Is It Cold in Here or Is It Just Me?
Analysis of Augmented Reality Temperature Visualization for Computer-Mediated Thermoception

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ABSTRACT

Modern augmented reality (AR) head-mounted displays comprise a multitude of sensors that allow them to sense the environment around them. We have extended these capabilities by mounting two heat-wavelength infrared cameras to a Microsoft HoloLens, facilitating the acquisition of thermal data and enabling stereoscopic thermal overlays in the user's augmented view. The ability to visualize live thermal information opens several avenues of investigation on how that thermal awareness may affect a user's thermoception. We present a human-subject study, in which we simulated different temperature shifts using either heat vision overlays or 3D AR virtual effects associated with thermal cause-effect relationships (e.g., flames burn and ice cools). We further investigated differences in estimated temperatures when the stimuli were applied to either the user's body or their environment. Our analysis showed significant effects and first trends for the AR virtual effects and heat vision, respectively, on participants' temperature estimates for their body and the environment though with different strengths and characteristics, which we discuss in this paper.

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Mixed / augmented reality; Human-centered computing—Visualization—Empirical studies in visualization

1 INTRODUCTION

The human sensory systems have developed and evolved over the course of our existence, helping us to survive and thrive in different environments. The sensing of temperature is one of our most critical abilities to perceive and understand our surrounding environment and adapt to different climates. Temperature perception (*thermoception*), the feeling of warm or cold with respect to one's body temperature or the environment, is influenced by multiple sensory channels, including thermoreceptors embedded in our skin, the visual system, and taste/smell [7, 24, 27]. In particular, human vision is known to influence thermoception [32]. A prime example of that are synesthesia and crossmodal correspondence effects that were documented for persons who associate and perceive temperatures with different colors, e.g., warm-red and cool-blue [10].

While thermal imaging mechanisms have been researched for more than 90 years [28], recent advancements in augmented reality (AR) and head-mounted display (HMD) technologies [15] provide us with the means to seamlessly superimpose and fuse live thermal information with the real world. As an extension of AR, Mann [20] introduced a more generalized concept of *mediated reality* (MedR), which refers to the ability to manipulate and mediate signals from the perceptible real world—for example, applying visual filters to see the real world through different channels, such as infrared thermal imagery. As people are more interested in the uses of MedR systems and technology, it becomes more important to study and understand how such mediation technology can change users' perception [17], which is specifically the case for thermoception.

Existing augmentation and mediation technologies are mainly focused on visual displays, which have shown much potential for eliciting changes in human perception. A large body of literature in the field of psychology has established the notion of *visual dominance* effects, which are characterized by an overreliance of the human perceptual system on visual information compared to other extraretinal cues [9, 23]. In this scope, an interesting prototype system called "BurnAR" by Weir et al. exploited such visual dominance effects and showed that the presence of virtual flames over a user's hands can elicit heating sensations in participants [32]. Similarly, for virtual stimuli associated with a "SnowWorld" [11], there is some evidence that virtual cooling stimuli, such as ice or fog in the environment or near a user's body, can reduce pain in burn patients.

In this paper, we investigate how different visualization and mediation approaches can influence human thermoception, particularly with respect to a user's sense of their *body* temperature, the temperature of their *environment*, and the relative difference between the two. For the purposes of a human-subject study, we developed a MedR prototype system that allows for visualization of temperature information on a Microsoft HoloLens via Unity either *indirectly*, through virtual effects that augment the real world and imply an associated temperature (such as virtual fire or icy fog), or *directly* through a thermal imaging (thermal vision) display mode which mediates the user's view with real temperature signals gathered from infrared cameras on the HMD.

We measured and analyzed participants' temperature estimates of both their body and the environment while varying the location of the temperature related visual effects to either on the participant's hand or in their surrounding environment. The degree of the simulated temperature visuals was controlled on a scale from one to five, with one being moderately cold and five being moderately warm. To achieve the mediation effect for the thermal vision conditions, the color of the overlay imagery corresponding to the location of the effect was shifted in the heat map color space to appear warmer or colder. In the augmentation conditions, the amount and intensity of the virtual fire or icy fog was scaled higher or lower to convey more or less extreme temperatures. We discuss the effects and observations for both the augmentation and mediation methods in detail below in sections 3, 4 and 5.

The main contributions of the work presented here are as follows:

- As far as we know, we present the first tangible working prototype that integrates two thermal infrared cameras for stereoscopic thermal visualization in Unity on the HoloLens.
- We show that thermal vision can induce subjective thermal

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responses from users, and provide the first tangible results that explore this emerging design space.

- We present tangible results that show that is possible to invoke warming or cooling sensations from a user in AR.
- We show that these sensations can be invoked either through visual stimuli located on the user's body or placed in their environment.

The remainder of this paper is structured as follows: Section 2 gives an overview of thermoception and prior research on thermal stimuli. Section 3 describes our human-subject study, in which we investigate the effects of two visualization and mediation methods on thermoception. Section 4 presents our results. Section 5 discusses our findings and implications. Section 6 concludes the paper.

2 Related Work

In this section, we provide background information on human thermoception and related work about AR and MedR temperature visualizations and stimuli.

2.1 Human Thermoception and Body Temperature

Temperature is a measure of the average kinetic energy contained in a system of particles. As more energy is introduced into a system, the particles move more rapidly and thus denote a higher temperature; if energy is released from the system, the particles move less rapidly and denote a lower temperature [26]. Humans can sense temperature directly through thermoreceptors embedded in the outer layer of our skin, which translate changes in temperature into electrical signals that are then sent to the central nervous system [30]. Additionally, we can infer certain body temperatures by observing their effects on our behavior or visual appearance, such as shivering, chattering of teeth, goosebumps, red, white or blue skin colors, or similar [22]. A healthy human body at rest has a typical core temperature of 37°C, which it regulates through the cardiovascular system by transferring heat to and from the parts of the body that surround the core. This transfer of heat can result in skin temperature readings on the extremities that are higher or lower than the core temperature. When humans have a fever, one's body increases the core temperature to 38–40°C. Core temperatures above 41°C and below 33°C may cause humans to lose consciousness [5].

2.2 Temperature Visualization

In the scope of this paper, we consider temperature visualization with respect to two different methods: (1) direct mediation using real heat signals and (2) indirect augmentation using virtual effects or archetypal temperature-associated objects.

2.2.1 Mediating Real Thermal Signals

Using a special lens to focus infrared light on a phased array of infrared-detector elements, it is possible to capture temperature information for rays of light emitted or reflected from surfaces in an environment. This enables modern thermal cameras to achieve real-time thermal image generation, similar to the mechanisms behind existing color cameras. Thermal cameras operate in the *long wave infrared range*, which is between $8-15\,\mu m$. In comparison, the wavelengths of light visible to humans are between $380-700\,nm$. Covering different temperature ranges, thermal cameras employ *auto-contrast-gain* and a transfer function to produce *heat maps* as a means for translating different parts of the sensed infrared spectrum to color in the visible range. Modern thermal cameras additionally provide *radiometric* output that interprets the sensed values on an absolute temperature scale. Such thermal cameras have recently become available as commercial off-the-shelf (COTS) consumer devices, e.g., by FLIR, with a small footprint and low cost.

