Assessing the Influence of Visual Cues in Virtual Reality on the Spatial Perception of Physical Thermal Stimuli

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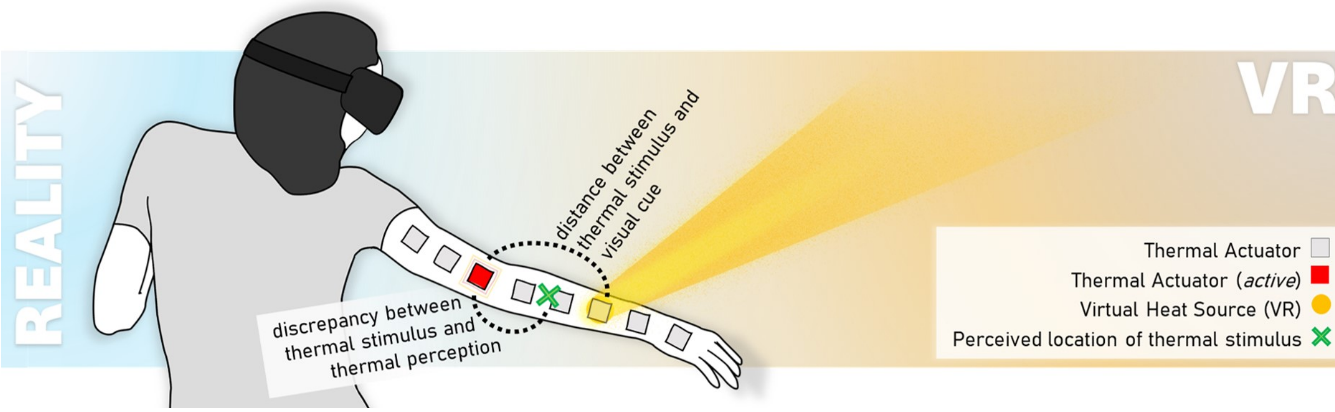

Figure 1: Illustrating the positions of physical thermal actuators and a visual heat source in VR. It indicates a possible discrepancy between the perceived location of the thermal stimulus and its actual location, influenced by the presence of visual cues.

ABSTRACT

Advancements in haptics for Virtual Reality (VR) increased the quality of immersive content. Particularly, recent efforts to provide realistic temperature sensations have gained traction, but most often require very specialized or large complex devices to create precise thermal actuations. However, being largely detached from the real world, such a precise correspondence between the physical location of thermal stimuli and the shown visuals in VR might not be necessary for an authentic experience. In this work, we contribute the findings of a controlled experiment with 20 participants, investigating the spatial localization accuracy of thermal stimuli while having matching and non-matching visual cues of a virtual heat source in VR. Although participants were highly confident in their localization decisions, their ability to accurately pinpoint thermal stimuli was notably deficient.

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CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **Virtual reality**; *User studies.*

KEYWORDS

thermal stimuli, haptic feedback, temperature, user study, virtual reality

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1 INTRODUCTION

The use of Virtual Reality (VR) technology has grown exponentially, offering users immersive experiences that combine visual, auditory, and ever improving haptic cues. However, while the visual and auditory features for VR have advanced significantly, haptic experiences remain challenging and researchers are investigating novel physical actuation methods for VR in order to bring us closer to the vision of an *ultimate display* [68].

In particular, one haptic feature that has received increasing attention in the field of Human-Computer Interaction (HCI) is temperature. Novel interaction concepts and techniques to create authentic temperature sensations in VR are most often leveraged through thermoelectric devices [6, 13, 40, 57, 58, 72, 74] or other air- or fluid-based actuators [23, 27, 30, 76]. As such, achieving seamless congruence between haptic and visual sensations has been the focus of HCI research to provide realistic experiences. However, achieving such congruence typically necessitates specialized setups, often leading to large and cumbersome devices that may negatively affect the applicability and wearability, especially in highly motion-based VR experiences. Yet, while the perceptional process of temperature sensation is complex and affected by various factors, such as the location, applied temperature, and duration of thermal actuation on the body [9, 34], the human thermal perception is also inherently inaccurate [9, 19], offering opportunities for less stringent congruency between thermal and visual stimuli, particularly when being disconnected from reality in a virtual environment.

In this work, we examined the accuracy of determining the location of thermal stimuli in dependency to presented visual cues in VR. Through a controlled experiment (N=20), we discovered significant discrepancies in the localization ability for physical thermal stimuli influenced by the depicted visual cues. We contribute by assessing the accuracy of locating thermal stimuli on different positions of the arm and provide the deviation ranges that still maintained authenticity of the thermal feedback within VR. To further underline the significance of this work, we conclude by discussing the implications of our findings and how they can inform the design of future thermal feedback.

2 RELATED WORK

This section outlines thermal feedback in HCI and their interdependencies with visual perception, particularly in VR.

2.1 Thermal Feedback in HCI, AR, and VR

Thermal feedback in HCI has been applied in a variety of scenarios to enhance user experiences. Examples include applying temperature to tangibles [4, 48], mobile devices [33, 73, 74], media [1, 25], accessories [54, 61, 80], assistive aids [53, 70], cars [11, 12, 51], as well as the augmentation of public spaces [52], actuating almost every body part, such as the hand [6, 32, 44, 47, 78], wrist [50, 66, 74], arm [23, 43, 45, 46, 70], feet [18], head or neck [27, 58–60, 76], upper body [13, 23, 63], and other body parts [37].

Particularly, Augmented Reality (AR) and VR research is increasingly incorporating thermal feedback to provide authentic temperature sensations. Besides *non-contact-based* approaches where thermal feedback is coming mostly from stationary sources, such as heatlamps [27, 30, 32, 78], fans [30, 76], or heating units [63], a large body of research investigated *contact-based* approaches. In these cases, thermal stimuli are applied directly to a user's body, typically by utilizing thermoelectric Peltier elements (e.g., [6, 39, 44, 56–59, 66]), liquid-based systems (e.g., [20, 23, 45]), or through stimulating the trigeminal nerve with chemicals [5]. Combined, these investigations emphasize the value of integrating thermal stimulation into VR, illustrating its significance in enhancing immersion, presence, and realism.

2.2 Effects between Thermal and Visual Perception

Most of the aforementioned AR and VR-based research has concentrated on specific applications of thermal feedback, primarily examining situations where thermal feedback and visual cues in VR are spatially congruent, or how thermal feedback can enhance the quality of virtual content. However, limited investigation has been conducted regarding the degree of congruence required between thermal stimuli and visual cues for the experience to be perceived as authentic.

Thermal perception is complex and closely tied to the varying sensitivities of different body parts [9, 49]. Research found that localizing temperature sensations is inherently inaccurate, for example, due to phenomena like thermal summation and referral [21, 55] where multiple temperature sources can be perceived as a single entity, similar to tactile phantom sensations [2, 15]. However, psycho-physiological studies often presented participants with explicit visual cues of the heat sources or omitted any visual cues to describe thermal stimulus locations.

In the domains of AR and VR, however, unfamiliar and incongruent situations between physical sensations and virtual environments are feasible. By deliberately creating discrepancies between the physically actuated location and the virtual scene, researchers have found ways to manipulate human perception. For instance, haptic retargeting techniques manipulate the virtual position of an arm towards a single haptic proxy-object that provides a tactile surface for multiple virtual objects, while maintaining genuine experiences [3, 7, 42, 79]. Similar research confirmed these observations for audio-visual incongruities in VR [38], further supporting the dominance of visuals [17].

Recent research suggested that this visual dominance is also prevalent when perceiving temperature. Studies have demonstrated that altering the body temperature and illusions of thermal stimuli can be achieved solely through virtual images that generate strong thermal expectations, such as fire and ice, without any physical sensation [16, 36, 41, 69, 71]. Conversely, incorporating physical thermal feedback into virtual experiences was identified as the dominant factor in the perception of temperature and temperature changes with significant influences on user comfort, presence, and even reaction times [4, 23, 77].

However, the extent to which spatial congruence between thermal stimuli and visual cues is essential for an authentic VR experience remains underexplored. Therefore, our research investigated the effects of thermal and visual location mismatches in virtual environments and the extent to which participants can detect these mismatches while still maintaining a realistic experience.

3 METHODOLOGY

We investigated the following research questions:

- **RQ1** To what extent can users precisely determine the localization of thermal stimuli in the presence of congruent and incongruent visual cues in VR?
- **RQ2** To what extent do visual cues in VR affect the temperature perception?

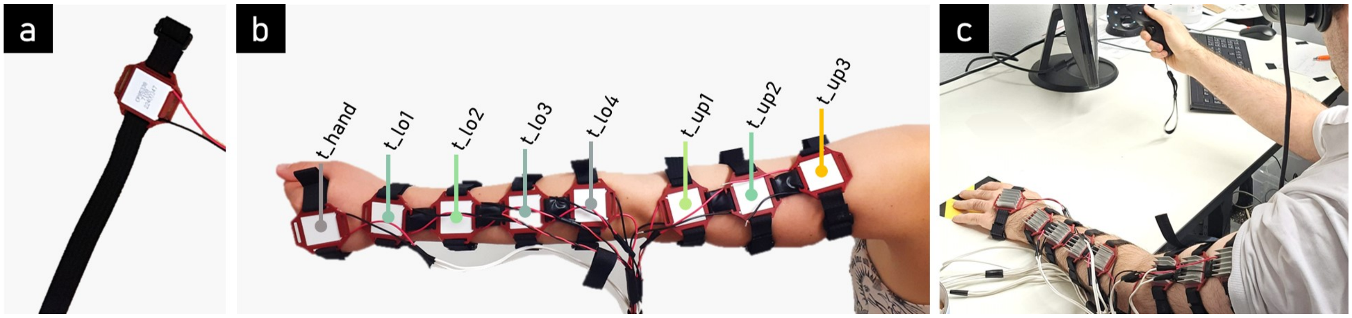


Figure 2: The experimental setup showing (a) a single thermoelectric actuator embedded into a 3D-printed housing (without the attached passive cooler), (b) a user wearing the apparatus, and (c) a participant during the study (passive coolers attached).

