

Thermal Illusions Reliably Shift Perceived Object Temperatures Across Materials in Mixed Reality

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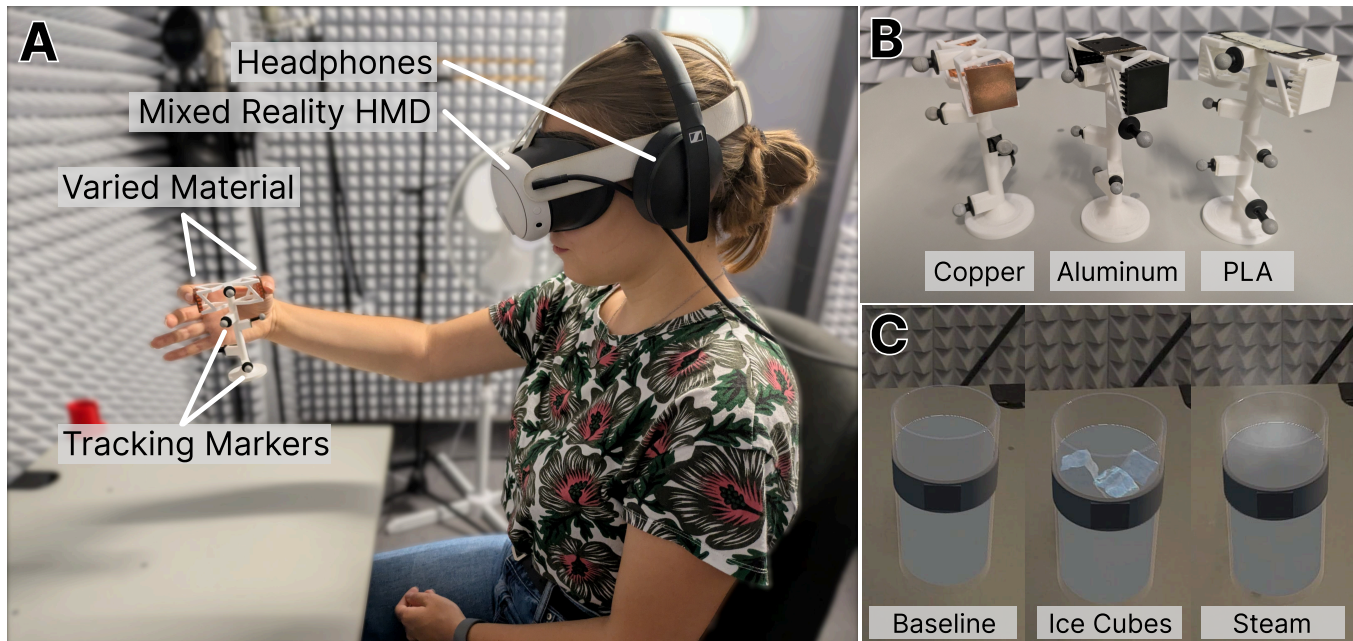


Figure 1: We investigate how visual, auditory, and visuo-auditory illusions affect thermal perceptions of objects in MR. **A** illustrates our apparatus consisting of an MR HMD and headphones to render the stimuli and physical props tracked by an optical tracking system. **B** shows the different physical materials used with varied thermal properties. **C** shows the visual stimuli rendered on top of the tracked physical props.

Abstract

Achieving realistic thermal feedback in extended reality has been a long-standing goal, as temperature shapes comfort, immersion, and affective communication. While hardware-based thermal devices show promise in virtual environments, their bulk makes them impractical in mixed reality, where users are less confined and engage freely with real objects. Thermal illusions offer a lightweight alternative by leveraging multisensory cues to alter temperature perception without specialized hardware. Yet, they are mainly studied in virtual contexts, neglecting the complexity of real physical environments. To address this, we adapted established thermal illusions and evaluated their effects in a mixed reality context (N=20). Results show illusions reliably shifted subjective temperature ratings across

materials without uniformly disrupting sensory congruence or coherence with real-world experiences. Moreover, colder illusions performed stronger with metals, and warmer illusions with plastic. These findings reveal both the robustness of thermal illusions and design opportunities for crafting richer thermal experiences for mixed reality.

CCS Concepts

• **Human-centered computing** → **Mixed / augmented reality; Haptic devices.**

Keywords

thermal illusions, temperature perception, mixed reality

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1 Introduction

In daily life, our rich sense of touch allows us to make sense of the world around us. Shape perception enables us to grasp the handle of a coffee cup, weight helps us lift it securely, and thermal sensations let us judge whether it is safe to drink. Yet, most extended reality (XR) systems still rely primarily on visual and auditory cues, or reduce haptics to simple vibrations produced by actuators in hand-held controllers. Such vibrotactile feedback covers only a narrow slice of the wide spectrum of haptic sensations we encounter every day. Accordingly, a large body of research has sought to deliver more precise or holistic haptic feedback for XR [41, 58]. Grounded robotic devices [36, 37] can provide accurate, strong, and adaptive forces, generating realistic geometric and material sensations. However, they are bulky, power-hungry, and require users to remain tethered. Wearable or hand-held devices, such as haptic gloves [24] and custom controllers [12], offer more mobility but require continuous contact, obstructing other natural tactile experiences. While these approaches continue to evolve, they have been developed primarily for fully virtual environments, where users are isolated from the real world. In contrast, augmented (AR) and mixed reality (MR) are becoming increasingly widespread with modern head-mounted displays (HMDs) such as the Meta Quest line¹ and Apple Vision Pro². In these contexts, current haptic solutions are often ill-suited: bulky equipment would remain visible in passthrough views, while wearable devices obstruct hands and prevent interaction with real objects. Haptic illusions offer a promising alternative. By leveraging crossmodal interactions [15], they alter haptic perception using visual or auditory cues, without requiring specialized hardware. Prior work has shown their effectiveness in modifying perceptions of shape [52], size [2], weight [47], texture [16], stiffness [61], and temperature [60]. However, like most active haptic rendering techniques, haptic illusions have mainly been studied in fully virtual settings [34]. We know little about how well they transfer to MR, where visual manipulations are more limited, and users continuously interact with both virtual and physical environments.