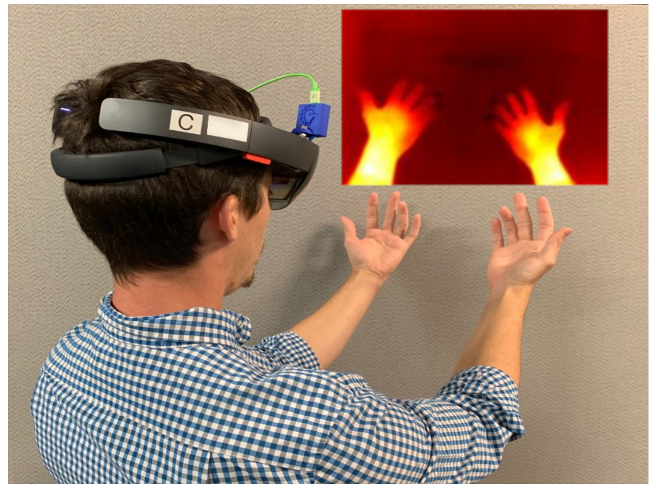


Figure 1: Photo of a user wearing the HoloLens binocular thermal vision prototype with two FLIR thermal cameras mounted on the top looking at his cold hands held in front of him. The inset shows the thermal vision view with the color scheme used in our human-subject study. Compared to seeing one's hands in a warm environment, the dark colors creeping up from the fingertips towards the palm of the user's hand indicate cool temperature sensations.

Different methods have been proposed to present the thermal imagery to users via MedR displays. With thermal vision goggles, thermal camera imagery is calibrated and registered with near-eye displays; by streaming the camera imagery in real time, users can walk around and observe heat sources in the environment. For instance, Orlosky et al. presented "VisMerge," a framework to spatially and temporally calibrate a video see-through HMD with an infrared camera using different visualization methods [21]. They conducted both system level and human-subject studies to investigate the effects of visualization techniques on users' perception and task performance.

A wide range of applications utilizes temperature visualization with thermal vision displays, ranging from firefighting to building maintenance [1, 18]. For instance, Bennett and Matthews developed a helmet with an infrared camera for firefighters, and evaluated the system with professionals in terms of the functionality, ergonomics, and operational benefits [3]. Schönauer et al. developed a headset with a depth sensor and a thermal camera aimed at finding fire victims based on their body temperature [25]. Zalud et al. employed a thermal camera together with a color camera in the context of remote-controlled reconnaissance robots to provide the operator with a better understanding of the robot's surroundings even in conditions with reduced visibility, such as in darkness or fog [33]. Hugues et al. developed a maritime navigation system with thermal vision, which enabled users to recognize objects or people floating on the sea in darkness [12]. Brickner compared thermal imaging with light intensifier systems, which amplify low-intensity ambient illumination, e.g., star and moon light, for helicopter pilots in darkness [6]. Systems by Ham and Golparvar-Fard [8] and Lagüela et al. [18] leveraged thermal imagery to visualize and understand the energy efficiency of buildings.

We are not aware of studies that investigated effects of such displays and visualization methods on a user's estimated temperature of their own body or in relation to the environment.

2.2.2 Augmentation with Virtual Thermal Effects

An alternative to such a mediation of thermal signals is to present objects, effects, or events that humans have learned to associate with different environment temperatures or body sensations. On the one hand, certain visual ambient effects imply *environment* conditions, such as fog that suggests cold humid air. On the other hand, certain effects in close proximity of a person or body part may imply that one's *body* is also affected by these external conditions, such as the cold humid air that is known to deliver cold sensations when exposed to skin, or other related cause-effect relationships that humans have learned through experience (e.g., fire burns or ice cools). Researchers started exploring such stimuli in AR and virtual reality (VR) to change users' perceived temperature or even pain from burn wounds, such as Weir et al.'s "BurnAR" [32] and the "SnowWorld" [11], respectively, with generally promising results.

The work presented in this paper was largely influenced by the BurnAR prototype [31,32]. In their work, the authors used a Cannon VH-2007 video see-through HMD to visualize 3D flames that were dynamically animated over the surface of participants' hands while fire sound effects were played. When exposing participants to this stimulus in a controlled environment, they found that six out of twenty participants experienced a heating sensation on their hand. An explanation for this effect is that humans are familiar with fire and its association with heat sensations, e.g., touching an open flame, which likely led to a portion of the observed experience of a tingling or warming effect.

There were also a few other works that rendered virtual flames in AR. Bane et al. presented an AR X-Ray vision system through which users could see inside buildings and they showed a simulated heat distribution using virtual flames [2]. Iwai et al. combined a standard RGB projector with an infrared projector to render warm virtual objects on a user's arm, and they evaluated their perceived presence of the objects [14]. However, there was little research related to the effects of such virtual objects on the perceived temperature in AR. We believe that more research is necessary to understand the associations between such visual stimuli and perceived temperature changes. In this paper, we investigate both heating and cooling effects based on fire and ice/fog on the participants' body as well as in the environment around their body.

3 EXPERIMENT

In this section, we describe the experiment that we conducted to analyze how AR virtual effects and thermal vision can affect human thermoception. In particular, we evaluate the participants' sense of feeling hot or cold with respect to their body and environment.

3.1 Hypotheses

Considering prior results in the literature, in particular the work of Weir et al. [32], we focused on the following hypotheses when designing our study:

H1 Participant's temperature estimates increase for higher simulated temperatures for all factors (i.e., *Moderately Cold* < *Somewhat Cold* < *Neutral* < *Somewhat Warm* < *Moderately Warm*).

H2 AR virtual effects show higher magnitudes of changes in estimated temperatures than the thermal vision stimuli (i.e., *thermal vision* < *AR Virtual Effects*).

H3 Stimuli on the *body* cause changes in estimated body temperatures but less (if at all) in estimated environment temperatures (i.e., *Environment* < *Body*).

H4 Stimuli in the *environment* cause changes in estimated environment temperatures but less (if at all) in estimated body temperatures (i.e., *Body* < *Environment*).

H5 Physiological data indicates natural body reactions to the simulated temperatures (i.e., *Moderately Cold* < *Somewhat Cold* < *Neutral* < *Somewhat Warm* < *Moderately Warm*).

3.2 Participants

After initial pilot tests, we estimated the effect size of the expected strong effects, and based on a power analysis, we made the decision to recruit 21 participants, which proved sufficient to show significant effects in our experiment. We recruited a total of 16 male and 5 female participants (ages between 18 and 36, $M = 25$, $SD = 5.83$). Eligible for participation in the experiment were only healthy people who did not have any cognitive or motor impairments. All of our participants had normal or corrected-to-normal vision. 8 wore glasses and 3 wore contact lenses during the experiment. None of the participants reported known visual or vestibular disorders, such as color or night blindness, dyschromatopsia, or a displacement of balance. The participants were student or non-student members of the local university community, who responded to open calls for participation, and received monetary compensation. 20 participants had used a VR HMD before; 11 of them had used an AR HMD before. 18 participants reported at least some experience with AR.

