An Examination of Ultrasound Mid-air Haptics for Enhanced Material and Temperature Perception in Virtual Environments

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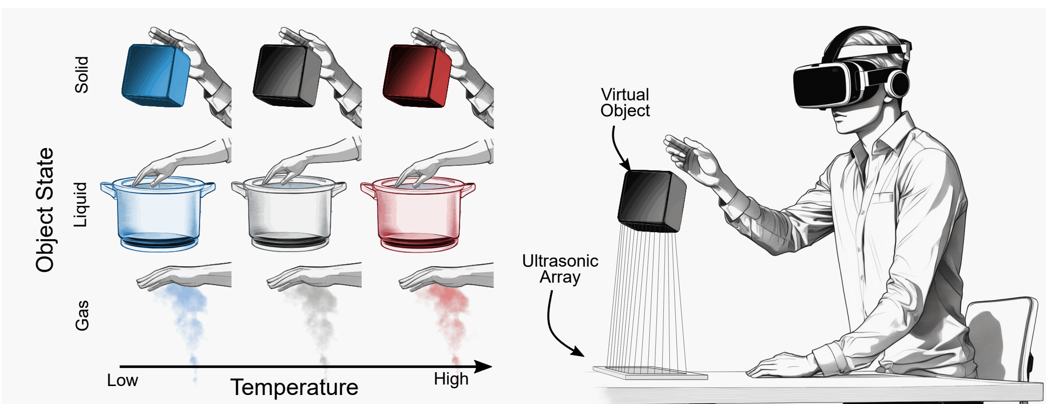

Fig. 1. In this paper we explore the efficacy of Ultrasonic Mid-air Haptics (UMH) in enhancing the perceived congruency of virtual objects with differing material states and color-temperature associations. Specifically, participants interacted with virtual objects rendered in three distinct physical states—Solid, Liquid, and Gas—while also exposed to three hue-temperature associations: Blue (cool), White (neutral), and Red (warm). The study compared these experiences in two conditions: with the presence of Ultrasonic Mid-air Haptic feedback and with Visual Only (no haptic feedback).

Rendering realistic tactile sensations of virtual objects remains a challenge in VR. While haptic interfaces have advanced, particularly with phased arrays, their ability to create realistic object properties like state and temperature remains unclear. This study investigates the potential of Ultrasound Mid-air Haptics (UMH) for enhancing the perceived congruency of virtual objects. In a user study with 30 participants, we assessed how UMH impacts the perceived material state and temperature of virtual objects. We also analyzed EEG data to understand how participants integrate UMH information physiologically. Our results reveal that UMH significantly enhances the perceived congruency of virtual objects, particularly for solid objects, reducing the feeling of mismatch between visual and tactile feedback. Additionally, UMH consistently increases the perceived

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temperature of virtual objects. These findings offer valuable insights for haptic designers, demonstrating UMH's potential for creating more immersive tactile experiences in VR by addressing key limitations in current haptic technologies.

CCS Concepts: • **Human-centered computing → User studies**; **Laboratory experiments**; **Haptic devices**.

Additional Key Words and Phrases: Ultrasonic Mid-air Haptics, Virtual Reality, Haptic Perception, VR Rendering

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1 Introduction

Humans gather information with multiple sensory channels when interacting with physical objects, yet in Virtual Reality (VR), it remains a challenge to provide a comparable sensory-rich experience. In contrast with visual and auditory rendering [74], rendering haptic object properties in VR implies stimulating multiple groups of physiologically divergent receptors [38, 45]. For example, the compliance of an object is primarily sensed through the joint receptors and tendons, while temperature phenomena are sensed through thermoreceptors [43, 44].

This has driven innovation in haptic technology, resulting in diverse haptic displays designed to stimulate specific receptors and create unique user experiences [83]. From force-feedback robots that provide a sense of touch and movement, [16] to haptic gloves offering a combination of vibration, force feedback, and even temperature sensations [28], these advancements open doors for richer and more immersive interactions. The development extends beyond gloves, with handheld devices that simulate texture, vibration, and shape feedback, as well as wearable devices like vibration bands and compliance rings, all contributing to this exciting frontier in haptic technology.

A recent approach that has gained traction among designers and researchers is using Ultrasonic Mid-air Haptics (UMH) [67] to render virtual objects. UMH stimulates the user's palm by using ultrasonic waves down-sampled to human-perceivable frequencies [13] and does not require the user to wear any additional device. UMH has been used in a wide range of applications, including automotive interfaces [30], aviation [27], virtual reality [35], fluid rendering [6], emotion encoding [62], and stiffness rendering [55]. Yet it carries limitations in effective workspace [34], stimulus intensity [79], and precision [67] that may impact the congruency of the rendered objects.

The perceived congruency of a virtual object is assessed based on participants' experiences with similar real-world objects [50, 51, 80]. Wee et al. [85] highlights the importance of material property congruency, identifying dimensions such as object shape, compliance, texture, and temperature as critical for haptic rendering in virtual reality. Although UMH has shown effectiveness in rendering most of these properties, its specific impact on temperature perception remains unexplored. This is despite several attempts to employ UMH alongside other technologies for temperature rendering [60, 61, 72], yet these attempts involve additional hardware, and often covering the user's hands [39, 40].