In this work, we investigate the effectiveness of haptic illusions in MR. Specifically, we focus on temperature perception, which is a crucial factor for immersion [50], affective communication [63], and comfort [31]. We adapt established thermal illusions (visual, auditory, and combined visuo-auditory) from virtual reality (VR) and project them in a video-passthrough MR setting onto physical prototypes with varying thermal properties. We then evaluate their effects on subjective temperature perception, crossmodal congruence, coherence with participants' real-world experiences, and their interaction with different base materials. We contribute (1) empirical findings of our study, showing that thermal illusions effectively alter subjective temperature assessments without disrupting congruence and coherence if matched accurately with base materials; and (2) practical derived insights for designing thermal experiences in future MR contexts.

2 Related Work

This work builds on a large body of research related to haptic and thermal feedback. In the following, we review approaches for active

thermal rendering and sensory illusion techniques that instead manipulate thermal perception.

2.1 Active Thermal Rendering

Haptics research has explored diverse methods for delivering warmth and cold through computing devices [26, 42]. In large, stationary setups, encounter-type systems use robotic arms [54], infrared heaters [50], or heated air streams [21, 51, 57]. These approaches free the user's hands but require bulky hardware installations. More commonly, thermal feedback is provided by Peltier elements, which generate hot and cold sensations via heat transfer under current flow. In XR, Peltiers have been integrated into devices targeting fingertips [39], hands [56], arms [29], or the HMD [9, 43, 45, 64]. Despite their compact size, Peltiers require heatsinks and substantial power supplies for sustained operation, making these systems rigid and restrictive. To enhance dexterity, pneumatic [8] and hydraulic [19] systems deliver heat through skin-contacting tubes, improving mobility but still tethering users to power-hungry hardware. Chemical stimulation of thermal receptors [7, 35] offers a low-power alternative, but current approaches remain slow, imprecise, and reliant on complex mounted systems. Overall, while diverse feedback methods exist, most face challenges of scalability, power consumption, and mobility. These limitations are amplified in MR contexts, where bulky or skin-bound devices cannot be easily hidden with virtual content and obstruct interaction with real-world objects. Consequently, only few thermal rendering approaches have been explored for MR, such as infrared heaters in projector-based AR [27] or a hydraulic finger ring [22], which enabled more natural interaction but remained tethered to pumps. These limitations highlight the need for approaches that generate thermal sensations in MR without bulky hardware or continuous skin contact. Here, thermal illusions present a promising alternative.

2.2 Haptic & Thermal Illusions

When interacting with the world, we naturally rely on multiple senses that integrate into a unified percept [15]. Sensory illusions arise when signals from different modalities conflict, shifting perception. In XR, where sensory cues can be controlled, such illusions allow visual or auditory information to influence and partially override haptic sensations. This has proven effective across many aspects of touch, from perceived object geometry (shape [3, 52] and size [2, 5]) to material properties like weight [47], stiffness [61, 62], and texture [16] (see [34] for a review). For thermal sensations, illusions are typically elicited through visual cues associated with heat or cold. In VR, full environmental control enables approaches that adjust perceived ambient temperature by immersing users in warm or cold settings [6, 7, 33, 44] (e.g., deserts/snowy landscapes) or applying weather effects such as sunlight or snow [19, 43]. For more localized feedback, many works replicate familiar natural phenomena or appliances linked with thermal experience. A common strategy is to visualize fire [19, 43, 50, 59], either in isolation or alongside heaters and furnaces [7, 19]. Beyond explicit depictions, color has been widely used to suggest thermal changes. The hue-heat hypothesis [66] posits that red and blue hues respectively increase and decrease perceived temperature. Although first studied for ambient temperature, later VR research has shown this effect

¹<https://www.meta.com/quest/>, accessed: 2026-02-03

²<https://www.apple.com/apple-vision-pro/>, accessed: 2026-02-03

for virtual objects [6, 55, 60]. Another prominent direction uses representations of liquids, where visualizations of ice [6, 60] and steam [6, 60] have been found particularly effective. Expanding beyond visuals, Weiss et al. [60] introduced auditory cues such as sizzling, boiling, or cracking ice, demonstrating that sound can be as potent, or even stronger, than visual signals. Although thermal illusions often produce modest effects [60], prior work shows they can reliably alter subjective assessments [19, 55, 60], influence behavior [6], and even trigger physiological responses [33]. These findings highlight their potential as a lightweight approach to thermal feedback or versatile complements to active thermal rendering approaches [7, 19, 43, 44, 50]. However, analogous to thermal devices, most research on thermal illusions has focused on fully immersive VR, where users are entirely embedded in the simulation and isolated from real-world cues [34]. In MR, where traditional thermal hardware would be visible and constraining, illusions could provide a more seamless alternative but have so far received little attention. Weir et al. [59] provided an early exploration by superimposing fire and smoke over users' hands, reporting strong immersion and involuntary heat sensations in a subset of participants. This work highlights the potential of thermal illusions beyond VR, yet it remains uncertain how these could be leveraged to create or modify the haptic feedback of interacted objects. To address this gap, we examine how the effect of illusions developed for fully immersive environments transfers to MR contexts.

