitigate order effects, we counterbalanced the conditions across participants. Furthermore, task durations were controlled and held consistent across participants to ensure that all participants had an equal amount of time for each task. Thus, the significant differences in skin temperature and perceptual responses we observed cannot be attributed to differences in fatigue, as such effects would not explain the variation between the conditions.

5.2 Implications

Avatar clothing can modulate both thermal sensation and physiological thermoregulation, but its effects depend on the environmental context. Our revealed subjective effects are important for designers and developers of immersive VR games. When seeking to influence players' thermal experience, virtual clothing can be leveraged as a subtle cue, especially when it aligns with the

surrounding environment or context. For example, when aiming to create a colder experience for players, our findings imply using light clothing such as summer attire in cold virtual environments may enhance the perception of coldness compared to warmer clothing (see Figure 8). The same applies to creating warmer game experiences. Hence, virtual clothing can be considered a design space for modulating players' thermal sensations. Another example could be adaptive avatars that visually change clothing in response to the scene to enhance the user's thermal experience in VR games. In many commercial VR games, players are immersed in virtual worlds that leverage changes in climate or weather to offer exciting experiences. For example, *Skyrim VR* [16] adds temperature mechanics such as cold regions or wetness from rain or snow. *Everest VR* [114] allows players to experience climbing high mountains depicting cold thermal conditions. Hence, when designing VR games that transport users into places with different thermal conditions, designers should consider adapting and changing the avatar's clothing accordingly to influence players' thermal experience.

When designing therapeutic applications such as SnowWorld [50], for example, which employs cold virtual thermal cues to alleviate the suffering of burn patients, it is important to recognize that avatars can influence the thermal experience. On the one hand, this effect can be potentially harnessed to enhance thermal perception, e.g., by increasing perceived cold through light clothes in cold environments (see Figure 8). On the other hand, however, careful consideration is required to avoid unintentionally inducing negative effects due to the avatar's visual appearance and the associated thermal concepts. Descriptively, participants felt warmer in the beach environment ($M = 0.583$, $SD = 0.830$), and thermal comfort ratings were numerically highest under winter clothing ($M = 0.917$, $SD = 0.717$), although the effect of avatar clothing on thermal comfort was not statistically significant ($F(1, 92) = 1.275$, $p = .262$). While participants' thermal comfort on average did not reach uncomfortable levels, some participants ($N = 5$) reported thermal comfort ratings of 2 on a scale ranging from -3 ("much too cool") to 3 ("much too warm"), indicating that they felt uncomfortably warm during the VR experience. Consequently, VR game designers should be aware that thermal cues represented by the avatar and the environment may induce discomfort in some players.

Due to the relatively small effects on skin temperature (within a range of 0.07 ℃; see Figure 7), these physiological responses are likely less relevant for the design of immersive VR games. However, the observed thermophysiological effects are scientifically important. They suggest that not only exaggerated avatars and environments, e.g., fire- or ice-themed avatars [69, 121], but also more naturalistic visual thermal cues can measurably influence users' thermoregulation, i.e., warm or cold virtual clothing and environments like beaches or arctic settings. Thus, these findings not only complement the revealed subjective effects and provide insight into potential underlying mechanisms, but also demonstrate that basal skin temperature is affected by those visual thermal cues. Consequently, as psychophysiological effects arise from the embodiment of avatars with different clothing and from the thermal characteristics of the virtual environment, both factors should be carefully considered in the experimental design process.

5.3 Limitations and Future Work

While previous work showed that an exposure time of 5 minutes is sufficient to induce thermophysiological effects [121, 133], longer-term thermoregulatory responses over a prolonged period of exposure remain unclear. As, for example, the duration of embodying avatars can influence experienced embodiment and sense of presence [58, 60], future studies should include longer interventions to investigate the temporal dynamics of visual-thermal adaptation affected by avatars and virtual worlds. In addition, we employed a controlled laboratory experiment using a gamified VR prototype with a simplified task to isolate the effects of our independent variables from potential

confounding factors, e.g., high physical activity. However, many immersive VR games involve more dynamic interactions, such as combat scenarios, cognitively demanding problem-solving tasks, and fast-paced movement requiring rapid reactions. Future research should therefore investigate these effects in more dynamic VR settings to assess both their robustness and their persistence over prolonged periods of time. Moreover, no tactile or airflow stimuli were present in our setup, and thus the results reflect purely visual priming effects. While this also allowed us to isolate the visual component, it also limits the ecological validity for scenarios where multisensory input is available. In line with prior work [69, 121, 133], we measured skin temperature at the hands using thermocouples. This may not fully reflect whole-body thermoregulation and core body temperature. From a game design perspective, less obtrusive methods for measuring skin temperature that allow players to move freely without compromising the gaming experience would be preferable. Hence, further research could include multiple sensor sites or integrate wearable sensing technologies to track more comprehensive physiological responses while maintaining a high level of game experience.