3.1 Study Design and Task

We defined two independent variables (IVs) for the experiment: (1) the THERMAL LOCATION and (2) VISUAL LOCATION. Both IV consisted of eight locations plus a no-haptics and a no-visual baseline respectively (t_{no} and v_{no}). In both cases, there was one location on the HAND (t_{hand} and v_{hand}), four on the LOWER ARM (t_{lo1}, t_{lo2}, t_{lo3}, t_{lo4}, v_{lo1}, v_{lo2}, v_{up1}, and v_{lo4}) and three on the UPPER ARM (t_{up1}, t_{up2}, t_{up3}, v_{up1}, v_{up2}, and v_{up3}). The THERMAL LOCATIONS were placed directly on the participant's arm using thermoelectric Peltier elements, while the VISUAL LOCATIONS were rendered at equivalent positions on the virtual avatar (cf. Section 3.3). In total, this resulted in $9 \times 9 = 81$ conditions. To reduce carry-over effects, the condition order was randomized for each participant. As the task, participants were instructed to determine the location of the thermal stimuli while being presented with the visual cues in VR on a self-assertion graph, as illustrated in the concept Figure 1.

3.2 Dependent Variables (DV)

We employed a self-assertion graph for the localization of the THERMAL LOCATIONS (Figure 3b). On this graph, participants had to specify the location on their arm where the thermal stimulus was perceived. While it was technically feasible to directly indicate the thermally actuated spot on the virtual or physical arm, we chose self-assertion on a virtual screen to prevent participants from selectively choosing the last visually stimulated spot or inadvertently touching their real arm, potentially sensing the attached actuators. Additionally, participants were asked to indicate the CONFIDENCE of their answer on another scale from 1 *not confident* to 7 *very confident* and to judge the MATCHING of the THERMAL LOCATION and the VISUAL LOCATION from 1 *not matching* to 7 *completely matching*.

Further, we asked for the perceived TEMPERATURE on a scale from 1 *colder*, 2 *neutral*, 3 *warmer* up to 7 *very hot*, even though the applied temperature was consistent during all conditions (not disclosed to participants). In a last question, we asked to rate the PLEASANTNESS on a scale from 1 *not pleasant* to 7 *very pleasant*.

3.2.1 Post-Questionnaire. After the experiment, we asked participants to answer a final survey assessing the overall confidence in locating the thermal stimuli, whether the thermal stimuli were appropriate, as well for the pleasantness and enjoyment of the feedback. In addition, participants could comment on positive and negative aspects in free text fields and by providing verbal feedback.

3.3 Apparatus and Setup

We designed an arm-worn prototype with eight individually controllable 30x30 mm thermoelectric Peltier elements (*CP85338*). We actuated them for a total duration of 10 seconds applying a fast and easily recognizable heating [9] of $3°C/sec$ until they reached $40°C$, similar to related experiments (e.g., [50, 58, 62, 74]). We used additional passive cooling elements as these naturally dissipate heat without requiring external activation. Their inherent design ensured improved actuation performances by constant stabilization of temperature changes and a reliable cool down to the neutral skin temperature afterward (Figure 2c). To control each actuator, we connected them to a microcontroller that communicated with our study application based on the ActuBoard platform [22]. For the power supply, we used a laboratory power station.

All thermoelectric elements were housed in 3D-printed holders and affixed to the participant's arm using Velcro (Figure 2a/b). While most of them were placed equidistant with a spacing of 7 cm to their respective center, we had to account for the anatomy of the arm and placed the elements on the hand and first lower arm elements (t_{hand} and t_{lo1}) with a distance of 8.5 cm, and both elements adjacent to the elbow joint with a distance of 11 cm (t_{lo4} and t_{up1}). To accommodate a comparable temperature and to avoid side effects from clothing [26], we asked for an uncovered arm (communicated to the participants beforehand).

The VR application was built in Unity and we used an HP Reverb 2 as Head-Mounted Display (HMD). The participants in the virtual environment were embodied by a virtual avatar[1], positioned in front of a virtual desk mirroring the real-world setting (Figure 3a). To enhance self-identification [31, 64], adjustments like skin tone or size could be made to the virtual avatar. Although customizing the virtual avatar's arm length was generally unnecessary, consistent with studies indicating that minor deviations in VR go unnoticed [79], we ensured participants felt represented. If discrepancies emerged, we adjusted the virtual avatar manually to enhance participants' sense of representation. The visual cues were rendered as bright rays representing virtual heat sources at the equivalent locations as the thermal actuators, displaying them depending on the current condition. The questionnaires and self-assertion graph were shown on two virtual displays in front of the participants after each condition (Figure 3b/c).

[1] http://www.makehumancommunity.org/

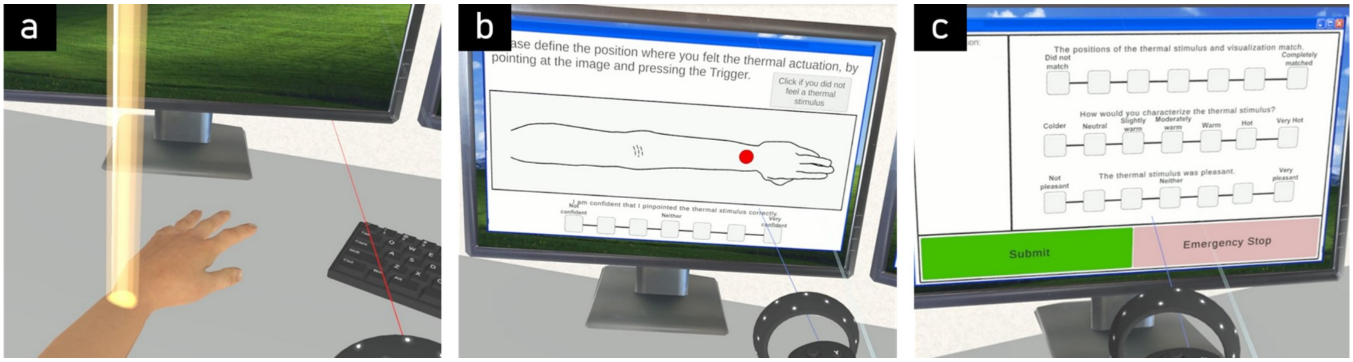


Figure 3: Virtual Reality (VR) perspective of the study depicting (a) a visual cue on the virtual avatar during actuation. (b) and (c) show the questionnaire after each condition, including the self-assertion graph.

3.3.1 Safety. To avoid excessive temperatures [28, 29] that could trigger nociceptors [65] or be harmful, we limited the maximum voltage and current of the thermal actuators using a laboratory power supply. All thermal elements were regularly inspected for correct functionality using a contact thermometer. Additional hard- and software switches were available for instant shutdowns. None of these emergency measures had to be activated during the study.

3.4 Procedure

Before the study. Participants were welcomed and informed about the procedure and safety in advance. They were briefed that they would feel thermal stimuli on their arm, without disclosing the exact number and locations. After answering potential questions and giving them the option to terminate the study at any point without providing reasons, we asked the participants to declare their willingness to conduct the study by signing an informed consent form. Once ready, the experimenter assisted in putting on the HMD and attached the thermal actuators to the unclothed arm, which were manually inspected by the experimenter beforehand. Therefore, a contact thermometer was used to verify the proper functionality of each Peltier element.

During the study. Participants were shown a virtual heat source per condition. Concurrently, one location on their arm was thermally actuated. Both stimuli were removed afterward and participants were asked to answer our questionnaire, including a self-assessment at which location they perceived the thermal stimulus, the confidence in their decision, the degree to which the thermal stimulus matched the visual cue, as well as the perceived degree of temperature and pleasantness of the actuation. Also, participants were invited to provide verbal feedback at any time, which was noted down by the experimenter. Once all items had been answered and participants were ready, the next condition started.

After the study. Participants could take off the HMD and the experimenter removed the thermal actuators. After that, participants were asked to fill out the post-questionnaire and complete a demographics questionnaire. In short debriefing conversations, participants were enlightened about the actuators and temperature, and potential further questions were addressed. On average, the study took 60 minutes per participant.

3.5 Participants

We invited 20 participants (8 female, 12 male) between 21 and 62 years (M=28.25, SD=11.05). Three stated they were proficient VR users while one said they were a regular user, eight used it a few times before, and another eight had no VR experience. Besides snacks and drinks, no compensation was provided.