3 Study Design

We conducted a controlled experiment in MR to investigate how thermal illusions affect the perceived temperature of physical objects, the overall congruency of sensory information, and the coherence of the interaction with users' experiences from real life. We tasked participants to grab and lift physical prototypes constructed of three diverse materials and overlaid with a variety of visual, auditory, or visuo-auditory stimuli that have been shown to alter temperature perception in virtual environments. With this, we address the following research questions (RQs):

RQ1: How do thermal illusions based on visual, auditory, and visuo-auditory cues affect the perceived temperature of touched objects in mixed reality?

RQ2: How do these illusions affect the perceived congruency of sensory information and the coherence of the experience with anticipations based on prior real-life experiences?

RQ3: How do different physical materials with varying thermal properties influence the illusions?

3.1 Stimuli

We employed a within-subject design and varied the applied visual and auditory stimuli eliciting the illusions (STIM) and the physical material of the touched prototypes (MAT).

STIM We selected a set of established thermal illusion techniques from VR in order to ensure comparability. We build on prior work [60] that aggregated and evaluated a wide range of thermal illusions from research [6, 30, 33, 55, 66], from which we adapted the most effective subset for MR: a neutral baseline showing a glass of gray liquid (*Baseline*), visualizations of steam (*Warm_V*) or ice cubes (*Cold_V*), auditory cues

Table 1: Specific Heat c of common substances. The materials we used are highlighted in bold. Lower specific heat capacities generally correspond with faster heat transfer and, therefore, cooler sensations when touched at room temperature.

Material	c (in $\text{J kg}^{-1} \text{K}^{-1}$)
Gold	129 [49]
Copper	387 [49]
Iron	448 [49]
Silicon	703 [49]
Glass	837 [49]
Marble	860 [49]
Aluminum	900 [49]
Wood	1700 [49]
PLA	1590 [17] - 1800 [20]

of sizzling on contact (*Warm_A*) or colliding ice cubes (*Cold_A*), and combined visuo-auditory cues for warmth (steam + sizzling, *Warm_{V,A}*) and coldness (ice cubes + ice cube sound, *Cold_{V,A}*). Visual conditions are shown in Figure 1C. Auditory cues are available in our repository (see section 8).

MAT Since users in MR interact with both virtual and physical environments, we varied the material of the objects on which the thermal illusions were applied, to investigate how the effects of such illusions interact with material properties. We focused on materials with distinct thermal characteristics, particularly their specific heat: the amount of energy required to raise the temperature of a given mass by one degree. Specific heat determines how much heat is exchanged during touch and thus shapes the perceived temperature of the object. Materials with lower specific heat tend to conduct heat more quickly, drawing warmth from the skin faster and thus producing a colder sensation [53] (see Figure 2 for an illustrative example). The specific heat of common materials is presented in Table 1. To cover a broad range, we selected copper, aluminum, and polylactide (PLA).

Each combination of STIM and MAT was repeated four times, resulting in a total of 84 trials ($7 \text{ STIM} \times 3 \text{ MAT} \times 4 \text{ Repetitions}$). We randomized the order of trials for each participant.

3.2 Measurements

For each trial, we asked participants to rate the perceived temperature of the object, the congruency of the sensory information, and the coherence of the sensations with real-life experiences. For their subjective temperature perception (**Q1**), we employed an established thermal sensation model [1, 55, 65], asking participants to rate their thermal sensation along 9 points (*very cold*, *cold*, *cool*, *slightly cool*, *neutral*, *slightly warm*, *warm*, *hot*, *very hot*). To capture congruency and coherence, we used visual analog scales [28], asking participants to rate their agreement with the statements (**Q2**) "When holding the object, the sensations of all senses complemented each other well" and (**Q3**) "When holding the object, the sensations resembled the ones I feel in real life" from *Strongly disagree* to *Strongly agree*.