Instead of introducing additional hardware to UMH, researchers can leverage cross-modal correspondences between haptics and other sensory inputs like vision or sound, a phenomenon known as Haptic Illusions (HI) [19]. This approach has gained traction in the haptics and HCI communities as a non-obstructive and cost-effective way to enrich haptic experiences [86]. HI could mitigate some of UMH's limitations, allowing it to simulate a wider range of sensations. Specifically, for temperature perception, the Hue-Temperature association hypothesis [90] suggests that cool colors lead to cooler temperature perceptions and warm colors to warmer temperature perceptions. However, the details of combining this color association with UMH for temperature rendering remain unexplored.

Overall, even if UMH has recently emerged as a plausible and versatile alternative to render object properties in VR, the question about the perceived congruence of object properties in VR remains as a gap in knowledge, especially in the case of temperature, where most of the attempts had consisted in integrating additional hardware [39, 40, 60, 61, 72], however, have not explored the thermal haptic properties of UMH alone. To address this gap, we conducted a lab study with 30 participants. The participant performed a simple exploration task with a virtual object that was presented depending on three Independent Variables; Hue-Temperature association (Blue-Cold, White-Neutral, Red-Warm), Object State (Solid, Liquid, Gas), and Presentation (Visual, Visuo-Haptic).

We found that Visuo-Haptic Presentation significantly increases the perceived congruency in all object states. Further, we collected empirical evidence to support that UMH performs better when rendering gas or liquid than solid objects. These results were consistent in a behavioral (trial-question Paradigm) and a physiological level (EEG). We discovered that even though the hue-temperature had a significant impact on the perceived temperature, UMH induced a stronger, and more consistent shift in the perceived temperature across all hue-temperature associations and all object states.

These findings have practical implications for both researchers and designers working on haptic experiences. If object temperature is crucial for the user experience, it's mandatory to consider how UMH can shift temperature perception. Additionally, incorporating UMH seems to significantly improve the overall realism of virtual objects. Objects with visuo-haptic feedback were perceived as more congruent than those with only visual feedback regardless of their State.

2 Related Work

2.1 Rendering Haptic Object Properties in VR

Haptic object property rendering has been identified as one of the primary research challenges for VR [85]; it encompasses attributes such as object dimensions, compliance, texture, and temperature. Several strategies have been employed to enable object property rendering in virtual reality (VR). For instance, compliance rendering has been explored through various methods, including vibrotactile feedback [2, 15, 54, 81, 82, 89], as well as force-feedback devices like the Geomagic Touch[1], Omega[2], and Novint Falcon [56]. Additionally, pneumatic interfaces have been explored in this context [75, 76, 91], along with wearable gloves [31, 32], hand-held devices [65, 66, 71], and finger-mounted devices [18, 69, 77].

Similarly, there have been developments in temperature rendering for VR. For instance, ThermoVR incorporates thermal haptic feedback directly into the VR headset by employing five Peltier elements in contact with the participant's face [63]. Fermoselle et al. [21] took a different approach by using a thermal glove to provide sensations of hot and cold objects. Cai et al. [12] adopted a similar strategy, creating a pneumatic glove to convey both compliance and temperature information regarding material properties. Additionally, thermal bracelets have been employed to represent material thermal properties[7]. Notably, Maeda and Kurahashi [53] expanded on this concept and introduced TherModule, a modular system designed to deliver thermal feedback to the forearm.

In recent years, UMH devices have emerged as a bare-hand interaction alternative to traditional interfaces [36, 67], this technique has demonstrated its effectiveness in enabling shape [33, 52], compliance [55], and texture rendering [23, 59]. However, an apparent gap exists in providing a

[1] https://de.3dsystems.com/haptics-devices/touch-x, last accessed: 2023-07-13
[2] https://www.forcedimension.com/products/omega, last accessed: 2023-07-13

solution for temperature rendering through this approach. This limitation may be attributed to the circumstance that most existing solutions focus on covering the surface of the user's hand, making it challenging for ultrasonic rendering to stimulate the entire area effectively [67, 83] or require additional hardware to function [39, 40, 60, 61, 72].

In light of these considerations, our paper proposes to leverage cross-modal interactions between the visual and haptic channels to enable the rendering of thermal sensations using ultrasonic feedback [19] within the context of enhanced virtual object property rendering [51].