3.6 Analysis

We performed a non-parametric approach to the analysis of the participants' responses using Aligned Rank Transform (ART) procedure [14, 75] with mixed-effects models (*type III Wald F tests with Kenward-Roger df*[2]) and further report the partial eta-squared η_p^2 as an estimate of the effect size following Cohen's classification as small, medium, or large [8]. If we found significant effects, we used the ART-C method proposed by Elkin et al. [14] for posthoc tests which has higher statistical power and a reduced inflation of Type I errors compared to regular t-tests or ART. Significant observations of THERMAL LOCATIONS or VISUAL LOCATIONS are reported in the respective results sections together with their median, and 1st and 3rd quartile ratings. The full statistical analysis including all results and their respective effect sizes (partial eta-square η_p^2 for main effects and Cohen's d for post-hoc tests [8]) can be found in the supplementary materials.

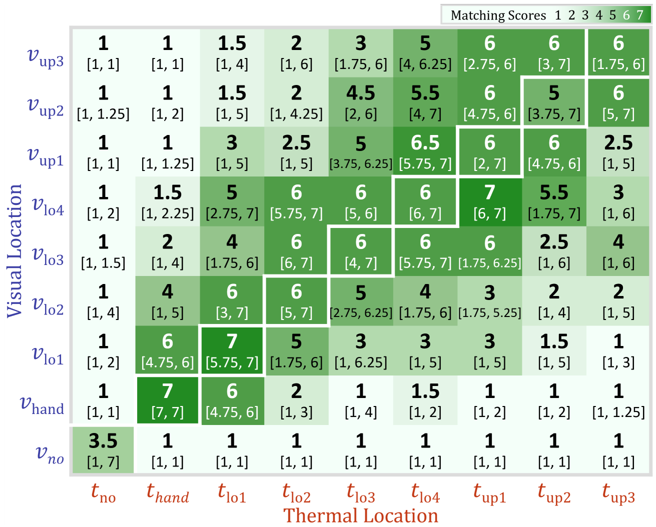
4 RESULTS

In the following, we analyzed matching and confidence ratings, report accuracy and detection thresholds for thermal stimuli, and provide perceived temperature, pleasantness ratings, and post-questionnaire insights.

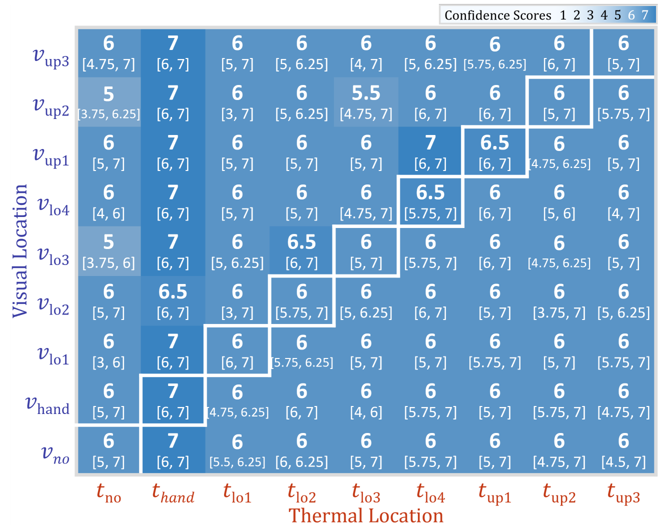
4.1 Matching and Confidence

4.1.1 Matching Ratings between THERMAL LOCATIONS and VISUAL LOCATIONS. Participants gave high matching ratings ($\tilde{x} \geq 5$) mainly for thermal-visual combinations that were not more than one or two adjacent actuators apart. Directly coincident combinations generally received the highest ratings ($\tilde{x} \geq 6$), except for the combination of t_{up2} and v_{up2} ($\tilde{x} = 5$). Baseline conditions without thermal or visual stimuli received the lowest ratings as expected ($\tilde{x} = 1$).

[2] https://cran.r-project.org/web/packages/ARTool/readme/README.html



(a) Matching Ratings



(b) Confidence Ratings

Figure 4: Heatmaps depicting participants' median ratings for (a) the matching of thermal and visual stimuli and (b) the confidence of their localization decisions. The x-axis shows which thermal actuator was active, while the y-axis represents the visual cue. The white outlined cells highlight the conditions where the visual and thermal locations were identical.

The analysis indicated significant effects for the THERMAL LOCATIONS ($F_{8,1520}$ = 32.558, p < .001, η_p^2=.15) with a large effect size . Post-hoc tests confirmed significant effects for all t_{no} (p <.001) and almost all HAND contrasts (all p <.001 except t_{hand}- t_{up2}, p <.01, and t_{hand}- t_{up3}, p >.01). Other significant effects were found for t_{lo1}- t_{up3} (p <.05), t_{lo2}- t_{up3}, t_{lo3}- t_{up3} (both p <.01), t_{lo4}- t_{up2}, t_{lo4}- t_{up3}, and t_{up1}- t_{up3} (all three p <.001).

The analysis also indicated significant effects for the VISUAL LOCATIONS ($F_{8,1520}$ = 36.9334, p < .001, η_p^2=.16) with a large effect size . Post-hoc tests confirmed significant effects for all v_{no} (p <.001) and all HAND contrasts (all p <.001 except v_{hand}- v_{lo1}, p <.01, and v_{hand}- v_{up3}, p <.05). Other significant effects were found for v_{lo3}- v_{up3}, v_{lo4}- v_{up1}, v_{lo4}- v_{up2} (all three p <.05), v_{lo1}- v_{lo4}, and v_{lo4}- v_{up3} (both p <.001). The analysis found significant interaction effects between the THERMAL LOCATIONS and the VISUAL LOCATIONS ($F_{64,1520}$ = 8.7541, p < .001, η_p^2=.27) with a large effect size . The MATCHING descriptives are depicted in Figure 4a.

4.1.2 Confidence in Localization Ratings. Although CONFIDENCE ratings don't directly reflect the ability to locate thermal stimuli, we were interested in participants' confidence levels. They consistently expressed high levels of confidence ($\tilde{x}$ = 6), regardless of whether the thermal stimuli and visualizations matched or mismatched. Notably, the highest confidence ($\tilde{x}$ = 7) was evident for the hand, aligning with its increased temperature sensitivity.

The analysis showed significant effects for the THERMAL LOCATIONS ($F_{8,1520}$ = 17.33, p < .001, η_p^2=.08) with a medium effect size . Post-hoc tests confirmed significant effects for the hand (all p <.001 except t_{hand}- t_{lo4} p <.01), and for t_{no}- t_{hand}, t_{no}- t_{lo4}, t_{no}- t_{up1}, t_{lo3}- t_{lo4} (all p <.001), t_{no}- t_{lo2}, t_{lo4}- t_{up2} (both p <.01), t_{lo3}- t_{up1}, and t_{lo4}- t_{up2} (both p <.05). We found no significant effects for the VISUAL LOCATIONS ($F_{8,1520}$ = 0.291, p > .05, η_p^2=.002) and no interaction effects between the THERMAL LOCATIONS and VISUAL LOCATIONS ($F_{64,1520}$ = 1.012, p > .05, η_p^2=.04) . Figure 4b depicts the descriptives of the CONFIDENCE ratings.

4.1.3 Baseline Observations. For both baselines (t_{no} or v_{no}) combined with at least one other stimulus, we expected a MATCHING rating of 1 (*non-matching*). However, we noticed a divergence in ratings for the combined condition with no applied thermal and visual stimulus (t_{no} with v_{no}). As such, the median rating of 3.5 appears misleading because participants rated either perfect *matching* (7) or *non-matching* (1). Moderate ratings indicating conflicting interpretations were absent, which means half of the participants perceived the absence of stimuli as "matching" (7), while the other half might have expected sensory input, perceiving it as "non-matching" (1) because there was nothing to compare them to initially. Despite individual baseline MATCHING ratings at both extremes (1 and 7), there still seems to be a general consensus among participants, as also supported by the high confidence rating ($\tilde{x}$ = 6).

4.2 Localization Accuracy and Deviations

After observing that high matching ratings ($\tilde{x}$ ≥ 5) were consistently given within the proximity of one or two adjacent locations, we wanted to further determine the localization accuracy between the perceived location of thermal stimuli and actual thermal location, in dependency of the visual cues.