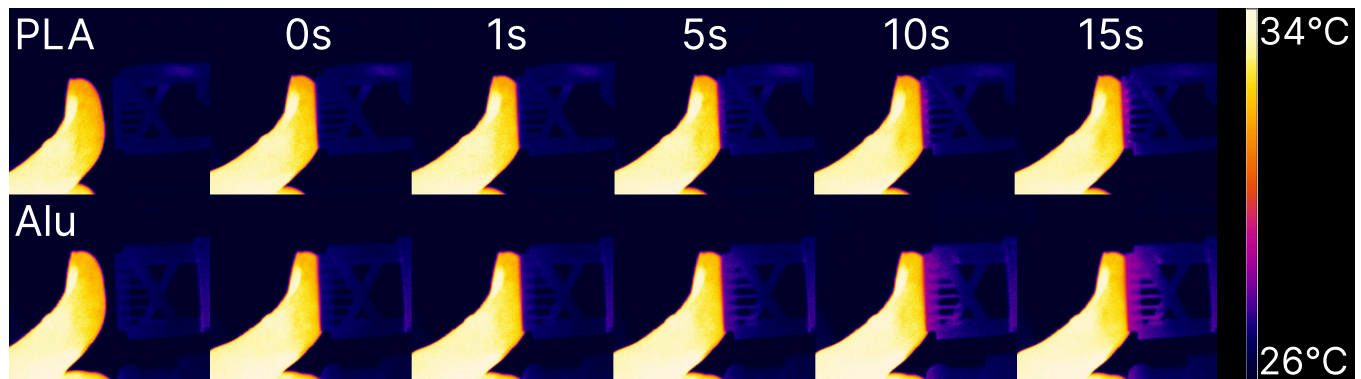


Figure 2: Infrared thermal imaging recordings of PLA (top) and aluminum (bottom) prototypes showing the differences in heat transfer during touch with a thumb at room temperature. We chose a 5-second contact duration as our target touch time.

3.3 Apparatus

To allow participants to grasp objects with variable material characteristics, we constructed three devices consisting of a 3D-printed frame, an attached material to grasp, and a tracking setup. The frame has a round base and a vertical column with extruding branches for holding the tracking setup and the touchable material. Depending on the device, we attached either copper, aluminum, or PLA to the outside of the frame. We used common copper and aluminum heatsinks and 3D-printed an analogous shape with the PLA. This allows the heat that is absorbed from the participant’s grasp to dissipate faster, lessening its potential confounding effect when grasping repeatedly. The heatsinks were attached at a 10cm height and spaced 8.2cm apart to allow comfortable grasping. The touchable area on the heatsinks spanned 2.5cm × 2.5cm. To track the devices, we used Optitrack³, a highly accurate optical tracking system with errors below 0.1mm [48]. For this, we attached retro-reflective markers to each frame in distinct constellations and set up an OptiTrack V120:Trio camera system on the side of our experimental area. Lastly, we attached metal weights to the top of the devices to offset weight differences among materials. The physical prototypes are presented in Figure 1B.

To display the virtual overlays, we utilized the Meta Quest 3⁴ head-mounted display (HMD) and its Mixed Reality passthrough feature. The virtual objects were built in Unity3D⁵ and overlaid over the tracked devices in the camera-passthrough in real-time. We displayed a transparent cylindrical glass with the same diameter as the physical devices (8.2cm). The glass was filled with an opaque gray liquid to minimize color correspondences to temperature (cf. [55]). We displayed a gray ring around the glass to indicate the touchable area. The cylindrical shape ensured that the participants’ hands would not visually clip through the object while grasping. We utilized the HMD’s optical hand tracking to overlay a virtual silhouette of the participant’s hand while grasping to avoid issues based on depth and occlusion miscalculations of the HMD. The physical and virtual coordinate systems were synchronized for each session using the retro-reflective markers and tracked HMD controllers.

To reduce environmental noise and display the auditory stimuli, we used over-ear headphones with active noise-cancellation⁶. Our complete setup is presented in Figure 1A.

3.4 Procedure & Task

After we informed participants about the experiment, their task, and our data processing procedure, they signed a consent form and filled out a demographics survey. We then seated participants in front of a table carrying the experimental setup, facing a neutral, gray wall. We adjusted their seat height to allow comfortable interactions. Participants put on the HMD and headphones and completed three training trials to familiarize themselves with the task. Each trial consisted of the same steps: Participants first saw the virtual glass in front of them on the table, co-located with the obfuscated physical device. Participants were tasked to grasp the object using the index finger and thumb of their right hand at the indicated contact points and lift it up in front of them. After holding it for 5 seconds, participants were prompted to put the object back down on the table. After releasing their grasp from the object, the camera-passthrough was turned off, and participants were transported to a neutral, completely virtual environment to input their ratings by interacting with virtual sliders using their free hands. Simultaneously, the experimenter removed the physical device and placed the new (or same) one for the subsequent trial. After both the physical device was set and the participant answered all questions, the next trial began, and the passthrough was re-enabled for participants to see their real surroundings and the superimposed virtual object. Following the training phase, participants proceeded through all 84 trials.

3.5 Participants

We recruited 20 participants through university mailing lists. Their age ranged from 21 to 68 ($M = 27.7, SD = 9.82$). 15 described themselves as male, 4 as female, and 1 as non-binary. 19 were right-handed and 1 was left-handed. 16 had experienced VR or AR before. Participants had normal or corrected-to-normal vision and no conditions affecting hearing or the tactile perception of their

³<https://optitrack.com/>, accessed: 2026-02-03

⁴<https://www.meta.com/quest/quest-3/>, accessed: 2026-02-03

⁵<https://unity.com/>, accessed: 2026-02-03

⁶Sennheiser HD300, <https://www.sennheiser-hearing.com/en/p/hd-300/>, accessed: 2026-02-03