3.3 Material

In this section, we describe the experimental setup and prototype HMD for thermal vision and AR virtual effects used in this experiment.

3.3.1 Experimental Setup

As shown in Figure 2, the experimental setup consisted of an isolation booth with floor area 2.1 m × 2.1 m and wall height 2.3 m. Participants were seated on a chair in front of a 0.69 m × 0.72 m panel. Participants were asked to wear an Empatica E4 wristband on their left hand, which they were then asked to place on the panel in front of them during the experiment. This wristband was connected to the Empatica server via Bluetooth, which connected with our Unity application over WiFi, and streamed the wearer's current skin temperature, heart rate, inter-beat interval, and galvanic skin response to the server to be logged.

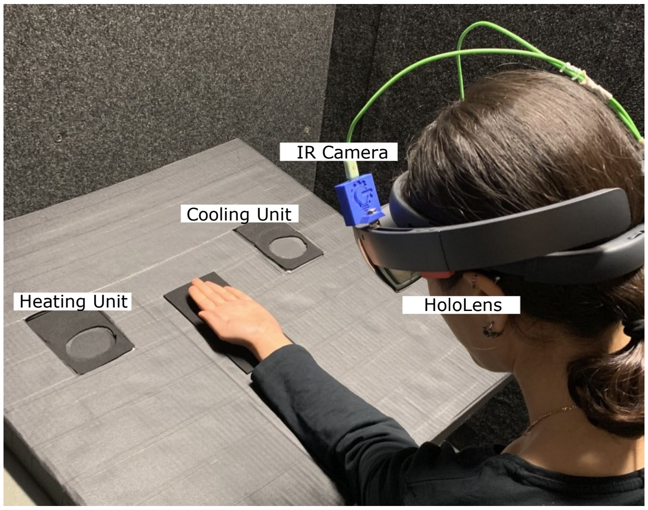
We further mounted a Logitech HD Pro C920 camera in front of the participants in the isolation booth, which we used to capture their behavior during the experiment.

3.3.2 Thermal Vision

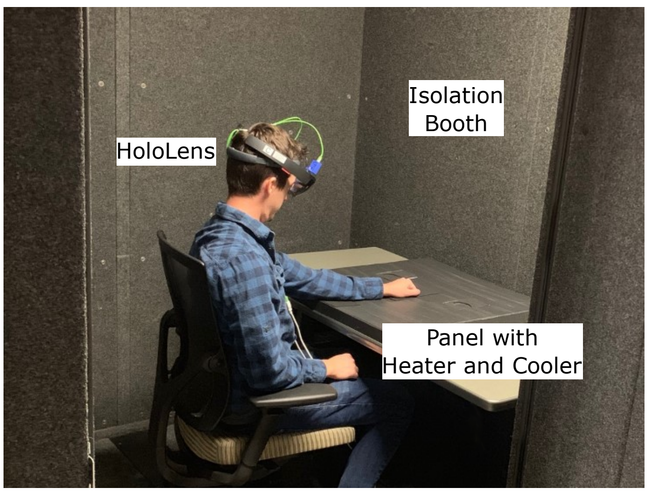
For this experiment, we developed a prototype thermal vision headset that consists of a Microsoft HoloLens with two FLIR Lepton 3.5 Radiometric infrared thermal cameras (housed in PureThermal 2 I/O modules) mounted to the top. The prototype display is shown in Figure 2. Effectively, we turned a COTS AR display into a MedR display using COTS thermal cameras.

The cameras have a resolution of 160×120 pixels and a field of view of 56° horizontally and 44° vertically, which is slightly larger than the HoloLens (30° horizontally and 17° vertically). The cameras sense the range of $8 - 14$ µm in the infrared spectrum known as thermal vision. The Lepton 2 breakout boards are attached to the top of the headset, 0.08 m above the participant's eyes and at a separation of 0.17 m apart. Due to the lack of USB ports on the HoloLens itself, the cameras were tethered to a desktop computer (Intel Core i7-8700K CPU @ 3.7 GHz, 32 GB RAM, GeForce 1070 TI Graphics Card, Windows 10 Pro), and everything was streamed to the HoloLens via Unity version 2018.2.11f1 in holographic remoting mode. We used the FLIR Lepton user app to connect and configure the cameras and we accessed the camera streams in Unity.

We calibrated the auto-contrast-gain (ACG) of the infrared cameras and the corresponding heat color spectrum using reference temperatures of two KADIP Dual Use USB heating and cooling coasters that we placed in front of the participants. The coasters provided constant temperatures at 15°C and 60°C and ensured that the scene looked identical to each participant in the experiment. These coasters were set in a panel that was constructed to obscure the devices. We allowed participants to touch them so that they



(a)



(b)

Figure 2: Experiment setup: (a) user wearing our prototype HoloLens with two mounted IR thermal cameras with a hand resting on the panel next to two built-in heating and cooling coasters, and (b) view showing the isolation booth and the user's pose in front of the panel.

understood the connection between the felt temperatures and the colors shown on the HoloLens.

For the heat color spectrum shown to participants we chose a coloration where the coldest objects in the scene were shown to be black and the hottest objects in the scene were shown to be white. The coloration of the objects between these endpoints were shown in shades of red, orange, or yellow, and were based on a linear scale of RGB values from black (0,0,0) to red (1,0,0) to yellow (1,1,0) to white (1,1,1). This common color scheme provides more range than a gray-scale or red-blue scheme and was found to be easy to understand for all users in pilot tests (see Figure 3a).

A method was needed to segment the regions of the IR thermal vision feed into sub-regions that defined the participant's hand from the rest of the image. In order to provide a real-time solution for the experiment without noticeable image processing latency, we decided on the following approach. We used the SLAM-based tracking of the HoloLens to place an invisible 3D bounding box around the region where the participants were to put their hand, which gave us a region in 3D space where we expected the hand to appear. This region was translated from 3D space into a 2D rectangular region on the thermal vision feed by casting rays from the thermal cameras' positions in 3D space through the front-left and back-right corners of the bounding box. These rays would continue and eventually intersect with the image plane on which the thermal vision feed was presented. The points of collision, which defined a rectangular region on the UI, were passed into a custom shader which would transform the rectangular region into a trapezoidal region with a wider base, which ensured that the entirety of the participant's hand and arm in the view would be within the trapezoidal region. This trapezoidal region was further segmented into pixels that represented the environment and pixels that represented the participant's hand by measuring the RGB value (i.e., heat value) of each pixel and checking if the value was above a predefined threshold that was slightly above room temperature, and which we computed from the temperature measured on the surface of the panel on which the participant's hand rested.

This shader would perform all of the simulated temperature shifts for the thermal vision based conditions by adding or subtracting RGB values from the appropriate pixels of the thermal vision feed according to the linear scale discussed above. This made it possible to manipulate the apparent temperature of the participant's hand or environment separately, and was reliable as long as the participant made no large or quick head motions.

3.3.3 AR Virtual Effects

We had several goals when deciding on which 3D visual effects to use for the study. We wanted the visual effects for both hot and cold stimuli to be dynamic such as the use of moving flames in Weir et. al's work [32]. We also wanted each visual effect to be paired with a sound that complemented the visuals.