Therefore, we calculated the median, first, and third quartile of all perceived thermal locations. Then, we defined the range as the difference between the 3rd and 1st quartiles, reflecting the 50% range of all localization decisions. Since the medians may not always coincide with the actual THERMAL LOCATION with a center point outside the 1st and 3rd quartiles, we also calculated the offset for each THERMAL LOCATIONS as the difference between the median

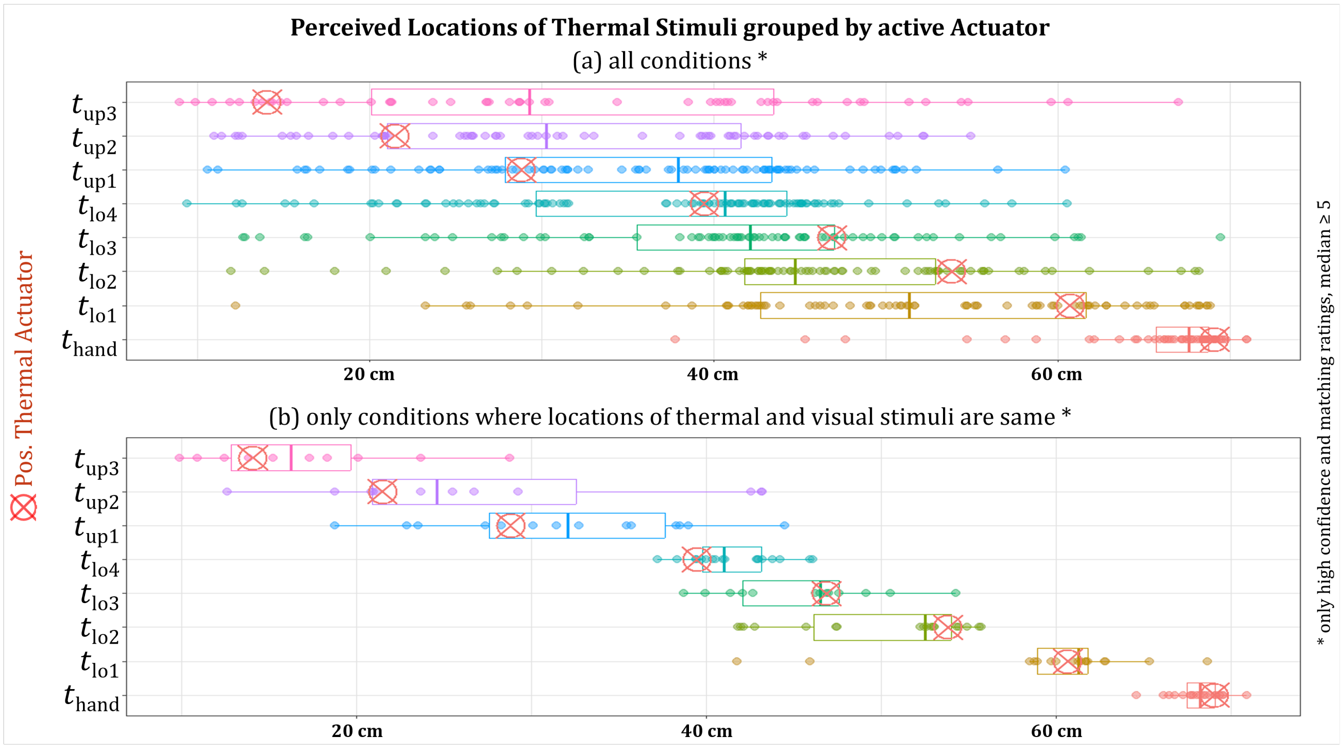


Figure 5: Scatter-Box plot of perceived locations of thermal stimuli, including only data points with high confidence and matching ratings ($\tilde{x} \geq 5$): (a) shows decisions for all conditions, and (b) only conditions with matching thermal and visual locations. Crossed points mark thermal actuator positions, boxes depict the 1st and 3rd quartiles of decisions (50% range).

Thermal Location	*actuation-center*	*loc. of thermal actuator = loc. of visual cue* Q1	median	Q3	50%range	offset	*aggregated over all combinations* $Q1_{all}$	$median_{all}$	$Q3_{all}$	$50\%range_{all}$	$offset_{all}$
t_{hand}	69	67.49	68.23	69.12	**1.63**	0.77	65.71	67.59	68.71	**3**	1.41
t_{lo1}	60.5	58.93	61.3	61.82	**2.89**	0.8	42.7	51.32	61.59	**18.89**	9.18
t_{lo2}	53.5	46.15	52.53	54.02	**7.87**	0.97	41.81	44.69	52.87	**11.06**	8.81
t_{lo3}	46.5	42.07	46.53	47.59	**5.52**	0.03	35.53	42.09	47	**11.47**	4.41
t_{lo4}	39.5	39.81	41.01	43.14	**3.33**	1.51	29.67	40.65	44.25	**14.58**	1.15
t_{up1}	28.5	27.59	32.07	37.63	**10.04**	3.57	27.85	37.91	43.35	**15.5**	9.41
t_{up2}	21.5	20.93	24.61	32.58	**11.65**	3.11	21.05	30.26	41.54	**20.49**	8.76
t_{up3}	14.5	12.8	16.28	19.67	**6.87**	1.78	20.12	29.31	43.49	**23.37**	14.81

Table 1: The table displays deviations in locating thermal stimuli, considering: (a) matching visual locations, and (b) every thermal stimulus combined with all visual locations. It presents quartiles, medians, and the total range, denoting the selection extent for each thermal location that include 50% of all data points. All measurements are in centimeters.

of the perceived and actual THERMAL LOCATION. Only data points with both, high CONFIDENCE and MATCHING ratings ($\tilde{x} \geq 5$), were considered in the analysis to focus on a high authenticity. We listed all descriptives in Table 1.

Subsequently, we first analyzed the accuracy of locating a thermal stimulus in conditions where the THERMAL LOCATIONS were identical with the VISUAL LOCATIONS as a ground truth. As expected, the majority of perceived locations were in closer proximity to the actual THERMAL LOCATION (Figure 5b). However, while more sensitive areas [49]), i.e. that are closer to the hand and elbow, had only low deviations (between 1.63 *cm* and 3.33 *cm*), actuations on less sensitive body parts, i.e., t_{lo2}, t_{lo3}, t_{up1}, t_{up2}, in contrast resulted in higher deviations of up to 11.65 *cm* (cf. Table 1: *range*).

More interestingly, when conditions where THERMAL LOCATION and VISUAL LOCATION didn't coincide but still resulted in high matching and confidence ratings ($\tilde{x} \geq 5$), we observed a larger variance in perceived thermal stimulus locations (Figure 5a). Upon closer examination of the data (cf. Table 1), we noted offsets and selection ranges increasing by 2-4 times the ground truth, despite participants' confidence in their localization abilities. Again, sensitivity

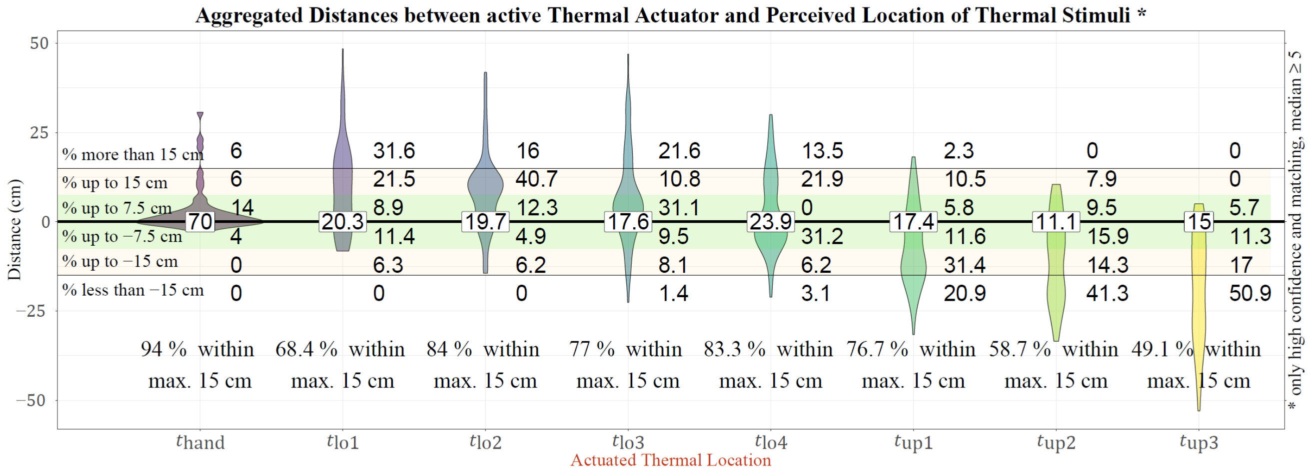


Figure 6: Distance deviations, represented as violin plots, between perceived and actual locations of the active thermal actuator. Values within the violins indicate decision accuracy in percentage, the y-axis illustrates aggregated distances in centimeters, and the x-axis denotes thermal locations. The data only includes data points with high confidence and matching ratings ($\tilde{x} \geq 5$).

played a factor, with the hand still as most accurately localized THERMAL LOCATION (range: 3.0 cm, offset: 1.41 cm), and the upper arm the worst (range: 23.37 cm, offset: 14.81 cm). Consequently, the participants' accuracy of correctly localizing a thermal stimulus drops to just 11.1% to 23.9%, with only the hand (t_{hand}) being at 70.0%. Considering a deviation resembling the distance to two adjacent actuators of ∓ 15 cm, the accuracy increases to values between 49.1% to 84.0% and 94.0% accuracy, depicted in Figure 6.

4.3 Other Results

4.3.1 Temperature Ratings. Although the actuated temperature remained consistent across all conditions, participants perceived variations in temperature. While the majority of TEMPERATURE ratings were consistent ($\tilde{x} = 4$ or $\tilde{x} = 5$), some THERMAL LOCATIONS were perceived as warmer (t_{hand}, t_{lo1}, t_{lo4}), suggesting heightened sensitivity in these areas which is in line with physiological research [49]. Comparisons with the no-thermal baseline confirmed the absence of temperature sensations for all visual cues ($\tilde{x} = 2$). However, in the no-visual baseline, participants perceived different temperatures depending on the location of thermal actuation despite the constant stimulation, again with the hand and around the elbow having slightly increased temperature ratings, reflecting higher sensitivity there [49].