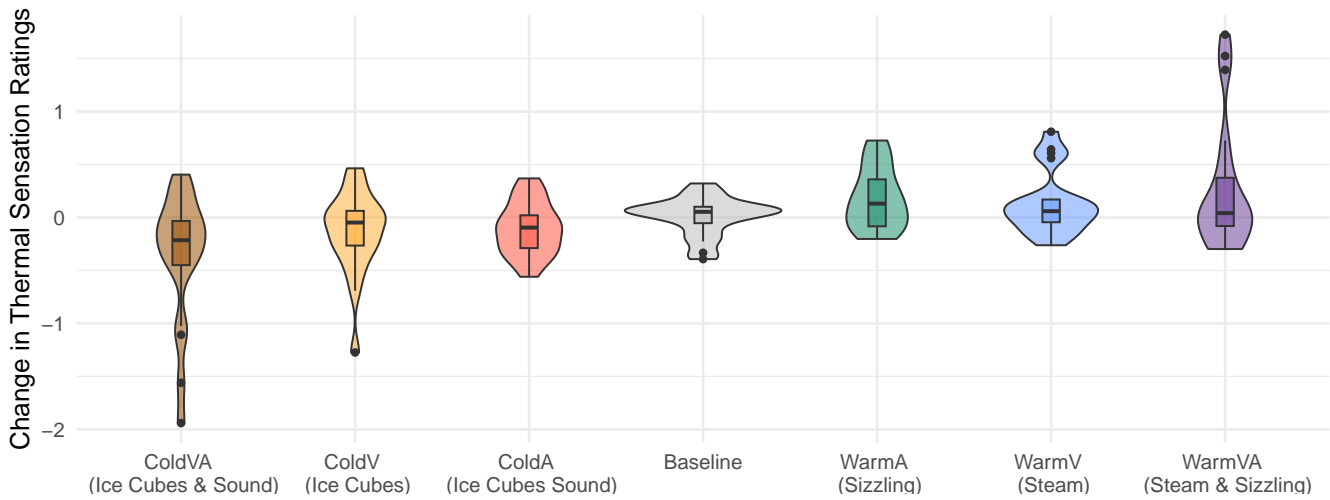


Figure 3: Change in thermal sensation ratings for STIM averaged across all levels of MAT. Ratings ranged from very cold (-4) to very hot (+4) and are shown relative to each participant’s mean to reduce interpersonal variability for a better overview.

hands. We offered each participant 10€ or university course credit as compensation. This study was approved by our institution’s ethics board.

3.6 Analysis

To analyze participants’ ordinal ratings of the temperature sensation from *very cold* (-4) to *very hot* (+4), we fitted Cumulative Link Mixed Models (CLMMs) using the *ordinal* R-package [13]. For these, we used logit link functions and the Gauss-Hermite quadrature approximation with 10 quadrature points. We modeled STIM, MAT, and their interaction as fixed effects, and included participant IDs as a random intercept to account for individual differences. For participants’ agreement ratings using visual analog scales from *Strongly disagree* (0) to *Strongly agree* (100), we fitted Linear Mixed Models (LMMs) with Restricted Maximum Likelihood (REML) using the *lme4* R-package [4]. We included the STIM, MAT, and their interaction as fixed effects and participants’ IDs and the trial count as random effects to account for interpersonal variability and possible fatigue. For both CLMMs and LMMs, we performed likelihood ratio tests (LRTs) comparing full models to reduced ones, in which we individually dropped one fixed effect or interaction. Where we found significant main or interaction effects, we conducted post-hoc pairwise comparisons with Bonferroni correction. Additionally, we assessed associations between dependent measures using Pearson correlation analyses.

4 Results

In the following, we report the results of our controlled experiment, organized around our three dependent variables. Perceived congruency and coherence ratings showed a strong positive correlation across trials ($r = .83, p < .001$).

4.1 Perceived Temperature

The changes in subjective thermal sensation assessments for levels of STIM are shown in Figure 3. LRTs revealed a significant

main effect of both STIM ($\chi^2(18) = 82.12, p < .001$) and MAT ($\chi^2(14) = 683.77, p < .001$), and no interaction effect between them ($\chi^2(12) = 16.74, p = .16$). Post-hoc comparisons on levels of STIM show significantly ($p < .05$) colder sensations for *ColdVA* ($M = -0.83, SD = 1.24$) compared to *Baseline* ($M = -0.46, SD = 1.03$), *WarmV* ($M = -0.34, SD = 1.26$), *WarmA* ($M = -0.29, SD = 1.15$), and *WarmVA* ($M = -0.20, SD = 1.48$). Similarly, *ColdV* ($M = -0.61, SD = 1.24$) was rated significantly colder than *WarmV*, *WarmA*, *WarmVA*, and *ColdA* ($M = -0.58, SD = 1.06$) was perceived significantly colder than *WarmA* and *WarmVA*. There were no significant differences between the warmer visual and auditory stimuli and the *Baseline*. For MAT, post-hoc tests revealed a significant difference among all groups, with *Aluminum* rated the coldest ($M = -1.00, SD = 1.16$), followed by *Copper* ($M = -0.84, SD = 1.12$) and finally *PLA* ($M = 0.43, SD = 0.85$) as the material perceived warmest.