The use of dynamic fire visual effects was an obvious choice due to the prior work of Weir et. al, however the selection for a cold effect was less obvious. We had originally looked into using a mass of ice that would grow from the participant's hand over time, however we were unable to find any sound effects that paired appropriately with such a visual. This, and our use of particle-based effects for the fire conditions, led us to consider particle-based effects for cold conditions as well, where we found that a dynamic icy fog was visually similar to the fire effects and could be paired with audio effects of high winds and winter storms to achieve an appropriate audio/visual pairing.

With the selection of fire and icy fog as the basis for all visual effects, we needed methods of displaying these visuals both in a way that could be directly applied to the participant's outstretched hand and in a way that only affected the environment around the participant. For body-located effect conditions, we decided to place a mass of fire or ice onto the participant's outstretched hand. This mass would be scaled larger for the 'moderately warm/cold' conditions, and smaller for the 'somewhat warm/cold' conditions. For environment located effect conditions, we positioned fire or icy fog in different places in the participant's environment. For the 'somewhat warm' condition, two small fires were placed on the desk alongside the user, within their reach yet not directly touching the participant. For the 'moderately warm' condition, the effect was intensified by mapping spreading flames across the walls of the isolation booth in which the participant was located. The effects for the cold environment conditions were less obvious choices and require some justification. We couldn't simply place a mass of icy fog on the desk as was done with the fires in the 'somewhat warm' environment condition, as we felt that whereas one can feel a temperature difference from a fire from several feet away, one typically wouldn't feel the temperature difference of a fog without being somewhat immersed in it. For this reason, we decided to place a body of fog around the user at waist height for the 'somewhat cold' environment condition. For the 'moderately cold' environment condition, this effect had to be somehow extended to imply an even colder temperature in the environment. Initial pilot tests showed that we couldn't scale up the opacity or density of the fog without making it appear like smoke, which could have implied a hot temperature, so we opted to keep the fog effect and add additional particle effects to the condition that made snow fall around the participant and the desk cover with a layer of ice.

Images of the AR virtual effect stimuli shown in Figure 3(b). We used a combination of several 3D assets from the Unity Asset Store, including the "Particle Collection SKJ (ICE)," "Unity Particle Pack," "Cute Snowman," and "Fire & Spell Effects" packages. The Particle Collection SKJ asset was used to create the icy fog effect that was displayed as a ball on the participant's hand as well as ice crystals that appeared on the hand or in the environment. We used the HoloLens' coordinate frame based on SLAM tracking with a World Anchor to place the AR virtual effects around the participant in the isolation booth, e.g., on the panel and on the walls.

3.4 Methods

We used a $2 \times 2 \times 5$ full-factorial within-subjects design. We evaluated the following three factors:

- **Visualization Method** (2 levels): *thermal vision* versus *AR virtual effects*
- **Stimulus Location** (2 levels): limited to their *Body* versus the entire *Environment* around their body
- **Simulated Temperature** (5 levels): *Moderately Cold*, *Somewhat Cold*, *Neutral*, *Somewhat Warm*, and *Moderately Warm*

We presented the visualization methods in two blocks of randomized order (all thermal vision conditions first or all AR virtual effects conditions first). Within these blocks, we presented the simulated temperature conditions and stimulus locations in randomized order to the participants. Details on the conditions are presented below, grouped into thermal vision and AR virtual effects.

Thermal vision Conditions

Examples of the thermal vision conditions are shown in Figure 3(a). In the thermal vision conditions, participants viewed a stereoscopic infrared feed of the scene while placing their hand onto the panel in front of them. In the conditions with a simulated temperature shift in the *Environment*, the apparent temperature of the environment slowly shifted in coloration to appear warmer or colder than it actually was while the user's hand remained at the same temperature color. In contrast, in the conditions where stimuli were focused on the participant's *Body*, their hand slowly shifted in coloration to appear as though it was getting warmer or colder while the rest of the scene remained the same.

In both cases, we calibrated the color spectrum such that the simulated temperatures *Moderately Cold/Warm* corresponded to a shift from the start temperature colors by a total of $\pm 10°C$, whereas they shifted for the *Somewhat Cold/Warm* conditions by a total of $\pm 5°C$. This temperature shift reached a peak at 45 seconds, and then remained the same for an additional 45 seconds. Nothing happened in the *Neutral* condition.

AR Virtual Effects Conditions

Examples of the AR virtual effects conditions are shown in Figure 3(b). In this portion of the study, we used AR virtual objects (whose selection was described in section 3.3.3), such as virtual flames and icy fogs that were visually superimposed into the real world in an attempt to invoke a thermoceptive response from the participant. Similar to the thermal vision conditions, we either presented the AR virtual effects in the *Environment* away from the participant's body or specifically applied them to the participant's *Body*.

For the *Environment* conditions, we scaled the amount of AR virtual effects in the environment relative to the five simulated temperature conditions, while the effects were displayed and scaled directly onto the participant's outstretched hand for the *Body* conditions. Each condition was shown for 90 seconds as in the thermal vision conditions with the first 45 seconds showing an increase of the effects while remaining in place for the second 45 seconds.

Among the Environment conditions, we varied the simulated temperature in five scales. Nothing happened in the *Neutral* condition. In the *Moderately Warm* condition, we presented virtual flames appearing across the walls of the isolation room in which the participant was seated in. We also added volumetric smoke that started to fill the room, as well as loud fire and burning building sound effects that were played through the HoloLens' speakers. In the *Somewhat Warm* condition, we dialed the effects back to just two small fires on the panel in front of the participant, together with smoke, as well as less intense fire sounds. The *Moderately Cold* condition, was characterized by thick icy fog rising from the floor and filling the room to the participant's waist, accompanied by snowfall, a virtual snowman and frost covering the desk, and sounds of howling wind. The *Somewhat Cold* condition consisted solely of fog placed at waist height around the participant and wind effects.

We varied the simulated temperature in the same five scales for the Body conditions as well. Nothing happened in the *Neutral* condition. The *Moderately Warm* condition was characterized by a large virtual flame and a bed of virtual embers on the participant's hand while loud cracking fire sound effects were played. The *Somewhat Warm* was dialed back to a small virtual flame and embers as well as more quiet fire sound effects. In the *Moderately Cold* condition, we showed a large and dense swirling ball of virtual icy fog over the hand, with virtual ice crystals appearing on the surface of the participant's hand, and loud howling wind sound effects playing. In the *Somewhat Cold* condition, we reduced this to a small ball of virtual swirling fog and more quiet wind effects.

3.5 Procedure

After reading a consent form and agreeing to take part in the study, participants were given a brief introduction of the study.

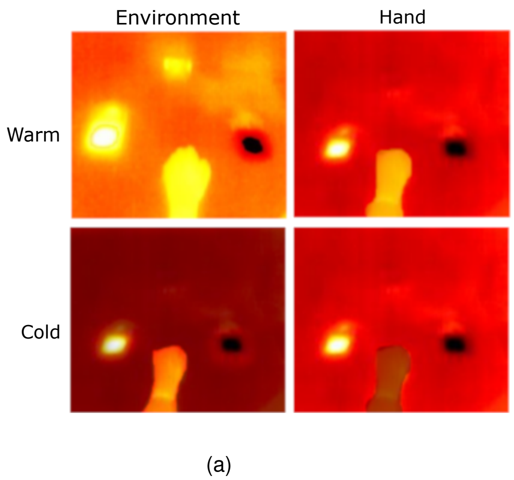
We then gave them a few minutes to familiarize themselves with the HoloLens and adjust the device to fit comfortably on their head. They were then asked to complete the HoloLens calibration routine to configure the HoloLens to their interpupillary distance (IPD) before continuing on.