2.2 A Visuo-Haptic Approach to Enrich Ultrasonic Virtual Objects

Haptic illusions (HIs) have been extensively studied as means to address the limitations present in pervasive technologies rendering haptic properties. These illusions leverage cross-modal interactions during perception, where visual and other sensory cues can influence and sometimes partially overwrite the haptic sensations experienced during exploration [19]. HIs generally require less complex hardware and can be integrated into existing systems due to their ability to address different sensory modalities. In HCI, research primarily focuses on manipulating visual cues on traditional desktop displays [48, 49], touchscreens [78], or virtual and augmented reality headsets [8, 70, 86]. HIs demonstrated to be effective in altering the subjective perception of objects' shape [5], size [8], surface texture [20], compliance [86], and weight [70]. For temperature perception, the hue-heat hypothesis [90] states that specific colors are linked to certain temperatures, such as red and blue, contributing to a hotter or colder thermal perception, respectively. This phenomenon has been effectively employed to reduce or increase the pain intensity and unpleasantness of hot water by visually displaying blue and red lights in the virtual environment [41]. Beyond this, research demonstrates that the presentation of explicit virtual objects – such as fire, heat lamps, and rain clouds [29] – or the use of labels and context objects – such as a tea kettle near the object or a winter landscape [10] – influences the thermal perception. Brooks et al. [11] instead emitted scents carrying eucalyptol or capsaicin and showed their influence on the perceived temperature of VR users.

While some HIs can produce effects in mid-air without additional haptic cues [42], most illusions are applied during active exploration of physical objects to modify, rather than entirely create, haptic or tactile sensations. To achieve the sensation of entirely novel objects in mid-air, researchers have employed techniques such as adjusting hand posture during the virtual gripping of an object to imply resistance, even though the forces originate from the palm during enclosure [9]. Additionally, positions of limbs in space may be redirected to enable haptic feedback for a virtual object by guiding users' hands towards another physical object [4] or a specific part of it [14].

In the context of ultrasonic rendering, HIs have been utilized to manipulate the perceived roughness of rendered tactile sensations using external sound cues generated by the same array [22]. Conversely, HIs have also employed ultrasonic stimulation to induce or enhance illusions, such as introducing a Rubber-Hand Illusion with mid-air tactile sensations [64, 68].

2.3 Ultrasonic Phased Arrays and Associated Challenges

UMH employs ultrasonic transducers to apply pressure to the palm. Ultrasound wavelengths are above 20 kHz, making it imperceptible to human hearing and touch. To effectively stimulate human touch receptors, it is sampled to frequencies below approximately 600 Hz [52]. A typical ultrasound phased array can render sensations within the 100 to 300 Hz range.

In the past decade, ultrasound mid-air haptic technology has gained popularity in human-computer interaction due to improved rendering algorithms [24, 25, 57], increasing market interest

[34] [13], and open source platforms for development [58]. Despite its successful application in diverse areas like automotive interfaces [30], aviation [27], virtual reality [35], fluid rendering [6], emotion encoding [62], and stiffness rendering [55], Ultrasound Mid-air Haptics faces limitations in effective workspace size, stimulus intensity, and precision [34, 67, 79]. These limitations can potentially hinder the perceived congruency of haptically rendered objects.

Given these factors, it is important to investigate the role of UMH in enhancing how users perceive object congruency and temperature in Virtual Reality. Exploring how UMH can be combined with HI elements can potentially improve the realism of virtual objects in VR.

3 Concept: Using Ultrasonic Mid-air Visuo-haptic presentation to render Objects Properties in VR

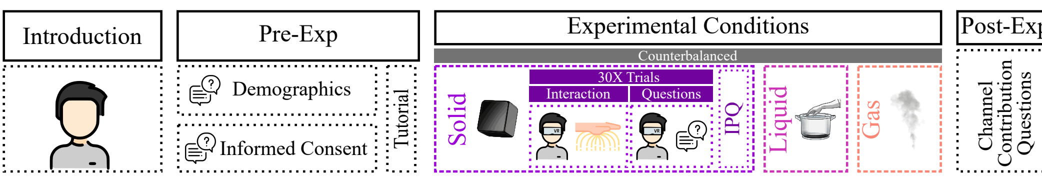


Fig. 2. Experimental Design Overview: Our study involved three distinct blocks, each aligned with a specific material state. We used the Latin Square design to counterbalance presentation order, mitigating potential order effects. Within each block, we randomized combinations of temperature color and haptics, each repeated five times. Each block included 30 trials, leading to a total of 90 trials.

UMH has been established as a viable technology rendering a diverse array of haptic sensations. However, the question of how congruent UMH feedback is in representing various object properties remains an open area of investigation. In particular, objects in different states of matter (solid, liquid, gas) present unique haptic characteristics. To explore the capabilities of UMH under these varying conditions, we selected these three object states for examination.

Further, to augment the potential of UMH in simulating temperature, we incorporated the Hue-Temperature Association Hypothesis. According to this hypothesis [90], cooler colors are associated with a colder temperature perception, while warmer colors evoke sensations of heat. Previous studies have explored this association without the addition of tactile cues [46]. UMH presents an intriguing opportunity in this context: it offers a touchless method to stimulate palm mechanoreceptors without necessarily engaging thermoreceptors. This additional layer of tactile stimulation may potentially strengthen the existing Hue-Temperature association.