4.2 Congruency

Regarding the congruency of the sensory information during the interaction, mean subjective ratings ranged from 76.23 ($SD = 20.07$) for *ColdVA* with *Aluminum* on the high end, down to 26.19 ($SD = 21.26$) for *WarmA* with *Aluminum*. Changes in ratings across STIM and MAT are displayed in Figure 4a. LRTs revealed significant main effects of STIM ($\chi^2(18) = 697.48, p < .001$), MAT ($\chi^2(14) = 314.96, p < .001$), and a significant interaction effect ($\chi^2(12) = 313.75, p < .001$). For STIM, we found significantly ($p < .05$) higher congruency ratings for *Baseline* ($M = 64.94, SD = 24.66$) and *ColdVA* ($M = 64.17, SD = 27.03$) compared to all other groups and no significant difference between *Baseline* and *ColdVA*. These are followed by *ColdV* ($M = 48.89, SD = 25.66$), which shows significantly higher ratings than lowest rated groups of the *WarmA* ($M = 33.20, SD = 25.08$), *WarmV* ($M = 37.73, SD = 26.43$), and *ColdA* ($M = 37.95, SD = 25.21$). Further, *WarmVA* ($M = 43.88, SD = 29.16$) was rated significantly higher than *WarmV* and *WarmA*. Regarding the material, we saw the lowest ratings for *Aluminum* ($M =$

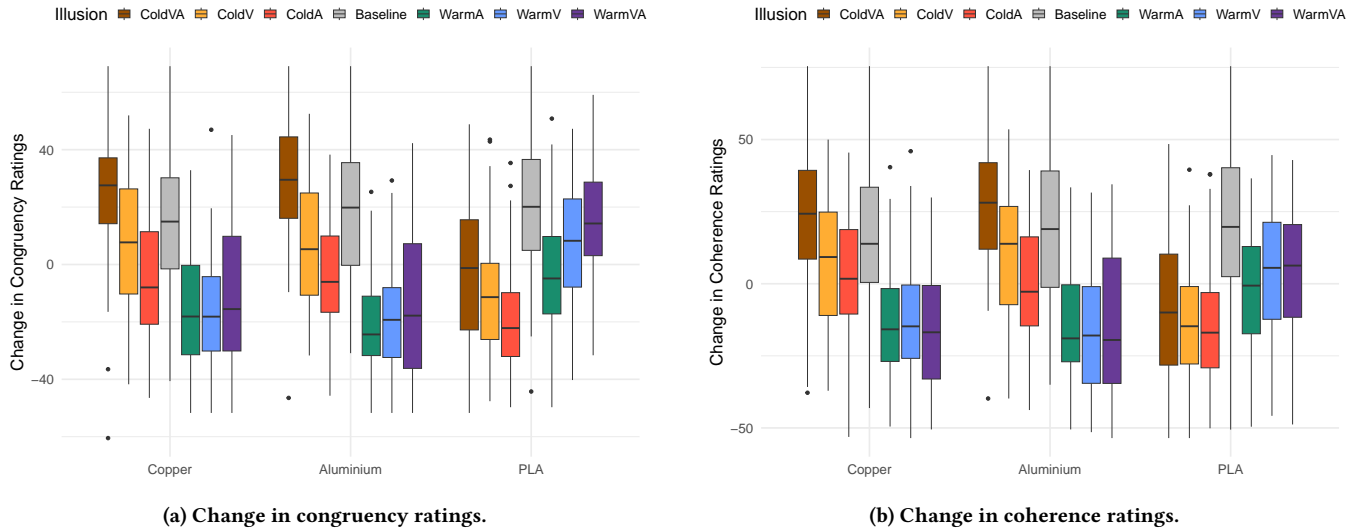


Figure 4: Changes in congruency (a) and coherence (b) judgments for all combinations of STIM and MAT. Ratings are relative to each participant’s mean.

64.62, $SD = 29.68$), followed by *Copper* ($M = 47.10, SD = 29.12$) and *PLA* with the highest ratings ($M = 48.03, SD = 27.40$), but we found no significant contrast among groups. For the significant interaction effect between STIM and MAT, we observe a clear pattern in how warmer versus colder illusions interact with different materials in terms of congruency ratings. Specifically, all colder visual and auditory stimuli ($Cold_A$, $Cold_V$, and $Cold_{VA}$) received significantly higher congruency ratings when applied to *Aluminium* and *Copper* than in conjunction with *PLA*. Adversely, warmer stimuli ($Warm_A$, $Warm_V$, $Warm_{VA}$) exhibited significantly higher ratings with *PLA* than the other two materials. Between the two metals (*Aluminium* & *Copper*), we found no clear differences except for the $Cold_{VA}$, which received significantly higher ratings for *Aluminium* than for *Copper*. The *Baseline* visualization did not exhibit significant differences in congruency ratings across materials.