Participants then experienced a total of 20 conditions that were 90 seconds long each, with short breaks of 10–15 seconds in between. After each condition, participants would rate their perception of temperature on their body and in the environment. Survey questions for the temperature perception on the body and in the environment were displayed through the HoloLens, and the participants verbally reported their responses. After the participant had completed ten conditions, the experimenter paused the experience to allow the participant to re-adjust the headset if needed, and to re-iterate the instructions for the second half. During the experience, the participant would place their hand in a designated place on the panel in front of them, and they were asked to look at their hand. We allowed them to look around the room in the AR virtual effects conditions.

After experiencing all 20 conditions, participants were asked to complete a post-experiment questionnaire about their demographics and experience, and had a short interview session where the experimenter asked them about their experience and their perception of the temperature changes.

3.6 Measures

To investigate the participant's perception of temperature with our two visualization and mediation methods, we measured both temperature estimates and objective physiological responses from the participants in the study.



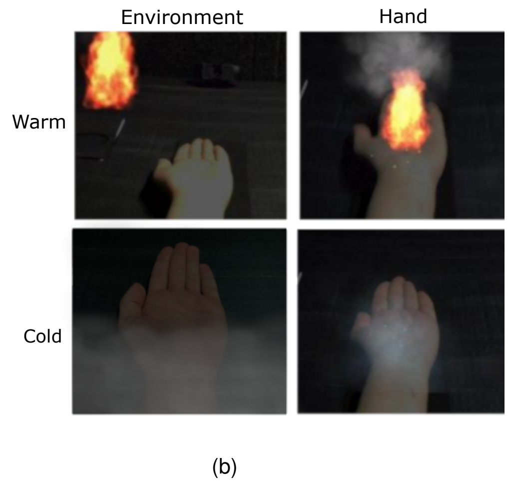


Figure 3: Mediated and augmented temperature stimuli used in the experiment: (a) thermal vision and (b) AR virtual stimuli. The stimuli were applied either to the *Environment* or to the participant's *Hand*. We either simulated an increase (*Hot*) or decrease (*Cold*) in temperature.

3.6.1 Temperature Estimates

To assess the participants' sense of thermoception and how it is affected by the stimuli in the different conditions, we prepared two questions to measure temperature estimates for their body and the environment. The questions appeared on the HoloLens together with a scale for the answers:

- *Use this scale for the following questions:*
  - *(1) Moderately Cold*
  - *(2) Somewhat Cold*
  - *(3) Neutral*
  - *(4) Somewhat Warm*
  - *(5) Moderately Warm*
- Question for Body: *"On a scale of 1 (Moderately Cold) to 5 (Moderately Warm), how would you describe the temperature of your hand and body?"*
- Question for Environment: *"On a scale of 1 (Moderately Cold) to 5 (Moderately Warm), how would you describe the temperature of your environment?"*

We feel that this 5-point likert scale both appropriately captured the presence or absence of a hot or cold sensation and also allowed the participant to classify the degree of the sensation experienced as one of two different levels. For these questions, we explained to participants that they should observe how their body and the environment felt with respect to temperature, rather than rating how it (visually) appeared with respect to temperature on the display. The questions appeared on the HoloLens after experiencing each condition. Note that these scales are for the participants' subjective responses; not the same as our simulated temperature conditions described in Section 3.4.

In addition, a post-questionnaire was presented at the end of the experiment which had the participants fill out demographics information and use their own words to describe any type of sensations they noticed during the experiment and in what circumstances the sensations occurred. We also added questions to assess if the participants experienced goosebumps or shivering during the course of the experiment.

3.6.2 Physiological Measures

We recorded physiological data to capture objective changes in participants' physiology in the different stimulus conditions and associated with the subjective temperature estimates [13]. We used an Empatica E4 wristband to measure biometric physiological data during the conditions. Precisely, we started logging at the beginning of the conditions and stopped logging after the 90 seconds stimulus phase. The Empatica E4 wristband can record skin temperature, heart rate, inter-beat interval, and galvanic skin response. Due to limitations of the Empatica E4 experienced in terms of the accuracy of the latter data types, we opted to analyze only skin temperature and heart rate.

4 Results

In this section we present the descriptive and inferential statistical analysis of the temperature estimates followed by physiological results and qualitative feedback collected during an informal interview at the end of the experiment.

We decided to perform parametric statistical tests to analyze the ordinal data from our Likert scale participant responses [19]. While there is controversy over using parametric tests on ordinal data, it is a widespread practice to treat Likert-type scales as interval-level measurements due to them being designed as quasi-intervals (e.g., see the discussion in [4, 16, 29]).

We analyzed the results with repeated measures ANOVAs and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. We tested the normality with Shapiro-Wilk tests at the 5% level and confirmed it with QQ plots if in question. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity in those cases when Mauchly's test indicated that the assumption of sphericity was violated.

4.1 Temperature Estimates

The results for the temperature estimates are shown in the left two columns of Figure 4. The x-axes shows the five simulated temperatures, increasing from left to right, divided for each temperature into stimuli on the participants' hand (cyan-green) and in the environment (tan). The y-axes show the mean responses for the participants' estimated temperatures (1 = Moderately Cold, 5 = Moderately Warm). The error bars show ± 1 standard error.

We found a significant main effect of the visualization method on body temperature estimates, $F(1,20) = 10.089$, $\boldsymbol{p = 0.005}$, $\eta_p^2 = 0.335$, indicating stronger responses for the AR virtual effects than for thermal vision.

We further observed an interaction effect between the visualization method and simulated temperatures on body temperature estimates, $F(4,80) = 5.779$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.224$. We also found an interaction effect between the stimulus location and the simulated temperatures on environment temperature estimates, $F(4,80) = 3.003$, $\boldsymbol{p = 0.023}$, $\eta_p^2 = 0.131$. We thus proceeded to analyze them as split groups additionally to the overall main effects.

4.1.1 Body Temperature Estimates

We found a significant main effect of the five simulated temperatures on body temperature estimates, $F(4,80) = 13.979$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.411$. The results show that higher simulated temperatures lead to higher estimated body temperatures.

Specifically, for AR virtual effects, we found a significant main effect of the simulated temperatures on body temperature estimates, $F(4,80) = 19.693$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.496$. We found significant main effects of the simulated temperatures on body temperature estimates for stimuli presented on the body, $F(4,80) = 19.815$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.498$, and stimuli presented in the environment, $F(4,80) = 5.101$, $\boldsymbol{p = 0.01}$, $\eta_p^2 = 0.203$.