Although changes in physical activity do not explain the interaction effect, prior work has shown that the visual appearance of avatars can influence physical activity levels (e.g., embodying non-athletic avatars [98, 99]). Therefore, we cannot rule out the possibility that physical activity is influenced by the combined effects of the environment and avatar appearance, e.g., embodying an avatar wearing winter clothing in a beach environment could reduce physical activity as a compensatory response to increased perceived warmth. However, whether visual thermal cues specifically affect physical activity remains unclear. Future work should therefore further investigate the effects of thermal visual cues and avatar embodiment on physical activity.

Finally, individual differences in baseline metabolism, sex, gender, age, and prior thermal experiences were not explicitly investigated. In our data, interaction effects on thermal comfort—indicating that winter clothing increased perceived warmth more for male than for female participants—were only evident in the survey, but not in the lab study. Therefore, future work should examine thermal perception and physiological responses in larger and more balanced samples, while also recording menstrual cycle phase and hormonal contraceptive use (c.f. Vellei et al. [122]). We also acknowledge that avatar features such as skin tone, age, and body shape are not only thermal or physiological cues. They may also carry social, cultural, racialized, gendered, and age-related meanings that can influence how participants interpret the avatar and the scene. Future work should therefore examine these factors with more diverse participant samples and with careful attention to representation, social meaning, and possible bias in avatar design.

We see several directions for future research: Future work can investigate the thermal effects of additional factors related to games. Our first study, for example, revealed significant effects of body shape and skin tone on assumed thermal comfort. These factors could be assessed in isolation or, to maximize the effects, in combination. When comparing a slim avatar with cool-light skin color dressed in summer clothing to a broad avatar with warm-dark skin color dressed in winter clothing, it is conceivable that there are even larger effects. In addition, the avatars were wearing black clothes during the VR experience to isolate the effects of the avatars' clothes from the effects caused by its displayed hue [89, 141]. However, black clothing may inherently activate thermal associations because its light-absorbing properties are commonly linked to increased heat absorption and higher temperatures. While previous work has shown that the effects of thermal cues are larger than those of color temperatures [133], future work could further investigate if the thermal effects can be systematically disentangled into effects caused by thermal cues and those caused by color temperature to learn more about its specific nuances. For example, such work could distinguish between black clothes associated with heat absorption through semantic or

learned associations (top-down processes) and red clothing subconsciously connected with warm temperatures through perceptual associations (bottom-up processes).

Studies could also explore whether other sensory cues, such as airflow, warmth, or haptic textures, amplify or diminish the effects of avatar clothing on thermal regulation. It would also be valuable to test adaptive avatar systems that dynamically change clothing in response to environmental transitions or physiological states. Furthermore, longitudinal studies could investigate habituation effects over time and examine how repeated exposure to consistent or inconsistent thermal cues alters user expectations and responses. Finally, integrating models of individual thermal preference and sensory processing could help build more personalized and context-aware VR systems that respond intelligently to both environmental cues and embodied states.

6 Conclusion

In this paper, we investigated the effects of realistic avatars and virtual environments on thermal perception and skin temperature. In an online survey with 100 participants, we assessed assumed thermal comfort and perceived realism of 64 virtual renderings, systematically varying clothing, body shape, skin tone, age, gender, and environmental context. We found that environment and avatar clothing have the largest effects on assumed thermal comfort and, therefore, have the greatest potential for eliciting robust and interpretable thermal effects in VR. Consequently, we conducted a second study in VR using a repeated-measures design with 24 participants, where we varied the environment and avatar clothing to investigate the effects on thermal perception and physiological regulation.

While normalized skin temperature declined over time across all conditions, our results suggest that in the arctic condition, participants with winter clothing exhibited a steeper temperature drop compared to those wearing summer clothing. In contrast, in the beach condition, summer clothing led to a stronger decline than winter clothing. We also show that users' thermal sensation was independently influenced by both environment and avatar clothing. Moreover, participants consistently reported higher thermal sensation in the beach environment compared to the arctic one, regardless of their virtual clothing. Likewise, avatars wearing winter clothing elicited higher thermal sensation than those wearing summer clothing across both environments. Hence, we conclude that naturalistic avatars' clothing and realistic virtual environments can influence both subjective thermal perception and physiological thermoregulation.