4.3 Coherence

Participants’ assessments on how well the sensations resembled the ones experienced in real life are displayed in Figure 4b. We observed average ratings from 74.00 ($SD = 20.19$) for $Cold_{VA}$ with *Aluminium* on the high end to 29.41 ($SD = 24.35$) for $Warm_V$ with *Aluminium* on the low end. As with congruency, coherence ratings followed analogous trends across illusions and materials, highlighting the strong alignment between these two measures in our investigated setup. Similarly to congruency ratings, LRTs showed significant main effects of both STIM ($\chi^2(18) = 588.79, p < .001$) and MAT ($\chi^2(14) = 290.09, p < .001$), as well as their interaction ($\chi^2(12) = 283.48, p < .001$). For levels of STIM, post-hoc comparisons again revealed significantly ($p < .05$) higher ratings for *Baseline* ($M = 64.68, SD = 26.47$) and $Cold_{VA}$ ($M = 60.53, SD = 28.34$) than all other groups and no significant difference between them. $Cold_V$ ($M = 47.94, SD = 26.51$) also shows significantly higher ratings than all warm illusions – $Warm_A$ ($M = 36.26, SD = 25.29$), $Warm_V$

($M = 37.95, SD = 26.03$), and $Warm_{VA}$ ($M = 38.00, SD = 27.42$) – and no significant difference to $Cold_A$ ($M = 42.91, SD = 25.97$). $Cold_A$ shows a significant increase in ratings over $Warm_A$, which received the lowest ratings overall. Regarding MAT, we found significantly higher ratings of *Aluminium* compared to *PLA*, but no other significant pairwise differences. For the interaction effect of STIM and MAT, we observe trends analogous to congruency ratings. Illusions suggesting coldness ($Cold_A$, $Cold_V$, $Cold_{VA}$) exhibited significantly higher ratings when applied to *Aluminium* and *Copper* than to *PLA*, while for warmer illusions ($Warm_V$, $Warm_{VA}$) we observe the opposite. The exception was $Warm_A$, which generally received low scores with no significant differences when applied to different underlying materials. We found no significant differences between illusions when applied to *Aluminium* or *Copper*. The *Baseline* showed no significant difference in coherence ratings across all materials.

5 Discussion

In the following, we discuss our findings in relation to our research questions and derive actionable insights for designing thermal experiences in MR.

5.1 Thermal Illusions Effectively Change Subjective Temperature Across Materials

Regarding RQ1 (see section 3), we found that thermal illusions significantly influenced perceived temperature, with clear differences in judgments between colder and warmer stimuli. The direction of these effects aligns with prior work on subjective temperature assessments in VR [19, 60]. With respect to modality, we found that combined multimodal illusions elicited stronger effects than unimodal (visual or auditory) cues alone. However, these differences were not statistically significant, aligning with prior findings

from VR context that multimodal illusions may operate subadditively [60]. Colder illusions produced larger perceptual shifts than warmer ones. Since all room-temperature objects were below skin temperature and thus felt slightly cool, some bias toward colder sensations was expected. However, the distance from baseline was substantially greater for colder illusions, and this effect was independent of material. This asymmetry cannot be explained by actual temperature alone. A plausible explanation is that thermal illusions amplify perceived deviations from baseline, making them especially promising for complementing actual changes in temperature, for instance, through active thermal devices [7, 19, 43, 44, 50]. Such amplification could lower power demands and support smaller, more flexible devices, enhancing their feasibility for MR systems. While earlier work [60] showed that thermal illusions have limited impact on shifting actual perception, their influence on subjective assessments was robust [19, 55, 60]. Our results extend these findings to MR contexts with physical objects: we show that the effects on subjective temperature sensation remain consistent across different base materials. The absence of a strong interaction with material type suggests that thermal illusions may operate independently of these properties, underscoring their potential for MR scenarios where illusions might be applied to a variety of objects and surfaces.

5.2 Thermal Illusions Influence Congruency and Coherence, but not Uniformly

Regarding RQ2, our findings show that thermal illusions systematically influence participants' evaluations of both the congruency of sensory information and the coherence of the interaction with real-world experiences. Across conditions, these two measures were strongly correlated, suggesting that they reflect closely related facets of a shared evaluative process rather than independent dimensions within our procedure. Accordingly, we interpret congruency and coherence jointly in the following, focusing on their convergent trends as indicators of how plausible and well integrated a given thermal illusion was perceived to be. As expected, the baseline visualization performed well. It represented a room-temperature glass object, closely matching the actual properties of the physical materials participants handled. Since glass has a specific heat capacity comparable to aluminum, it would be expected to evoke similar thermal sensations. Moreover, the physical objects were stored at room temperature, further aligning with this visualization. Consistent with these factors, the baseline condition elicited high evaluations of both congruency and coherence, reflecting a strong alignment between visual appearance, thermal sensation, and users' real-world expectations. By contrast, exaggerated thermal stimuli altered participants' evaluations of congruency and coherence, though these effects were not uniformly negative. Colder illusions generally performed better than warmer ones, likely because materials at room temperature—and metals in particular—tend to feel cool to the touch, making cold representations more consistent with prior experience. In addition, multimodal presentations consistently outperformed unimodal ones. Notably, the multimodal cold condition even surpassed the baseline for both metal materials, although this difference did not reach statistical significance. Nevertheless, this pattern demonstrates that well-designed multimodal thermal illusions do not necessarily reduce perceived congruency

or coherence. Whether such illusions can reliably enhance these qualities beyond baseline conditions remains an open question for future work.

With regard to RQ3, our results further reveal that the effectiveness of thermal illusions depends strongly on the interplay between the illusion itself and the material properties of the object. Colder illusions aligned more closely with metals, whereas warmer illusions were judged as more congruent and coherent when applied to PLA, although still less so than the baseline condition. This highlights the importance of matching thermal illusions to the inherent thermal characteristics of the materials they augment; mismatches risk undermining both the perceived congruency of the sensory experience and its coherence with users' real-world expectations. Finally, we observe that lower evaluations of congruency and coherence were associated with reduced effectiveness of the illusions in altering perceived temperature. Taken together, this relationship suggests that congruency and coherence function as tightly coupled indicators of whether a thermal illusion is accepted as plausible within an MR context. While future work could further disentangle these dimensions, our findings indicate that both are necessary conditions for designing effective thermal experiences, particularly in MR scenarios involving diverse everyday physical objects.