Our analysis indicated significant effects for the THERMAL LOCATIONS ($F_{8,1520} = 96.436$, $p < .001$, η_p^2=.34) with a large effect size . Post-hoc tests confirmed significant effects for all t_{no} (p <.001). Significant effects were also found for t_{hand}- t_{lo1}, t_{hand}- t_{lo2} (both p <.01), t_{lo3}- t_{up3} (p <.05), t_{hand}- t_{lo3}, t_{hand}- t_{up2}, t_{hand}- t_{up3}, t_{lo1}- t_{up3}, t_{lo2}- t_{up3}, t_{lo3}- t_{lo4}, t_{lo3}- t_{up1}, t_{lo4}- t_{up2}, t_{lo4}- t_{up3}, t_{up1}- t_{up2}, and t_{up1}- t_{up3} (all p <.001).

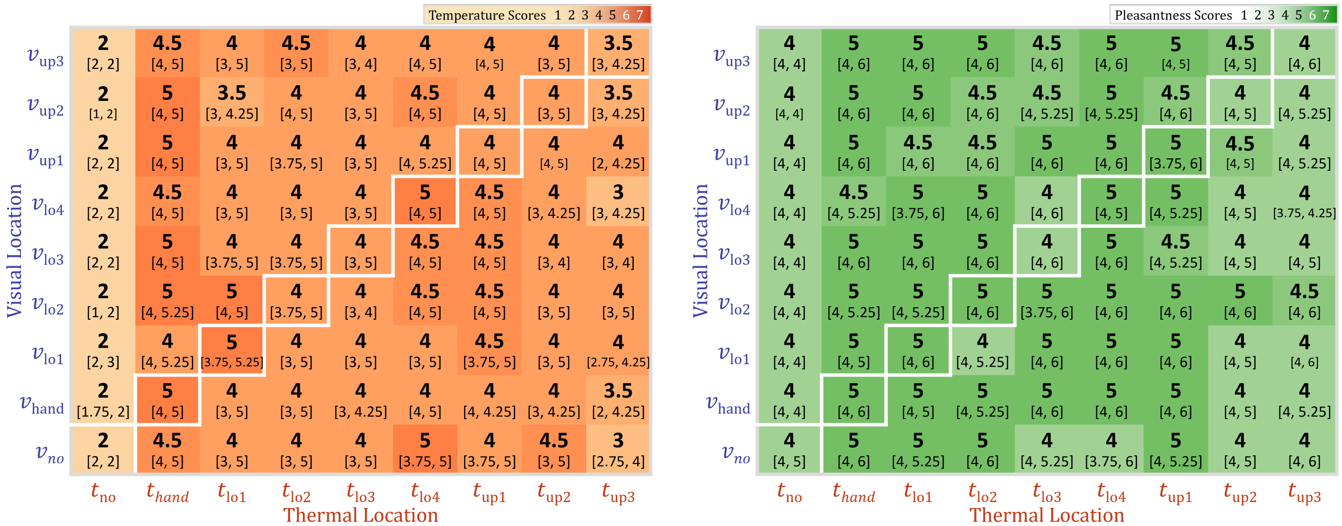
There were no significant effects for the VISUAL LOCATIONS ($F_{8,1520} = 0.528$, $p > .05$, η_p^2=.003) and no interaction effects between the THERMAL LOCATIONS and VISUAL LOCATIONS ($F_{64,1520} = 0.575$, $p > .05$, η_p^2=.02) found. The descriptives for all conditions are shown in Figure 7a.

4.3.2 Pleasantness Ratings. Since the actuation temperature was kept constant, we also expected the perceived pleasantness ratings on a similar level across all conditions which was confirmed by the data analysis ($\tilde{x} = 5$). The analysis indicated significant effects for the THERMAL LOCATIONS ($F_{8,1520} = 12.95$, $p < .001.06$) with a medium effect size . Post-hoc tests confirmed significant effects for all t_{no} (all p <.001 except t_{no}- t_{up3} with p <.05). Further, significant effects were found for t_{hand}- t_{lo1} (p <.001), t_{hand}- t_{lo1}, t_{hand}- t_{lo1}, t_{hand}- t_{lo1} (all three p <.01), and t_{hand}- t_{lo1} (p <.05).

No significant effects for the VISUAL LOCATIONS($F_{8,1520} = 0.475$, $p > .05$, η_p^2=.002) and no interaction effects between the THERMAL LOCATIONS and VISUAL LOCATIONS ($F_{64,1520} = 0.825$, $p > .05$, η_p^2=.03) were found. Descriptives are depicted in Figure 7b.

4.3.3 Post-Questionnaire Results. The post-questionnaire confirmed the high confidence ratings of participants in locating thermal stimuli ($\tilde{x} = 5$ [$Q_1 = 5$, $Q_3 = 6$]) despite the actual low decision accuracy (cf. Section 4.2). Participants further rated both, the appropriateness of the thermal actuations ($\tilde{x} = 6$ [$Q_1 = 4.75$, $Q_3 = 7$]) and level of enjoyment ($\tilde{x} = 6$ [$Q_1 = 4$, $Q_3 = 6.25$]) as high. Similarly, the general pleasantness of the applied thermal stimuli was also rated high, although the distribution of the ratings was much more spread out ($\tilde{x} = 5$ [$Q_1 = 3.75$, $Q_3 = 6$]). The responses are depicted in Figure 8.

4.3.4 Subjective Feedback. During the experiment and in our post-questionnaire, we asked for qualitative feedback. Many appreciated the idea of having thermal feedback that was slightly warm, mostly describing it as comfortable. In particular, first-time VR users expressed their enjoyment of the overall experiment. Some participants found the alignment task between visual and thermal cues engaging and were intrigued when they felt a visual cue and thermal stimulus matched - even though unknown to participants, both might not coincide -, supporting the measured data showing a high decision confidence. Typically, the temperature was described as pleasant and satisfying, akin to a warm touch. However, some



(a) Perceived Temperature Rating **(b) Pleasantness Ratings**

Figure 7: Heatmaps depicting participants' median ratings for (a) perceived temperature and (b) actuation pleasantness. The x-axis shows which thermal actuator was active, while the y-axis represents the active visual cue. The white diagonals highlight the conditions where the visual and thermal locations were identical.

participants voiced discomfort when they had the impression the temperature would get too warm, even though the temperature remained the same for all conditions. Towards the end, a few participants reported difficulty distinguishing the sensations that might occur due to residual warmth between conditions, which would be in alignment with related work [10, 21, 34]. One participant interestingly reported an unfamiliar sensation akin to goosebumps when only a specific portion of their lower arm was heated but could not describe it further.

5 DISCUSSION

Our experiment confirmed the difficulties in locating thermal stimuli, particularly when disconnected from the real world and shown virtual heat sources in VR. In particular, our results showed that participants had limited accuracy in locating thermal stimuli, despite having high confidence in their decisions.

While the discrepancy in locating thermal stimuli was already off by a few centimeters when the VISUAL LOCATION was equal to a THERMAL LOCATION, the participants' ability to accurately locate the thermal stimuli was low. More precisely, we found that only actuations on the hand could be reliably located, which would match the hand's higher temperature sensitivity [49]. However, the accuracy on the lower and upper arms was largely affected by the depicted visual cues in VR with already low localization accuracies during congruent conditions, but even lower when the VISUAL LOCATION did not coincide with the THERMAL LOCATION. However, despite being off by several magnitudes, the high matching ratings combined with the high confidence of participants' decisions supported the hypothesis that authentic thermal feedback could be still maintained.

5.1 Recommendation for Number of Actuators

Based on our findings, we recommend deploying one thermal actuator on the lower arm, upper arm, and hand each. Despite notable discrepancies in the participants' ability to accurately locate thermal stimuli, the high matching ratings and confidence levels in their decisions indicate that an authentic thermal feedback experience can still be maintained. The effectiveness of thermal feedback is particularly prominent on the hand, attributed to its higher temperature sensitivity, always requiring an actuator on its own. In contrast, the lower and upper arms' accuracy is notably lower and strongly influenced by depicted visual cues in VR, leading to lower localization accuracies. For these two, participants could typically distinguish if the lower or upper arm was actuated, emphasizing the necessity for one additional actuator on each part of the arm.

Since our experiment was conducted as lab-study where participants had to focus on the thermal and visual stimuli, we expect that real-world applications outside the lab exhibit even lower accuracy in locating thermal stimuli, as participants would typically focus on an interactive objective rather than the localization aspect. However, further studies are needed to confirm this assumption.