For thermal vision, we did not find a significant main effect of the simulated temperatures on body temperature estimates, $F(4,80) = 1.569$, $p = 0.191$, $\eta_p^2 = 0.073$. We neither found significant main effects of the simulated temperatures on body temperature estimates for stimuli presented on the body, $F(4,80) = 1.063$, $p = 0.381$, $\eta_p^2 = 0.50$, nor for stimuli presented in the environment, $F(4,80) = 1.491$, $p = 0.213$, $\eta_p^2 = 0.069$.

4.1.2 Environment Temperature Estimates

We found a significant main effect of the five simulated temperatures on environment temperature estimates, $F(4,80) = 7.833$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.281$. Similar to the results for body temperature estimates, higher simulated temperatures lead to higher estimated environment temperatures.

Specifically, for AR virtual effects, we found a significant main effect of the simulated temperatures on environment temperature estimates, $F(4,80) = 9.718$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.327$. We found significant main effects of the simulated temperatures on environment temperature estimates for stimuli presented on the body, $F(4,80) = 7.698$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.278$, and stimuli presented in the environment, $F(4,80) = 7.456$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.272$.

For thermal vision, we did not find a significant main effect of the simulated temperatures on environment temperature estimates, $F(4,80) = 1.258$, $p = 0.293$, $\eta_p^2 = 0.059$. We did not find a significant main effect of the simulated temperatures on environment temperature estimates for stimuli presented on the body, $F(4,80) = 0.493$, $p = 0.741$, $\eta_p^2 = 0.24$, but we found a **trend** for stimuli presented in the environment, $F(4,80) = 2.447$, $p = 0.053$, $\eta_p^2 = 0.109$.

4.2 Physiological Results

We analyzed the measured body temperature and heart rate from the Empatica E4 wristband during the conditions.

Body Temperature The results for the body temperature changes during the experiment are shown in the right column of Figure 4. The x-axes shows the five simulated temperatures. The y-axes show the relative skin temperature changes measured by the Empatica device from the beginning to the end of the trials. The error bars show $\pm$ 1 standard error.

Prior to analysis, the individual Empatica temperature logs for each participant were plotted and inspected for interruptions in the recording of data as well as for inconsistent spikes. Due to missing data points observed in these log files, we had to remove nine potentially affected data sets, leaving twelve valid data sets for the analysis.

On average, over all conditions, our participants' skin temperature decreased by 0.16°C ($SD = 0.429$°C), suggesting that the actual temperature in the room (between 21.4–21.7°C) was cooling their skin throughout the experiment, compared to a higher outside temperature when participants entered the laboratory space. Hence, if the results show no decrease in skin temperature (e.g., for some of the thermal vision conditions) it could be interpreted as a slight warming effect.

Our results suggest a **trend** for an effect of the visualization method on the physiological body temperature changes, $F(1,11) = 2.32$, $p = 0.16$, $\eta_p^2 = 0.174$, however we found no significant effect of the visualization method, stimulus location, or simulated temperature (all $p > 0.05$).

The accuracy of the temperature sensing capabilities of the Empatica E4 (which is stated in the documentation to be $\pm$ 0.2 °C), may have also had some effect on these results, however since we are concerned with temperature shifts as opposed to direct temperature measurements, the impacts of the E4's accuracy should be minimal.

Heart Rate We calculated the average heart rate per trial condition from the results provided by the Empatica E4 wristband at the beginning and at the end of the 90 seconds stimuli. We then computed the difference between the two for each condition, and this value was used for the analysis. Again, due to issues with the Empatica logging, we removed ten potentially affected data sets, leaving eleven valid data sets for the analysis.

We found no significant effect or discernible trend for the physiological heart rate changes in relation to visualization method, stimulus location, or simulated temperature (all $p > 0.05$).

4.3 Qualitative Feedback

We asked our participants to use their own words to describe any of the effects or things that they may have noticed over the course of the experiment. We received several interesting qualitative responses from our 21 participants:

1. 6 participants (29%) described a "cold" or "cooling" sensation during the thermal vision conditions.

2. 14 participants (67%) described a "cold" or "cooling" sensation during the AR virtual effects conditions.

3. 9 participants (43%) described a "heating" or "warming" sensation during the thermal vision conditions.

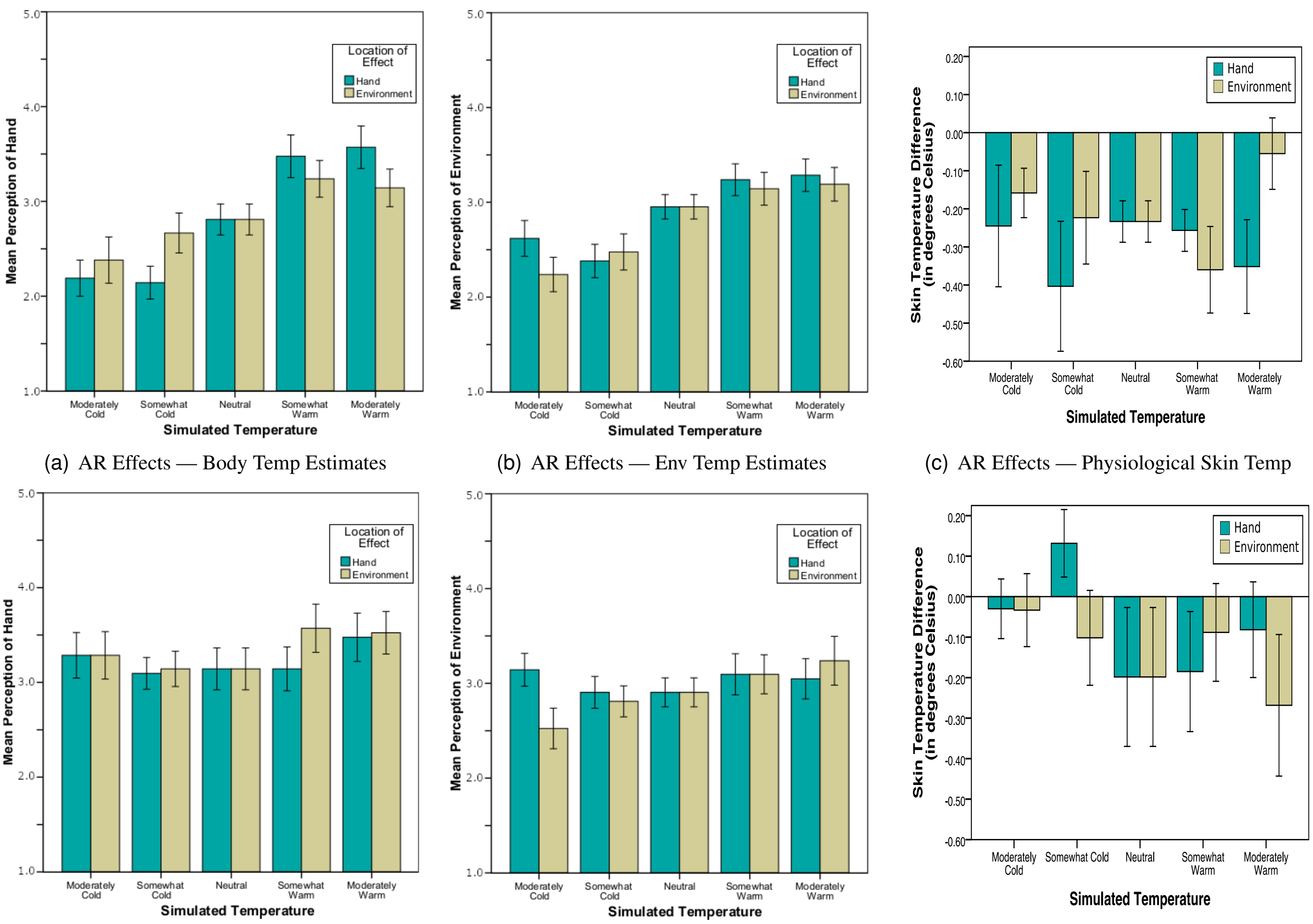
4. 5 participants (24%) described a "heating" or "warming" sensation during the AR virtual effects conditions.