Given this context, we propose two hypotheses:

- **H1:** The congruency of haptic feedback rendered through UMH will vary significantly across different object states.
- **H2:** The addition of tactile cues from UMH will strengthen the pre-existing hue-Ttemperature association, leading to a more pronounced or significant shift in perceived temperature based on color cues

3.1 Experimental Design

We conducted a laboratory experiment using a within-subject design to explore how the combination of UMH and HIs can enhance the representation of material properties in virtual reality (VR). Specifically, our investigation explored the effects of ultrasonic rendering on three distinct states of

[3] https://emerge.io/
[4] https://www.ultraleap.com/

matter (gas, liquid, and solid) and how this rendering impacts the overall perception of material consistency. Additionally, we examined how the combination of ultrasonic rendering influences the perception of object temperatures within the VR environment. Accordingly, we manipulated three variables: Material State, Temperature Color, and Haptics. Material State had three levels: Gas, Liquid, and Solid, Temperature Color also had three levels: Blue, White, and Red. Finally, Haptics had two levels: Active and Inactive. We organized our experiments into three distinct blocks, with each block corresponding to a specific Material State. To minimize any potential order effects, we used a Latin Square design to counterbalance the order of presentation for these blocks. Within each block, we randomized the combinations of Temperature Color and Haptics, ensuring each combination was repeated five times. In total, each block consisted of 30 trials, resulting in a total of 90 trials. Participants were able to see their hands during all the experiment.

3.2 Participants

We recruited a total of thirty participants ($N = 30$) through the university's mailing lists from which fifteen identified as female, fifteen as male, and no participants indicated a self-specified gender. Our sample had an average age of twenty-five years ($M = 25.47$, $SD = 8.69$). Participants reported a low familiarity with haptic devices in general ($M = 1.33$, $SD = 0.60$), and a low to medium level of familiarity with VR ($M = 2.53$, $SD = 1.00$). Participants were compensated 6 euros/30 min for their involvement. The study was approved by an ethics committee (Grant Nr. <removed>).

3.3 Apparatus

We used a Meta Quest 2 headset [5] along with an Ultraleap STRATOS Explore device [6] to provide Visuo-Haptic feedback. The VR environment was developed using Unity3d and executed on an ACER Predator Helios computer [7]. Additionally, we incorporated a 64-electrode R-net EEG system [8] from which we used 32 electrodes. To ensure synchronization between the VR environment and the EEG recording device, we employed the Labstreaming Layer[9].

3.4 Stimuli

Participants were given instructions to interact with a virtual object for a fixed duration of 5 seconds. Following this interaction period, they were asked to provide responses to two questions and continue with the next object. Participants were allowed to touch the object multiple times during this phase, the object's presentation was a combination of the following factors:

3.4.1 Hue-Temperature Association. The Hue-Temperature Hypothesis posits that specific colors are subjectively linked to temperatures; i.e., blue is often perceived as colder than red [90]. Evidence supporting this can be found in physiological research [73] and human-computer interaction studies [46]. We applied it to VR objects to simulate temperature; we rendered three colors: blue (`#2F48C5`), neutral (white) (`#D1D1D1`), and red (`#AB3737`). We included white as a control point given its lower color temperature association [73]. Based on beta-tester feedback during the design process, in the Liquid condition, we colored the container itself, given that fluids often do not exhibit a color change in response to increased temperature (Figure 3).

[5] https://www.meta.com/de/en/quest/products/quest-2/
[6] https://www.ultraleap.com/company/news/press-release/stratos-platform/
[7] https://www.acer.com/de-de/predator/laptops/helios/helios-300
[8] https://www.brainproducts.com/solutions/r-net/
[9] https://github.com/sccn/labstreaminglayer

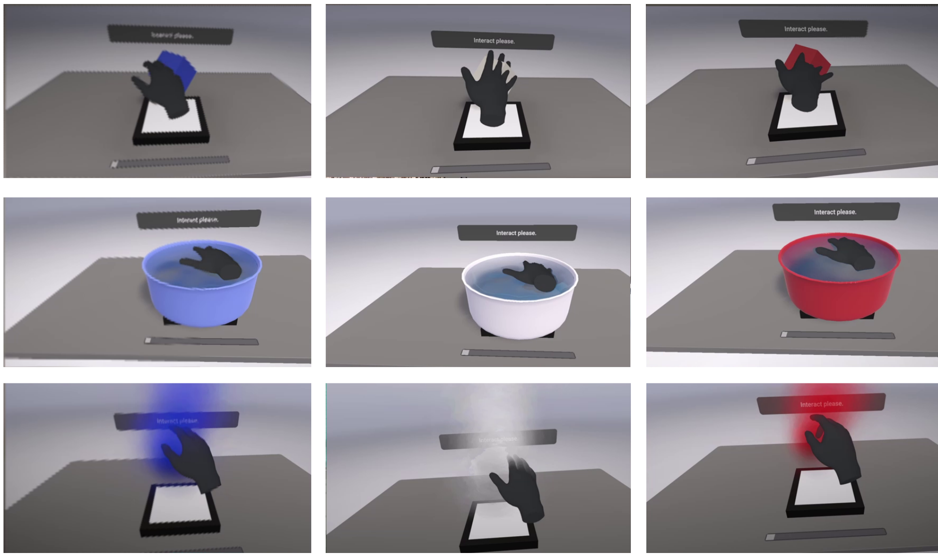


Fig. 3. Example stimulus combinations in VR: The solid object was represented using a cube, the Liquid using a water shader in a colored pot, and the gas using a particle system

3.4.2 Material State. We rendered the material state in three forms: a solid cube to symbolize the solid state, a pot incorporating a fluid shader to depict the liquid state, and a steam particle system to represent the gas state (Figure 3).