5.3 Implications for Designing Thermal Experiences in MR

From our findings, we derive several vital insights for designing thermal experiences for MR contexts:

5.3.1 Illusions enable integration of real-world objects. Thermal illusions worked consistently across different base materials, indicating that they can be applied to arbitrary real-world objects in MR. This makes them especially valuable in settings where designers cannot control the material composition of the environment. Here, illusions could lower perceived temperature of props without embedding hardware into every surface. For instance, it can enhance haptics in collaborative XR settings, which currently predominantly rely on passive props held in hand [18, 32, 40] or placed on tabletops [25, 46] or around the environment [10, 14].

5.3.2 Leverage amplification effect of illusions. Our results reveal that colder sensations inherent to materials were reliably amplified by illusions, substantially extending the range of thermal experiences that can be created at room temperature. This finding is particularly valuable because physically cooling objects is technically challenging, as it requires continuous heat extraction from the material. In contrast, warmer sensations are likely more effective when combined with active thermal rendering, such as a complement to body-worn [19, 43, 56] or encounter-type systems [21, 54]. In such hybrid approaches, illusions can amplify the perceived effect of heating, making it possible to deliver convincing warmth with reduced power demands and smaller, more efficient devices.

5.3.3 Ensure illusions match the applied material. The subjective experience that the illusions elicit depends heavily on matching them to the thermal qualities users naturally expect and perceive from different materials. Colder illusions work best on materials with low specific heat capacities that already tend to feel cool (e.g., metals), while warmer illusions are more coherent when applied

to less thermally conductive materials such as plastics (e.g., PLA). In contrast, mismatched applications – such as applying warmth to metals or coldness to plastics – risk breaking the sensation of congruency and coherence with anticipations, which might undermine immersion. These findings may inform the effects of illusions applied to other kinds of commonly available materials with thermal properties within our investigated range, such as glass, iron, or wood (see Table 1). Effectively matching thermal illusions to the properties of physical materials is key to support realistic interactions with augmented physical objects in MR.

6 Limitations & Future Work

This work set out to extend investigations of thermal illusions beyond purely virtual environments in order to better understand their potential in future XR systems. However, both the complexity of sensory illusions and the novel challenges of transferring them into the more physically entangled contexts of MR required us to constrain our study design. First, while our chosen stimuli were informed by prior work aggregating common approaches to thermal illusions, many alternative stimuli and combinations may also elicit thermal illusions, which we could not explore in this study. Future work should therefore investigate how our findings on thermal illusions in MR, and their interaction with material properties, transfer to other forms of stimuli, such as color correspondences [11, 30, 55, 66] or ambient cues [6, 7, 19, 33, 44]. Furthermore, practical considerations limited the range of physical materials we could examine. We selected three materials spanning a broad spectrum of thermal conductivities (see Table 1), but continuous experimental use required sufficient heat dissipation, necessitating the use of heatsinks. This prevented us from testing other relevant materials with distinct thermal or tactile properties, such as glass or alternative plastics. Our sample was also skewed toward younger male participants, limiting the generalizability of our findings across age groups and genders. Notably, perceived congruency and coherence were highly correlated in our study, indicating that they capture closely related facets of participants’ judgments rather than fully independent constructs. While we reported these outcomes separately to maintain conceptual clarity, future work could explore composite or alternative measures. Finally, MR itself introduces constraints compared to VR. Because users must remain aware of and interact with their physical surroundings, study setups are inherently noisier, and the range of apparatus that can be deployed is more restricted. Large thermal devices used in psychophysical research [60] are difficult to integrate or conceal in MR environments, limiting the experimental configurations that can be tested. For this reason, we focused on passive props without active thermal rendering and obtained broader subjective assessments rather than more tightly controlled psychophysical measurements. However, advancements in real-time masking and infilling [23, 38] might enable bulkier, more complex, and more constraining experimental procedures for future MR research.

7 Conclusion

We investigated how visual, auditory, and multimodal thermal illusions influence the perceived temperature of physical objects in MR. Our results show that colder illusions reliably shifted subjective

temperature, while warmer illusions had more limited effects, and these patterns were largely independent of material type. Thermal illusions also shape users’ sense of congruency and their coherence with real-world experiences. Colder illusions were most effective on conductive materials like metals, while warmer illusions aligned better with less conductive materials such as PLA. Multimodal presentations generally enhanced the perceived congruence of sensory information and the coherence of the experience. From a design perspective, these findings suggest that thermal illusions can: (1) augment real-world objects without embedding hardware, (2) amplify temperature changes with minimal energy use, and (3) improve immersive experiences when accurately matched with material properties of the respective physical objects. Overall, our work demonstrates that thermal illusions are a versatile, perceptually robust tool for MR, enabling designers to create compelling thermal experiences across diverse materials or enrich existing thermal rendering approaches.

8 Open Science

We make our project, dataset, analysis scripts, and used auditory stimuli available in our OSF repository: <https://osf.io/dq24x/>

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