5. 4 participants (19%) described a "twitch" or "tingling" sensation during the thermal vision conditions.

6. 3 participants (14%) described a "twitch" or "tingling" sensation during the AR virtual effects conditions.

5 Discussion

In this section we resume and discuss our main findings.



(a) AR Effects — Body Temp Estimates

(b) AR Effects — Env Temp Estimates

(c) AR Effects — Physiological Skin Temp

(d) thermal vision — Body Temp Estimates

(e) thermal vision — Env Temp Estimates

(f) thermal vision — Physiological Skin Temp

Figure 4: Subjective results for the (a,b,c) augmented reality and (d,e,f) thermal vision stimuli for the (a,d) perception of body temperature and (b,d) perception of environment temperature.

5.1 Higher simulated temperatures result in higher temperature estimates—for AR virtual stimuli

Overall, our results support Hypothesis **H1** in that they show that participants' temperature estimates were affected by the simulated temperatures for AR virtual effects. For the AR effects associated with cooling sensations, e.g., the virtual icy fog, we found that the temperature estimates decreased from the neutral baseline, whereas the AR effects associated with heating sensations, e.g., the virtual fire, resulted in an increase from the baseline. The results imply that the AR virtual effects were capable of eliciting different temperature responses, which support Weir et al.'s results for their BurnAR evaluation [32], and extend them by showing that they can also work for cooling sensations.

However, this effect was not generally noticeable for the thermal vision stimuli. When we applied the changes in the colors of the thermal vision mode, we only observed a trend for the stimulus applied to the entire environment when participants were asked to estimate the temperature of the environment. We found no effects for stimuli applied to the participants' body.

The main motivation for the effects for AR virtual effects as mentioned in Section 2.1 is centered around the conceivable notion that humans may develop a mental association between seeing something hot or cold and feeling the temperature from the thermoreceptors in their skin.

One might argue that participants had no prior association between the thermal vision stimuli and a feeling of warmth or cold, which thus elicited no such effects.

Another potential explanation for the variance in the thermal vision responses may be due to a relative effect that occurs when viewing the temperature shifts in thermal vision. For example, if a participant is experiencing a slightly cold shift on their hand, they will see the coloration around their hand turn darker while the coloration of their environment remains stable. While in this example, the coloration of the environment is staying the same, one can easily interpret this as "the environment is warming in relation to my hand" instead of "my hand is cooling in relation to the environment." This ambiguity when focusing one's attention on one's hand was reported by multiple of our participants. In contrast, when stimuli were applied to the environment, the visual changes were larger, such that when participants were asked to rate the temperature of the environment, we observed a pattern and a trend, which is interesting for future research in this direction.

Bottom line, our informal feedback combined with the formal results suggest that thermal vision could potentially induce similar changes in temperature estimation as AR virtual effects, but that the participants are not familiar enough with such displays to interpret changes in temperature and are not sufficiently sensitive to subtleties in thermal vision. This is in line with our Hypothesis **H2**. Our results show a significant difference between results for AR virtual effects and thermal vision. We found that AR virtual stimuli had a clear effect on participants' temperature estimates but thermal vision to a much lower degree (if at all).

5.2 Simulated AR temperature effects elicit different temperature estimates based on their location

Our results in Figure 4 show that the magnitude by which participants' responses deviate from the neutral baseline depends on whether stimuli are applied to their hand or the environment. In particular, Figure 4(a) shows that AR virtual effects applied to the participant's hand led to stronger warm and cold estimates of their body temperature than effects applied to the environment. A similar effect can be observed in Figure 4(c) for temperature estimates of the environment when AR virtual effects are applied to the environment compared to their hand. These results are in line with both of our Hypotheses **H3** and **H4**.

Moreover, the results for AR virtual effects show that both stimuli on the participant's body and in the environment had a significant effect on both temperature estimates of their body and of the environment. This makes sense as a fire in the environment is likely to also warm one's body, and a fire on one's hand is likely to warm a room-sized environment as well, albeit not to the same magnitude.

Overall, our results extend Weir et al.'s findings for BurnAR [32] by characterizing that such effects can be simulated in different locations in one's environment and thus might apply to different body parts as well, which can inform future work.

5.3 Simulated temperatures might elicit physiological changes

Affected by the reduced number of data sets provided by the Empatica E4 sensor, the physiological results for the sensed body temperature of our participants shown in the right column of Figure 4 did not reveal the expected physiological changes in line with Hypothesis **H5**. It seemed reasonable to assume that the human cardiovascular system that regulates the transfer of heat to and from the parts of the body that surround the core might take into account the simulated visual cues about one's body temperature or that in the environment.

However, we consider it an interesting observation that in nearly every condition the participants experienced an average negative temperature shift and their skin cooled down slightly. These negative temperature shifts can be explained by the room temperature of our testing environment, which was measured for every participant and was always between 21.4–21.7°C compared to a higher outside temperature. The shifts could also be explained partially or entirely by the accuracy of the Empatica E4's temperature sensing capabilities, as mentioned in section 4.2.

We always observed this cooling effect—except for the conditions that used thermal vision with a cooling temperature shift. Even though the number of data sets was greatly reduced, we observed a different pattern and near-significant trend in the results. We consider this an exploratory observation that may inform future studies in this direction.

6 Conclusion

In this paper, we presented a prototype based on two heat-wavelength infrared cameras and a HoloLens that allows us to visualize live thermal information and provides users with thermal awareness of their body and of the environment. We presented a controlled human-subject study, in which we simulated different temperatures either by manipulating the thermal vision stimuli or augmenting the view to the real world with AR virtual effects that are known from the real world to be associated with different temperatures.

We found that the warm or cool AR virtual effects significantly elicited differences in participants' temperature estimates in line with the stimulus. In comparison, we found that the responses for the thermal vision conditions were greatly reduced compared to the AR virtual effects. We discuss these with respect to differences in the stimuli and participants' interpretation of temperature changes with thermal vision displays. We further found that the location of AR virtual effects matters: Stimuli presented on one's body are more likely to elicit heating or cooling estimates of one's body than the environment, and vice versa, while we also observed cross-effects that stimuli on the body affected temperature estimates of the environment, and vice versa. Finally, we explored physiological responses related to skin temperature and heart rate and observed trends that did not show a significant effect but can guide future research on visually mediated thermoception.