3.4.3 Presentation. We provided UMH feedback using the ultraleap STRATOS Explore phased array. We employed spatiotemporal modulation a method detailed in previous research [84]. We calculated collision points where fingers interacted with virtual objects. Subsequently, we created a curve connecting these points and moved the focal point rapidly along this curve trajectory [52].

3.5 Measures

We gathered data from multiple sources; two per-trial questions, a questionnaire after each block of trials, and, brain signal data from an EEG device [10]. To elaborate further, we measured:

3.5.1 Perceived Temperature. We assessed participants' subjective temperature perception using the Bedford Thermal Scale, specifically the extended University of California Berkeley (UCB) model with nine distinct levels. This instrument employed the question, "Please rate your thermal sensation," on a scale that spanned from "Very Cold" to "Very Hot." [3].

3.5.2 Perceived Congruency. We measured congruency by asking the following question: *How much did your experiences in the virtual environment seem consistent with your real-world experiences?* on a 9-point Likert scale once per trial ranging from *Very Inconsistent*, to *Very Consistent* [88].

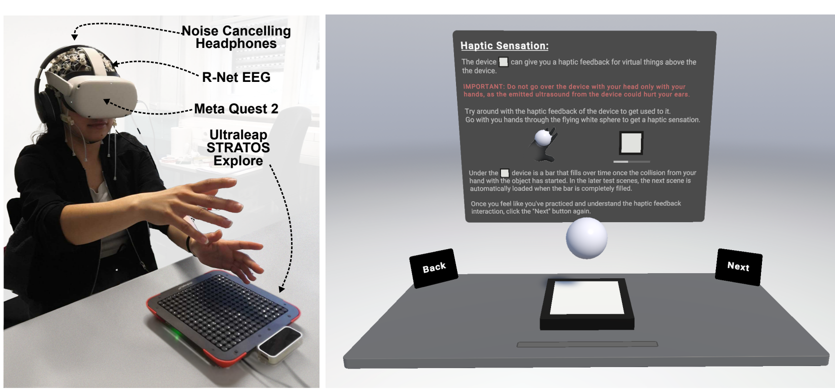
3.5.3 Presence. We used the Igroup Presence Questionnaire (IPQ), the IPQ comprises four subscales: Sense of Being There, Spatial Presence, Involvement, and Experienced Realism. We administered the IPQ to participants after the completion of each block of trials.

[10]https://www.brainproducts.com/solutions/r-net/

3.5.4 Perceived Channel Contribution to the Overall Experience. We evaluated participants' perceptions of the relative contributions of the sensory channels (visual and haptic) to both the perceived temperature and congruency of the object using four questions at the end of the experiment: **Q1:** *"My perception of temperature was mainly influenced by the tactile feedback."*, **Q2:** *"My perception of temperature was mainly influenced by the visual feedback."*, **Q3:** *"My perception of the material state was mainly influenced by the tactile feedback."*, and **Q4:** *"My perception of the material state was mainly influenced by the visual feedback."*

3.5.5 Processed Congruency. We quantified congruency through a metric called Mismatch Negativity, derived from the EEG signal. This metric was introduced by Gehrke et al. [26] as an alternative to subjective evaluations of haptic inconsistencies [11]. When users encounter a visuo-haptic mismatch, the negativity of the resulting Event-Related Potential (ERP) signals at the forehead (FCz location) decreases (the signal becomes more positive). This means that a more negative value represents a more matching stimulation. Throughout the experiment, we continuously monitored EEG signals and identified the first instance of contact between the participant's hand and the object in each trial to assess the mismatch negativity. In our study, we explored this recently introduced association to study congruency from the neurophysiological perspective. Yet, we want to emphasize that his metric has not been extensively validated by Gehrke et al. [26]; therefore, it is for informative purposes only. For this reason, we do not center our analysis on the neurophysiological metrics of congruency but on the self-reported metrics.

3.6 Procedure



(a) User exploring a virtual object in VR

(b) Snapshot of one of the tutorial screens pre-experiment

Fig. 4. Experimental setup and tutorial screen: Our setup included Noise Canceling headphones to mask environment sounds and the Ultrasonic Array noise, We used a combination of Meta Quest 2 for Visual rendering and Ultraleap Stratos for Haptic rendering, additionally we included an R-Net EEG device to measure participant's brain responses. Please note that the spherical shape was only used during the tutorial phase.