5.2 Implications for Future Thermal Devices

The findings of our experiment complement existing research on thermal feedback and temperature perception. On one side, physiological studies have already shown the inherent inaccuracies in thermal perception due to different sensitivities [19, 49, 67], spatial summations [21, 55], and complexity of thermal perception [9, 34]. In VR, on the other side, we have the ability to intentionally introduce discrepancies between the virtual and physical worlds, allowing for behaviors that deviate from strict physical accuracy [4, 23, 24, 38]. For example, prior research by Kocur et

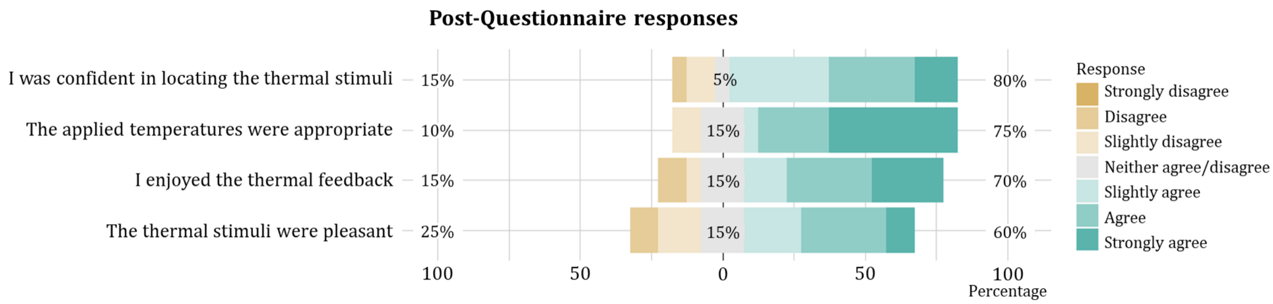


Figure 8: The participants' post-questionnaire responses depicting (1) their overall confidence in their localization decisions, (2) the appropriateness of the applied temperature, (3) their enjoyment impression of thermal feedback, and (4) the pleasantness of the applied thermal stimuli on Likert scales.

al. [41] and others [16, 36, 69, 71], demonstrated the manipulation of temperature expectations and changes in body temperature just by changing the visual appearances of objects or the environment without any thermal feedback. Other work, such as from Balcer et al. [4] and Günther et al. [23], highlighted that the perceived temperature is primarily influenced by the applied thermal stimuli, with fewer effects coming from the visuals. Whereas in our study, visual cues in VR were again a driving factor by influencing the accuracy of locating physical thermal stimuli, making it challenging for users to precisely locate physical heat sources.

Together, these findings provide valuable guidance for the design of future haptic devices aimed at improving efficiency and reducing hardware size. Firstly, the reduced reliance on precise thermal accuracy may allow for fewer thermal actuators, potentially streamlining device design. Secondly, the ability to manipulate perceived intensity, immersion, and comfort through congruent and incongruent thermal stimuli and visual cues offers new possibilities for enhancing user experience. Consequently, these implications suggest reduced device complexity and power consumption, ultimately leading to fewer constraints and improved wearability, especially in highly dynamic VR applications.

6 LIMITATIONS AND FUTURE WORK

In our experiment, we chose to test only the left arm to ensure better control over experimental conditions. While individuals may possess greater skill with their other arm, the equal distribution of thermoceptors in both arms, combined with our fixed-arm setup, helped mitigate potential differences.

Further, while our experiment focused on the actuation of the arm, we believe that the overarching implications are also applicable to other body parts. Yet, further studies are needed to get the accurate thresholds for a better understanding of where actuators are required for authentic feedback, based on the sensitivity of different body parts [19, 49]. In addition, while the same temperature was applied across all conditions, participants sometimes perceived the stimuli as different levels of warmth. As such, further studies that also apply different temperatures are necessary to understand to which degree the temperature perception in VR is affected. Particularly, cold stimuli have to be investigated as well since they rely on other cutaneous receptors than warm stimuli [9, 35] and are typically perceived as more intense [67].

With regard to our study, we focused on a controlled lab experiment. Thereby, we limited the visual cues to basic light rays resembling the radiation of a heat source that was mostly static and did not pose any interactivity. Also, the whole setup was fixed at a stationary desktop to mitigate confounding effects from physical activity. However, outside the lab, VR is typically highly engaging and requires a lot of motion that might directly affect the body temperature. Combined with an increased focus on the VR activity rather than localizing a thermal stimulus, we further expect that the accuracy is even less pronounced than in our experiment. However, further studies have to be conducted. Likewise, our study was conducted with a number of 20 participants that allowed us to identify the aforementioned significant effects. Yet, a larger number of individuals taking part in such a study likely yield more pronounced accuracies, potentially with reduced effect sizes.

Additionally, when looking into the matching ratings for the baseline condition with no thermal and visual stimulus combined, we found discrepancies in what participants rated as matching or non-matching. While some participants felt that a combined absence of stimuli is matching, others interpreted this as non-matching. In this context, this raises the question of whether "matching" even applies when there's nothing to compare on both sides in the first place. In essence, without objects or attributes present, the concept of "matching" may not be applicable.

7 CONCLUSION

In this work, we contributed the findings of a controlled experiment with 20 participants assessing the accuracy of localizing physical thermal stimuli on the arm while being shown visual cues in the form of virtual heat sources in VR. As a result, we found that the accuracy is significantly affected by the location of the visual cues since both, congruent and incongruent stimuli, were inaccurately localized at largely deviating positions, even though participants perceived it as a matching sensation and were highly confident in their decisions. Our research, thereby, highlights actuation thresholds in situations where participants are in direct contact with virtual heat sources, for example, when touching virtual objects or engaging with others through hugs, grasping, etc., to maintain a realistic virtual experience. Additionally, our findings provide valuable insights to inform the design of future thermal feedback, supporting less specialized, smaller, and more efficient devices.

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REFERENCES

[1] Moses Akazue, Martin Halvey, and Lynne Baillie. 2017. Using Thermal Stimuli to Enhance Photo-Sharing in Social Media. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 2 (June 2017), 1–21. https://doi.org/10.1145/3090050

[2] David Alles. 1970. Information Transmission by Phantom Sensations. *IEEE Transactions on Man Machine Systems* 11, 1 (March 1970), 85–91. https://doi.org/10.1109/TMMS.1970.299967

[3] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2016. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1968–1979. https://doi.org/10.1145/2858036.2858226

[4] Carrie Anne Balcer. 2014. Visual Cues effects on temperature perception. (2014). https://commons.nmu.edu/theses

[5] Jas Brooks, Steven Nagels, and Pedro Lopes. 2020. Trigeminal-based Temperature Illusions. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376806

[6] Shaoyu Cai, Pingchuan Ke, Takuji Narumi, and Kening Zhu. 2020. ThermAirGlove: A Pneumatic Glove for Thermal Perception and Material Identification in Virtual Reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 248–257. https://doi.org/10.1109/VR46266.2020.00044

[7] Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. 2017. Sparse Haptic Proxy: Touch Feedback in Virtual Environments Using a General Passive Prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 3718–3728. https://doi.org/10.1145/3025453.3025753

[8] Jacob Cohen. 1988. *Statistical Power Analysis for the Behavioral Sciences* (2nd editio ed.). Routledge, New York, New York, USA. https://doi.org/10.4324/9780203771587

[9] Ian. Darian-Smith and Kenneth O. Johnson. 1977. Thermal Sensibility and Thermoreceptors. *Journal of Investigative Dermatology* 69, 1 (July 1977), 146–153. https://doi.org/10.1111/1523-1747.ep12497936

[10] Stanislas Dehaene. 2003. The neural basis of the Weber–Fechner law: a logarithmic mental number line. *Trends in Cognitive Sciences* 7, 4 (apr 2003), 145–147. https://doi.org/10.1016/S1364-6613(03)00055-X

[11] Patrizia Di Campli San Vito and Stephen Anthony Brewster. 2022. TempSeat: Investigating the Suitability of a Heated Car Seat for Feedback Purposes. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. ACM, New York, NY, USA, 1–6. https://doi.org/10.1145/3491101.3519688

[12] Patrizia Di Campli San Vito, Gözel Shakeri, Stephen Brewster, Frank Pollick, Edward Brown, Lee Skrypchuk, and Alexandros Mouzakitis. 2019. Haptic Navigation Cues on the Steering Wheel. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–11. https://doi.org/10.1145/3290605.3300440

[13] Abdallah El Ali, Xingyu Yang, Swamy Ananthanarayan, Thomas Röggla, Jack Jansen, Jess Hartcher-O'Brien, Kaspar Jansen, and Pablo Cesar. 2020. ThermalWear: Exploring Wearable On-chest Thermal Displays to Augment Voice Messages with Affect. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376682

[14] Lisa A. Elkin, Matthew Kay, James J. Higgins, and Jacob O. Wobbrock. 2021. *An Aligned Rank Transform Procedure for Multifactor Contrast Tests*. Vol. 1. Association for Computing Machinery. https://doi.org/10.1145/3472749.3474784 arXiv:2102.11824

[15] Hesham Elsayed, Martin Weigel, Florian Müller, Martin Schmitz, Karola Marky, Sebastian Günther, Jan Riemann, and Max Mühlhäuser. 2020. VibroMap: Understanding the spacing of vibrotactile actuators across the body. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 4, 4 (Dec. 2020), 1–16. https://doi.org/10.1145/3432189

[16] Austin Erickson, Kangsoo Kim, Ryan Schubert, Gerd Bruder, and Greg Welch. 2019. Is it cold in here or is it just me? analysis of augmented reality temperature visualization for computer-mediated thermoception. *Proceedings - 2019 IEEE International Symposium on Mixed and Augmented Reality, ISMAR 2019* (2019), 202–211. https://doi.org/10.1109/ISMAR.2019.000-2

[17] Marc O Ernst and Martin S Banks. 2002. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* 415, 6870 (Jan. 2002), 429–433. https://doi.org/10.1038/415429a

[18] Bettina Eska, Jeff Owens Iyalekhue, Sebastian Günther, Jasmin Niess, and Florian Müller. 2023. ThermoFeet: Assessing On-Foot Thermal Stimuli for Directional Cues. *ACM International Conference Proceeding Series* (2023), 160–165. https://doi.org/10.1145/3626705.3627974

[19] Nicola Gerrett, Yacine Ouzzahra, and George Havenith. 2016. *Measuring the Skin: Distribution of Skin Thermal Sensitivity.* Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-26594-0