Overall, we extend previous work by demonstrating that thermal perception and regulation are influenced not only by virtual worlds with exaggerated thermal cues but also by naturalistic environments and avatars' virtual clothing. This is important for VR games and applications exposing users to immersive virtual environments and avatars that convey thermal cues. Designers of such environments should therefore carefully consider their potential effects on thermal perception and regulation. Importantly, this consideration should go beyond merely preventing negative outcomes. Additional research involving more diverse participant samples is needed to better understand how these thermal effects can be utilized as design choices to enhance users' thermal experiences in immersive video games using dynamic game mechanics. Future research should further explore habituation effects—specifically, how repeated exposure to virtual experiences with hot or cold cues shapes thermal perception and regulation over time.

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A Appendix



Fig. 10. Renderings of the 32 male-gendered avatars used in the online survey systematically varied by environment, clothing, skin tone, body shape, and age.

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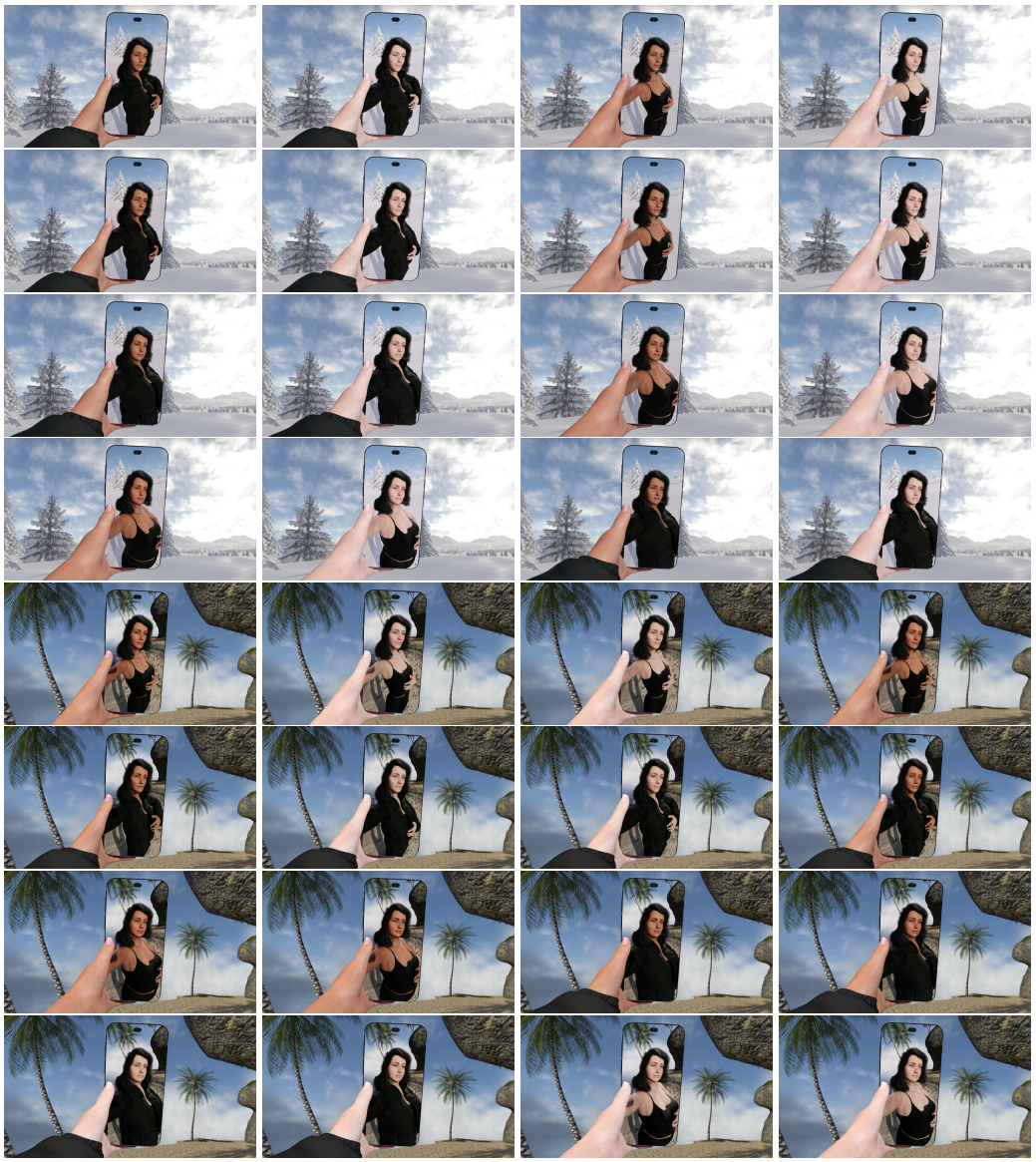


Fig. 11. Renderings of the 32 female-gendered avatars used in the online survey systematically varied by environment, clothing, skin tone, body shape, and age.