Participants then received an introduction to the VR hardware and system functionality and were asked to provide informed consent. Next, an experimenter securely attached the EEG headset,

[11] It is important to emphasize that this metric does not have formal validation. Therefore, it should not be regarded as a ground-truth measurement.

ensuring that electrode impedance remained below 50k Ω. To minimize external disturbances, participants were instructed to wear noise-canceling headphones, which masked environmental sounds and any noise generated by the active haptic array. Subsequently, participants were assisted in putting on the VR headset, and then they had to complete a tutorial to acquaint themselves with the experiment's flow, including interactions and questions (see Figure 4 for an example screen). Following, the formal experiment commenced, with participants being assigned a specific order of experimental conditions. Over the course of the study, participants were required to complete a total of 90 interactions. Following each interaction, they answered questions regarding perceived temperature and congruency. After completing each block of trials, participants also filled out the IPQ questionnaire. Notably, all questionnaires were administered within the VR environment to minimize disruptions to participant immersion. The entire study, including the setup of EEG equipment and questionnaire completion, lasted one hour.

4 Results

4.1 Data Analysis

Linear Mixed Models. We employed Linear Mixed Models (LMMs) for our data analysis, which are statistical models designed to manage correlated data. LMMs encompass both fixed effects (predictors) and random effects (room-temperature, and humidity in our case), making them suitable for analyzing intricate datasets with nested or repeated measurements, as in our case. we accounted for the non-independence resulting from multiple responses from the same participant, as recommended by Winter [87]. We followed the model selection process outlined by Zuur et al. [92] using a top-down strategy. Inspection of residual plots did not reveal deviations from homoscedasticity or normality. P-values were obtained through likelihood ratio tests, comparing the full model with the predictor in question to a simplified model without the predictor. Additionally, we utilized the *lmerTest* package [47], which approximates degrees of freedom for t- and F-tests using the Satterthwaite method and provides p-values for the fixed effects.

EEG Analysis. For EEG data analysis, we utilized the Python MNE library. We applied a high-pass filter at 1 Hz and a low-pass filter at 15 Hz, following the methods described in previous studies [1, 17]. The data was re-referenced to the average of all channels, and a notch filter was employed to eliminate the 50 Hz powerline noise. Subsequently, we segmented the epochs into time blocks spanning from -0.3 ms to 0.7 ms, with 0.0 ms indicating the stimulus onset. The period between -0.3 ms and 0.0 ms served as a baseline for the measured stimulus signal. To identify and discard epochs likely to contain noise, we employed the Autoreject Library [37].

Control Variables. We measured the temperature and humidity of the experimental room at the start and end of each experiment. We used this information as control variables in all the models presented in this section. Additionally, we report the mean values and variations during the experiment here. The average room temperature was 26 degrees Celsius (M = 26.00, SD = 1.01), with an average variation (end temperature minus start temperature) of 0.79 degrees Celsius (M = 0.79, SD = 0.27). The average relative humidity of the room was 42 (M = 42.48, SD = 6.16), which is within the recommended values for room temperature (Min = 30, Max = 60). The average variation in relative humidity was 1.64 (M = 1.64, SD = 1.97).

4.2 Object Congruency Perception

In order to determine the contribution of Presentation to the explanatory power of the Congruency model, we compared a *reduced* and a full model. The reduced model included only Material

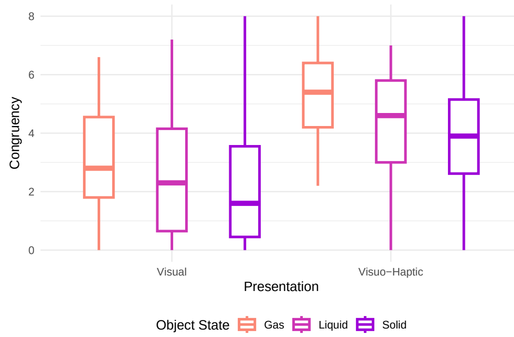


Fig. 5. Perceived Congruency per Object State and Presentation, Overall, Visuo-Haptic objects were perceived as more congruent than Visual objects. Further, Gas was generally perceived as more congruent than Liquid and Solid, the latter being the one perceived as least congruent

State as a fixed effect, along with random effects for Participant and Hue-Temperature. The full model additionally incorporated Presentation as a fixed effect.

A likelihood ratio test indicated that the inclusion of Presentation led to a statistically significant improvement in model fit ($\chi^2(1) = 184.61, p < 0.001$). This was corroborated in the goodness-of-fit measures by lower values of both the Akaike Information Criterion ($AIC_f = 2051.7$, full model vs. $AIC_r = 2234.3$, reduced model) and the Bayesian Information Criterion ($BIC_f = 2081.7$ full model vs. $BIC_r = 2260.0$, reduced model). Indicating Presentation (presence or absence of haptics) as a significant predictor for accurate data representation.

Considering the influence of Material State on Congruency ratings under two Presentation modalities: Visuo-Haptic and Visual.