[20] Dustin T. Goetz, David K. Owusu-Antwi, and Heather Culbertson. 2020. PATCH: Pump-Actuated Thermal Compression Haptics. In *2020 IEEE Haptics Symposium (HAPTICS)*. IEEE, 643–649. https://doi.org/10.1109/HAPTICS45997.2020.ras.HAP20.32.c4048ec3

[21] Barry G. Green. 1977. Localization of thermal sensation: An illusion and synthetic heat. *Perception & Psychophysics* 22, 4 (July 1977), 331–337. https://doi.org/10.3758/BF03199698

[22] Sebastian Günther, Florian Müller, Felix Hübner, Max Mühlhäuser, and Andrii Matviienko. 2021. ActuBoard: An Open Rapid Prototyping Platform to integrate Hardware Actuators in Remote Applications. In *Companion Proceedings of the 13th ACM SIGCHI Symposium on Engineering Interactive Computing Systems (EICS '21 Companion)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3459926.3464757

[23] Sebastian Günther, Florian Müller, Dominik Schön, Omar Elmoghazy, Max Mühlhäuser, and Martin Schmitz. 2020. Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. ACM, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376195

[24] Sebastian Günther, Julian Rasch, Dominik Schön, Florian Müller, Martin Schmitz, Jan Riemann, Andrii Matviienko, and Max Mühlhäuser. 2022. Smooth as Steel Wool: Effects of Visual Stimuli on the Haptic Perception of Roughness in Virtual Reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*. ACM, New York, NY, USA. https://doi.org/10.1145/3491102.3517454

[25] Martin Halvey, Michael Henderson, Stephen A. Brewster, Graham Wilson, and Stephen A. Hughes. 2012. Augmenting Media with Thermal Stimulation. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 7468 LNCS (2012), 91–100. https://doi.org/10.1007/978-3-642-32796-4_10

[26] Martin Halvey, Graham Wilson, Yolanda Vazquez-Alvarez, Stephen A. Brewster, and Stephen A. Hughes. 2011. The effect of clothing on thermal feedback perception. *ICMI'11 - Proceedings of the 2011 ACM International Conference on Multimodal Interaction* (2011), 217–220. https://doi.org/10.1145/2070481.2070519

[27] Ping-Hsuan Han, Yang-Sheng Chen, Kong-Chang Lee, Hao-Cheng Wang, Chiao-En Hsieh, Jui-Chun Hsiao, Chien-Hsing Chou, and Yi-Ping Hung. 2018. Haptic around: Multiple Tactile Sensations for Immersive Environment and Interaction in Virtual Reality. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. ACM, New York, NY, USA, 1–10. https://doi.org/10.1145/3281505.3281507

[28] James D. Hardy, Harold G. Wolff, and Helen Goodell. 1952. Pricking Pain Threshold in Different Body Areas. *Experimental Biology and Medicine* 80, 3 (July 1952), 425–427. https://doi.org/10.3181/00379727-80-19644

[29] Joel L.K Harrison and Karen D Davis. 1999. Cold-evoked pain varies with skin type and cooling rate: a psychophysical study in humans. *Pain* 83, 2 (Nov. 1999), 123–135. https://doi.org/10.1016/S0304-3959(99)00099-8

[30] Felix Hülsmann, Julia Fröhlich, Nikita Mattar, and Ipke Wachsmuth. 2014. Wind and Warmth in Virtual Reality: Implementation and Evaluation. In *Proceedings of the 2014 Virtual Reality International Conference*, Vol. 2014-April. ACM, New York, NY, USA, 1–8. https://doi.org/10.1145/2617841.2620712

[31] Wijnand A IJsselsteijn, Yvonne A. W de Kort, and Antal Haans. 2006. Is This My Hand I See Before Me? The Rubber Hand Illusion in Reality, Virtual Reality, and Mixed Reality. *Presence: Teleoperators and Virtual Environments* 15, 4 (Aug. 2006), 455–464. https://doi.org/10.1162/pres.15.4.455

[32] Daisuke Iwai, Mei Aoki, and Kosuke Sato. 2019. Non-Contact Thermo-Visual Augmentation by IR-RGB Projection. *IEEE Transactions on Visualization and Computer Graphics* 25, 4 (April 2019), 1707–1716. https://doi.org/10.1109/TVCG.2018.2820121

[33] Ken Iwasaki, Takashi Miyaki, and Jun Rekimoto. 2010. AffectPhone: A Handset Device to Present User's Emotional State with Warmth/Coolness.. In *B-Interface*. 83–88.

[34] L.A. Jones and H.-N. Ho. 2008. Warm or Cool, Large or Small? The Challenge of Thermal Displays. *IEEE Transactions on Haptics* 1, 1 (Jan. 2008), 53–70. https://doi.org/10.1109/TOH.2008.2

[35] Jon H. Kaas. 2012. Somatosensory System. In *The Human Nervous System* (third edit ed.), Jürgen K. Mai and George Paxinos (Eds.). Elsevier, San Diego, Chapter 30, 1074–1109. https://doi.org/10.1016/B978-0-12-374236-0.10030-6

[36] Shoko Kanaya, Yuka Matsushima, and Kazuhiko Yokosawa. 2012. Does Seeing Ice Really Feel Cold? Visual-Thermal Interaction under an Illusory Body-Ownership. *PLoS ONE* 7, 11 (Nov. 2012), e47293. https://doi.org/10.1371/journal.pone.0047293

[37] Astrid Maria Louise Kappers and Myrthe A. Plaisier. 2019. Thermal Perception and Thermal Devices Used on Body Parts Other Than Hand or Face. *IEEE*

Transactions on Haptics 12, 4 (Oct. 2019), 386–399. https://doi.org/10.1109/TOH.2019.2925339

[38] Hayeon Kim and In-Kwon Lee. 2022. Studying the Effects of Congruence of Auditory and Visual Stimuli on Virtual Reality Experiences. *IEEE Transactions on Visualization and Computer Graphics* 28, 5 (May 2022), 2080–2090. https://doi.org/10.1109/TVCG.2022.3150514

[39] Lawrence H. Kim and Sean Follmer. 2019. SwarmHaptics: Haptic Display with Swarm Robots. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300918

[40] Seung-Won Kim, Sung Hee Kim, Choong Sun Kim, Kyoungsoo Yi, Jun-Sik Kim, Byung Jin Cho, and Youngsu Cha. 2020. Thermal display glove for interacting with virtual reality. *Scientific Reports* 10, 1 (Dec. 2020), 11403. https://doi.org/10.1038/s41598-020-68362-y

[41] Martin Kocur, Lukas Jackermeier, Valentin Schwind, and Niels Henze. 2023. The Effects of Avatar and Environment on Thermal Perception and Skin Temperature in Virtual Reality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, Vol. 1. ACM, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3580668

[42] Luv Kohli, Mary C. Whitton, and Frederick P. Brooks. 2012. Redirected touching: The effect of warping space on task performance. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 105–112. https://doi.org/10.1109/3DUI.2012.6184193

[43] Vasil Kotsev, Atanas Nikolev, Kasper Pawlak, and Markus Löchtefeld. 2017. Investigating the usage of Thermal Feedback as an Active Game Element. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia*. ACM, New York, NY, USA, 91–95. https://doi.org/10.1145/3152832.3152853

[44] Jinwoo Lee, Heayoun Sul, Wonha Lee, Kyung Rok Pyun, Inho Ha, Dongkwan Kim, Hyojoon Park, Hyeonjin Eom, Yeosang Yoon, Jinwook Jung, Dongjun Lee, and Seung Hwan Ko. 2020. Stretchable Skin-Like Cooling/Heating Device for Reconstruction of Artificial Thermal Sensation in Virtual Reality. *Advanced Functional Materials* 30, 29 (July 2020), 1909171. https://doi.org/10.1002/adfm.201909171

[45] Yuhu Liu, Satoshi Nishikawa, Young ah Seong, Ryuma Niiyama, and Yasuo Kuniyoshi. 2021. ThermoCaress: A Wearable Haptic Device with Illusory Moving Thermal Stimulation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3411764.3445777

[46] Markus Löchtefeld, Tuomas Lappalainen, Jani Väyrynen, Ashley Colley, and Jonna Häkkilä. 2017. Comparing Thermal and Haptic Feedback Mechanisms for Game Controllers. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1829–1836. https://doi.org/10.1145/3027063.3053172

[47] Markus Löchtefeld, Nadine Lautemann, Sven Gehring, and Antonio Krüger. 2014. AmbiPad: Enriching Mobile Digital Media with Ambient Feedback. In *Proceedings of the 16th International Conference on Human-Computer Interaction with Mobile Devices & Services (MobileHCI '14)*. Association for Computing Machinery, New York, NY, USA, 295–298. https://doi.org/10.1145/2628363.2628395

[48] Diana Löffler, Robert Tscharn, and Jörn Hurtienne. 2018. Multimodal effects of color and haptics on intuitive interaction with tangible user interfaces. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*, Vol. 2018-Janua. ACM, New York, NY, USA, 647–655. https://doi.org/10.1145/3173225.3173257

[49] Maohui Luo, Zhe Wang, Hui Zhang, Edward Arens, Davide Filingeri, Ling Jin, Ali Ghahramani, Wenhua Chen, Yingdong He, and Binghui Si. 2020. High-density thermal sensitivity maps of the human body. *Building and Environment* 167 (Jan. 2020), 106435. https://doi.org/10.1016/j.buildenv.2019.106435