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References

[1] F. Amon, N. Bryner, and A. Hamins. Thermal Imaging Research Needs for First Responders: Workshop Proceedings. In *NIST Special Publication 1040*, 2005.

[2] R. Bane and T. Höllerer. Interactive tools for virtual X-ray vision in mobile augmented reality. In *Proceedings of the Third IEEE and ACM International Symposium on Mixed and Augmented Reality*, pp. 231–239, 2004. doi: 10.1109/ISMAR.2004.36

[3] M. V. Bennett and I. Matthews. Life-saving uncooled IR camera for use in firefighting applications. In B. F. Andresen and M. S. Scholl, eds., *Infrared Technology and Applications XXII*, vol. 2744, pp. 549–554, jun 1996. doi: 10.1117/12.243495

[4] N. Blaikie. *Analyzing quantitative data*. SAGE Publications Ltd, 2003.

[5] J. Bligh and K. Voigt. *Thermoreception and Temperature Regulation*. Springer-Verlag Berlin Heidelberg, 1990.

[6] M. S. Brickner. Helicopter Flights with Night-Vision Goggles Human Factors Aspects, 1989.

[7] M. Fulkerson. Rethinking the senses and their interactions: the case for sensory pluralism. *Frontiers in Psychology*, 5:1426, 2014.

[8] Y. Ham and M. Golparvar-Fard. An automated vision-based method for rapid 3D energy performance modeling of existing buildings using thermal and digital imagery. *Advanced Engineering Informatics*, 27(3):395–409, 2013. doi: 10.1016/j.aei.2013.03.005

[9] J. Hartcher-O'Brien, C. Levitan, and C. Spence. Extending visual dominance over touch for input off the body. *Brain Research*, 1362:48–55, 2010.

[10] H.-N. Ho, G. H. Van Doorn, T. Kawabe, J. Watanabe, and C. Spence. Colour-temperature correspondences: when reactions to thermal stimuli are influenced by colour. *PloS One*, 9(3):e91854, 2006.

[11] H. G. Hoffman, G. T. Chambers, W. J. Meyer, L. L. Arceneaux, W. J. Russell, E. J. Seibel, T. L. Richards, S. R. Sharar, and D. R. Patterson. Virtual reality as an adjunctive non-pharmacologic analgesic for acute burn pain during medical procedures. *Ann Behav Med*, 41:183–191, 2011.

[12] O. Hugues, J.-M. Cieutat, and P. Guitton. An experimental augmented reality platform for assisted maritime navigation. In *Proceedings of the 1st International Conference on Augmented Human*, pp. 12:1–6. ACM Press, New York, New York, USA, 2010. doi: 10.1145/1785455.1785467

[13] B. E. Insko. Measuring Presence: Subjective, Behavioral and Physiological Methods. In G. Riva, F. Davide, and W. A. IJsselsteijn, eds., *Being There: Concepts, Effects and Measurement of User Presence in Synthetic Environments*. IOS Press, 2003.

[14] D. Iwai, M. Aoki, and K. Sato. Non-Contact Thermo-Visual Augmentation by IR-RGB Projection. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 25(4):1707–1716, 2019.

[15] K. Kim, M. Billinghurst, G. Bruder, H. Been-Lirn Duh, and G. F. Welch. Revisiting Trends in Augmented Reality Research: A Review of the 2nd Decade of ISMAR (2008–2017). *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 24:2947–2962, 2018.

[16] T. Knapp. Treating ordinal scales as interval scales: an attempt to resolve the controversy. *Nursing research*, 39:121–123, 1990.

[17] E. Kruijff, J. E. Swan, and S. Feiner. Perceptual Issues in Augmented Reality Revisited. In *IEEE International Symposium on Mixed and Augmented Reality*, pp. 3–12, 2010.

[18] S. Lagüela, J. Armesto, P. Arias, and J. Herráez. Automation of thermographic 3D modelling through image fusion and image matching techniques. *Automation in Construction*, 27:24–31, 2012. doi: 10.1016/j.autcon.2012.05.011

[19] R. Likert. A technique for the measurement of attitudes. *Arch. Psychol*, 22:5–55, 1932.

[20] S. Mann. Mediated reality with implementations for everyday life. *Presence Connect, MIT Press journal PRESENCE: Teleoperators and Virtual Environments*, 2002.

[21] J. Orlosky, P. Kim, K. Kiyokawa, T. Mashita, P. Ratsamee, Y. Uranishi, and H. Takemura. VisMerge: Light Adaptive Vision Augmentation via Spectral and Temporal Fusion of Non-visible Light. In *IEEE International Symposium on Mixed and Augmented Reality*, pp. 22–31, 2017. doi: 10.1109/ISMAR.2017.19

[22] P. Paulev and G. Zubieta-Calleja. *New Human Physiology*. University of Copenhagen, 2 ed., 08 2004.

[23] M. I. Posner, M. J. Nissen, and M. Klein. Visual dominance: An information processing account of its origins and significance. *Psychological Review*, 83:157–171, 1976.

[24] R. J. Schepers and M. Ringkamp. Thermoreceptors and thermosensitive afferents. *Neurosci. Biobehav. Rev.*, 34:177–184, 2010.

[25] C. Schonauer, E. Vonach, G. Gerstweiler, and H. Kaufmann. 3D building reconstruction and thermal mapping in fire brigade operations. *Augmented Human International Conference*, pp. 202–205, 2013. doi: 10.1109/VR.2013.6549445

[26] J. F. E. Schooley. *Temperature: Its Measurement and Control in Science and Industry*, vol. 6. 1993.

[27] J. Simner. Beyond perception: synaesthesia as a psycholinguistic phenomenon. *Trends in Cognitive Sciences*, 11(1):23–29, 2006.

[28] M. Vollmer and K.-P. Möllmann. *Infrared Thermal Imaging: Fundamentals, Research and Applications*. Wiley-VCH, 2010.

[29] S. M. W. Kuzon Jr, M. Urbanchek. The seven deadly sins of statistical analysis. *Annals of plastic surgery*, 37:265–272, 1996.

[30] S. D. Waldman. Chapter 109 - functional anatomy of the thermoreceptors. In S. D. Waldman, ed., *Pain Review*, p. 190. W.B. Saunders, Philadelphia, 2009. doi: 10.1016/B978-1-4160-5893-9.00109-X

[31] P. Weir, C. Sandor, M. Swoboda, T. Nguyen, U. Eck, G. Reitmayr, and A. Dey. BurnAR: Feel the heat. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 331–332, 2012.

[32] P. Weir, C. Sandor, M. Swoboda, N. Thanh, U. Eck, G. Reitmayr, and A. Dey. BurnAR: Involuntary Heat Sensations in Augmented Reality. In *Proceedings of IEEE Virtual Reality (VR)*, pp. 43–46, 2013.

[33] L. Zalud, P. Kocmanova, F. Burian, and T. Jilek. Color and Thermal Image Fusion for Augmented Reality in Rescue Robotics. In *Lecture Notes in Electrical Engineering (The 8th International Conference on Robotic, Vision, Signal Processing & Power Applications)*, vol. 291, pp. 47–55. 2014. doi: 10.1007/978-981-4585-42-2_6