We found that for Visuo-Haptic Presentation, Material State was a significant predictor of Congruency ratings ($\chi^2(2) = 61.75, p < 0.001$). The goodness-of-fit measures further supported this: $AIC_f = 944.59$ was lower than $AIC_r = 1002.34$, and $BIC_f = 966.18$ was lower than $BIC_r = 1016.74$. Within this modality, we found that Solid had the lowest mean Congruency rating ($M = 3.85, SD = 1.86$), followed by Liquid ($M = 4.35, SD = 1.78$), and Gas had the highest ($M = 5.34, SD = 1.47$).

Similarly, in the Visual Presentation, Material State was also a significant predictor for Congruency ($\chi^2(2) = 20.76, p < 0.001$). Here, the full model had an $AIC_f = 981.39$ and $BIC_f = 1003.19$, both lower than the reduced model's $AIC_r = 998.15$ and $BIC_r = 1012.5$. The mean Congruency rating for Solid was $M = 2.18, SD = 2.06$, for Liquid it was $M = 2.59, SD = 1.98$, and for Gas it was $M = 3.04, SD = 1.92$.

In the Visuo-Haptic Presentation, the average scores for each Material State were higher compared to Visual Presentation (see Figure 5). These results lend empirical support to **H1**, indicating that objects with lower kinaesthetic complexity are perceived more congruently in a virtual reality environment compared to objects with high kinaesthetic complexity. Furthermore, our data reveals that the incorporation of tactile cues—specifically, UMH—significantly enhances the overall perception of object congruency.

4.2.1 ERP Analysis and Mismatch-Negativity. We observed differences in Event-related Potentials (ERP) at the FCz electrode based on Material State and Presentation. Figure Figure 6 illustrates

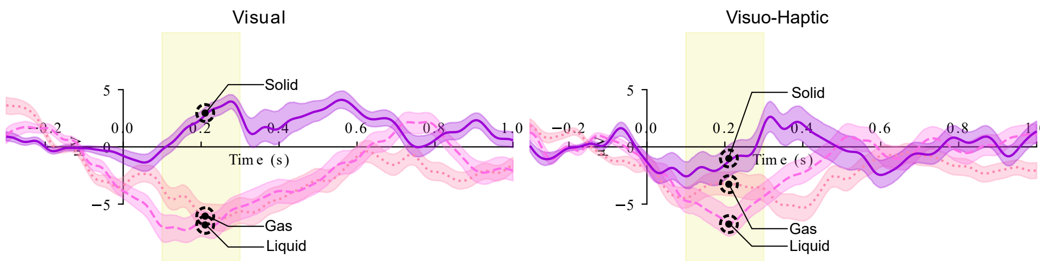


Fig. 6. Mismatch Negativity (Prediction Errors) in ERP response , Lower values are associated with more congruent stimulus, A higher value is associated with a more unrealistic VR interaction [26].

the negativity response elicited by the exploration stimulus. According to the metric proposed by Gehrke et al. [26], higher negativity is indicative of a more congruent virtual reality experience. [12]

Consistent with the Congruency ratings we reported earlier, the Solid State had the lowest levels of congruency. On the other hand, the Liquid and Gas states performed better in terms of congruency across both Presentation modalities. Interestingly, Figure 6 shows that the negativity for the Solid State is heightened during Visuo-Haptic Presentation. This suggests that participants found the Solid State to be more congruent when experienced in the Visuo-Haptic mode also at a physiological level. However, additional studies focusing on Mismatch Negativity are needed to confirm these findings.

4.3 Object Temperature Perception

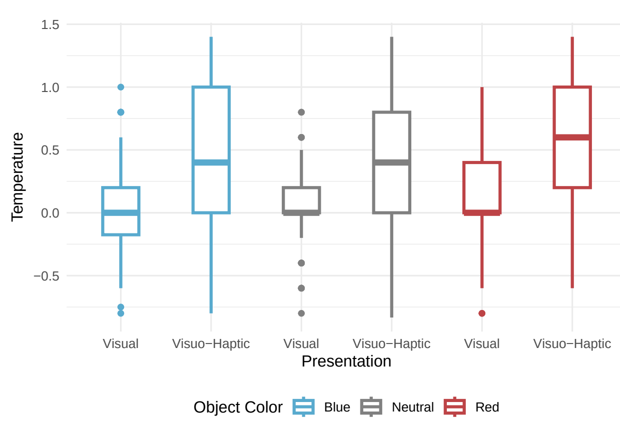


Fig. 7. Perceived Temperature, Haptic feedback consistently shifted the perceived temperature across all Hue-Temperature associations.

To examine H2, we employed a three-step approach. First, we developed a model to investigate the perceived temperature in relation to the Hue-Temperature Association, aiming to validate if participants associated the object color with the object temperatures. Second, we assessed whether the Presentation modality influenced this color-temperature association. Finally, we conducted a

[12]It is important to emphasize that this metric does not have formal validation. Therefore, it should not be regarded as a ground-truth measurement.

level-specific analysis to determine if the inclusion of haptic cues amplified the Hue-Temperature Association effect

To assess the influence of Hue-Temperature on the Perceived Temperature of virtual objects, we employed both a reduced and a full model. The reduced model incorporated Material State and Presentation as fixed effects, with Participant as a random effect. In contrast, the full model extended this framework by including Hue-Temperature as an additional fixed effect.