[50] Tomosuke Maeda and Tetsuo Kurahashi. 2019. TherModule: Wearable and Modular Thermal Feedback System based on a Wireless Platform. In *Proceedings of the 10th Augmented Human International Conference 2019*. ACM, New York, NY, USA, 1–8. https://doi.org/10.1145/3311823.3311826

[51] Xiaru Meng, Jiawen Han, George Chernyshov, Kirill Ragozin, and Kai Kunze. 2022. ThermalDrive - Towards Situation Awareness over Thermal Feedback in Automated Driving Scenarios. In *27th International Conference on Intelligent User Interfaces*. ACM, New York, NY, USA, 101–104. https://doi.org/10.1145/3490100.3516453

[52] Takuji Narumi, Akagawa Tomohiro, Young Ah Seong, and Michitaka Hirose. 2009. Characterizing the Space by Thermal Feedback through a Wearable Device. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. Vol. 5622 LNCS. 355–364. https://doi.org/10.1007/978-3-642-02771-0_40

[53] Arshad Nasser, Kai-Ning Keng, and Kening Zhu. 2020. ThermalCane: Exploring Thermotactile Directional Cues on Cane-Grip for Non-Visual Navigation. In *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3373625.3417004

[54] Arinobu Niijima, Toki Takeda, Takafumi Mukouchi, and Takashi Satou. 2020. ThermalBitDisplay: Haptic Display Providing Thermal Feedback Perceived Differently Depending on Body Parts. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–8. https://doi.org/10.1145/3334480.3382849

[55] Jun Oohara, Hiroshi Kato, Yuki Hashimoto, and Hiroyuki Kajimoto. 2010. Presentation of Positional Information by Heat Phantom Sensation. 445–450. https://doi.org/10.1007/978-3-642-14075-4_66

[56] Roshan Lalintha Peiris, Liwei Chan, and Kouta Minamizawa. 2018. LiquidReality: Wetness Sensations on the Face for Virtual Reality. In *EuroHaptics 2018: Haptics: Science, Technology, and Applications*, Domenico Prattichizzo, Hiroyuki Shinoda, Hong Z Tan, Emanuele Ruffaldi, and Antonio Frisoli (Eds.). Springer International Publishing, Cham, 366–378. https://doi.org/10.1007/978-3-319-93399-3_32

[57] Roshan Lalitha Peiris, Yuan-Ling Feng, Liwei Chan, and Kouta Minamizawa. 2019. ThermalBracelet: Exploring Thermal Haptic Feedback Around the Wrist. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–11. https://doi.org/10.1145/3290605.3300400

[58] Roshan Lalintha Peiris, Wei Peng, Zikun Chen, Liwei Chan, and Kouta Minamizawa. 2017. ThermoVR: Exploring Integrated Thermal Haptic Feedback with Head Mounted Displays. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 5452–5456. https://doi.org/10.1145/3025453.3025824

[59] Kirill Ragozin, Dingding Zheng, George Chernyshov, and Danny Hynds. 2020. Sophroneo: Fear not. A VR Horror Game with Thermal Feedback and Physiological Signal Loop. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–6. https://doi.org/10.1145/3334480.3381659

[60] Nimesha Ranasinghe, Pravar Jain, Shienny Karwita, David Tolley, and Ellen Yi-Luen Do. 2017. Ambiotherm: Enhancing sense of presence in virtual reality by simulating real-world environmental conditions. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, Vol. 2017-May. ACM, New York, NY, USA, 1731–1742. https://doi.org/10.1145/3025453.3025723

[61] Thijs Roumen, Simon T. Perrault, and Shengdong Zhao. 2015. NotiRing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 2497–2500. https://doi.org/10.1145/2702123.2702350

[62] Katsunari Sato and Takashi Maeno. 2012. Presentation of Sudden Temperature Change Using Spatially Divided Warm and Cool Stimuli. In *EuroHaptics 2012: Haptics: Perception, Devices, Mobility, and Communication*, Poika Isokoski and Jukka Springare (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 457–468.

[63] Emily Shaw, Tessa Roper, Tommy Nilsson, Glyn Lawson, Sue V.G. Cobb, and Daniel Miller. 2019. The Heat is On: Exploring User Behaviour in a Multisensory Virtual Environment for Fire Evacuation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300856

[64] Mel Slater. 2008. Towards a digital body: The virtual arm illusion. *Frontiers in Human Neuroscience* 2 (2008). https://doi.org/10.3389/neuro.09.006.2008

[65] Lynne U. Sneddon. 2018. Comparative physiology of nociception and pain. *Physiology* 33, 1 (2018), 63–73. https://doi.org/10.1152/physiol.00022.2017

[66] Nicholas Soucy, Nimesha Ranasinghe, Avery Rossow, Meetha Nesam James, and Roshan Peiris. 2021. THED: A Wrist-Worn Thermal Display to Perceive Spatial Thermal Sensations in Virtual Reality. In *Proceedings of the Future Technologies Conference (FTC) 2020, Volume 2*, Kohei Arai, Supriya Kapoor, and Rahul Bhatia (Eds.). Springer International Publishing, Cham, 809–829. https://doi.org/10.1007/978-3-030-63089-8_53

[67] Joseph C. Stevens and Kenneth K. Choo. 1998. Temperature sensitivity of the body surface over the life span. *Somatosensory & Motor Research* 15, 1 (Jan. 1998), 13–28. https://doi.org/10.1080/08990229870925

[68] Ivan Sutherland. 1965. The Ultimate Display. In *Proceedings of the IFIP Congress*. 506–508. http://citeseer.ist.psu.edu/viewdoc/summary?doi=10.1.1.136.3720

[69] Jun'ya Takakura, Takayuki Nishimura, Damee Choi, Yuka Egashira, and Shigeki Watanuki. 2015. Nonthermal sensory input and altered human thermoregulation: effects of visual information depicting hot or cold environments. *International Journal of Biometeorology* 59, 10 (Oct. 2015), 1453–1460. https://doi.org/10.1007/s00484-015-0956-3

[70] Jordan Tewell, Jon Bird, and George R. Buchanan. 2017. Heat-Nav: Using Temperature Changes as Navigational Cues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1131–1135. https://doi.org/10.1145/3025453.3025965

[71] Peter Weir, Christian Sandor, Matt Swoboda, Thanh Nguyen, Ulrich Eck, Gerhard Reitmayr, and Arindam Day. 2013. Burnar: Involuntary heat sensations in augmented reality. In *2013 IEEE Virtual Reality (VR)*. IEEE, 43–46. https://doi.org/10.1109/VR.2013.6549357

[72] Graham Wilson, Gavin Davidson, and Stephen A. Brewster. 2015. In the Heat of the Moment: Subjective Interpretations of Thermal Feedback During Interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, Vol. 38. ACM, New York, NY, USA, 2063–2072. https://doi.org/10.1145/2702123.2702219

[73] Graham Wilson, Euan Freeman, and Stephen A. Brewster. 2016. Multimodal affective feedback: Combining thermal, vibrotactile, audio and visual signals. *ICMI 2016 - Proceedings of the 18th ACM International Conference on Multimodal Interaction* 9781450345, January (2016), 400–401. https://doi.org/10.1145/2993148.

2998522
[74] Graham Wilson, Martin Halvey, Stephen A. Brewster, and Stephen A. Hughes. 2011. Some like it hot: thermal feedback for mobile devices. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*. ACM Press, New York, New York, USA, 2555. https://doi.org/10.1145/1978942.1979316
[75] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*. ACM Press, New York, New York, USA, 143. https://doi.org/10.1145/1978942.1978963
[76] Jiayi Xu, Yoshihiro Kuroda, Shunsuke Yoshimoto, and Osamu Oshiro. 2019. Non-contact Cold Thermal Display by Controlling Low-temperature Air Flow Generated with Vortex Tube. In *2019 IEEE World Haptics Conference (WHC)*. IEEE, 133–138. https://doi.org/10.1109/WHC.2019.8816089
[77] Dongwoo Yeom, Joon Ho Choi, and Sin Hwa Kang. 2019. Investigation of the physiological differences in the immersive virtual reality environment and real indoor environment: Focused on skin temperature and thermal sensation. *Building and Environment* 154, February (2019), 44–54. https://doi.org/10.1016/j.buildenv.2019.03.013
[78] Yuki Yoshikawa, Daisuke Iwai, and Kosuke Sato. 2013. A study of thermal sensation with visuo-thermal projection interfaces. In *2013 IEEE 2nd Global Conference on Consumer Electronics (GCCE)*. IEEE, 118–119. https://doi.org/10.1109/GCCE.2013.6664767
[79] Andre Zenner and Antonio Krüger. 2019. Estimating detection thresholds for desktop-scale hand redirection in virtual reality. *26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019 - Proceedings* (March 2019), 47–55. https://doi.org/10.1109/VR.2019.8798143
[80] Kening Zhu, Simon Perrault, Taizhou Chen, Shaoyu Cai, and Roshan Lalintha Peiris. 2019. A sense of ice and fire: Exploring thermal feedback with multiple thermoelectric-cooling elements on a smart ring. *International Journal of Human-Computer Studies* 130 (Oct. 2019), 234–247. https://doi.org/10.1016/j.ijhcs.2019.07.003