A likelihood ratio test revealed Hue-Temperature as an statistically significant improvement in model fit ($\chi^2(2) = 11.945, p < 0.005$). The model had a goodness-of-fit (AIC_f = 609.28 vs. AIC_r = 617.23, BIC_f = 643.19 vs. BIC_r = 642.66). Indicating Hue-Temperature as a significant predictor for accurate representation of the data. This provides evidence that participants associated the temperature of the presented object with the color of the object. Specifically, blue was perceived as cooler (M = 0.22, SD = 0.53) compared to red (M = 0.34, SD = 0.50). However, the neutral color was rated even colder than blue (M = 0.19, SD = 0.45). Suggesting a consistent heat association for Red, but a less clear one for Blue and Neutral.

Next, to explore the influence of Presentation on the Perceived Temperature of virtual objects, the reduced model incorporated Material State and Hue-Temperature as fixed effects, with Participant as a random effect. In contrast, the full model extended this framework by also including Presentation as an additional fixed effect (Similar to the full model for Hue-Temperature association).

A likelihood ratio test indicated that the inclusion of Presentation led to a statistically significant improvement in model fit ($\chi^2(2) = 96.17, p < 0.001$). The model had a goodness-of-fit (AIC_f = 609.28 vs. AIC_r = 703.45, BIC_f = 643.19 vs. BIC_r = 733.12). Therefore, Presentation was identified as a significant predictor for data representation, suggesting a substantial influence on the perceived Temperature of the virtual object. Specifically, objects in the Visuo-Haptic Presentation were rated as warmer (M = 0.44, SD = 0.56) compared to those in the Visual Presentation (M = 0.07, SD = 0.34). Importantly, this difference in perceived Temperature was more pronounced than the variance attributed to the Hue-Temperature association.

At the level of individual colors, we observed that objects were consistently rated as warmer in the Visuo-Haptic Presentation compared to the Visual Presentation. Although both Presentation and Hue-Temperature Association serve as significant predictors for perceived temperature, their impact diverges from our initial hypothesis. Specifically, Visuo-Haptic Presentation does not amplify the Hue-Temperature association; rather, it uniformly elevates the perceived temperature (see Figure 7). This trend remains consistent across all combinations of Material State and Hue-Temperature Association, as further detailed in Table 1.

Table 1. Temperature Associations across all Object States, Hue-Temperature Associations, and Presentation

	Solid - M (SD)		Liquid - M (SD)		Gas - M (SD)	
	Visual	Visuo-Haptic	Visual	Visuo-Haptic	Visual	Visuo-Haptic
Blue	0.02 (0.30)	0.23 (0.56)	0.05 (0.36)	0.37 (0.61)	0.10 (0.40)	0.56 (0.65)
Neutral	0.04 (0.28)	0.34 (0.51)	-0.04 (0.31)	0.36 (0.55)	0.07 (0.27)	0.43 (0.50)
Red	0.14 (0.41)	0.49 (0.46)	0.10 (0.36)	0.59 (0.64)	0.17 (0.32)	0.60 (0.48)

4.4 IPQ

We measured the overall impact on presence at the end of each block, Figure 8 presents an overview of the data for the four sub-scales (*Sense Of Being There*, *Spatial Presence*, *Involvement*, *Experienced Realism*) as well as the composite *Presence* score. As the data did not follow a normal distribution, we employed the *Friedman test* in this case.

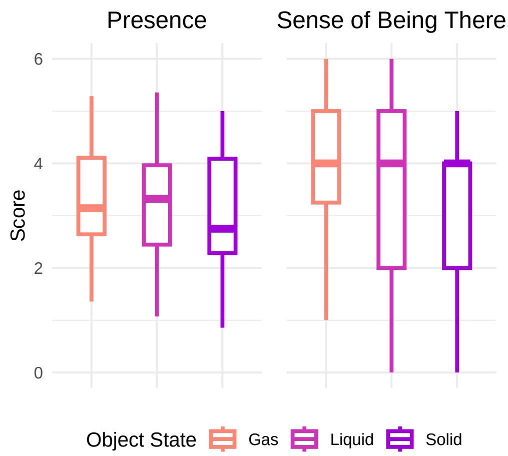
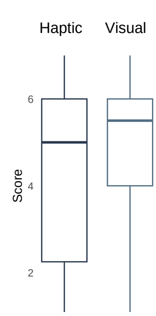


Fig. 8. IPQ General presence and Sense of Being There subscale: We found significant differences in the Sense of Being There subscale for Gas and Solid states, yet, no differences were observed in the remaining subscales

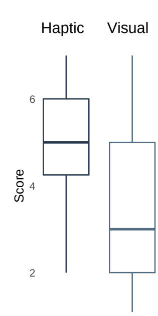
Only the *Sense Of Being There* sub-scale exhibited a significant difference across object states, as indicated by a $\chi^2(2) = 11.877, p < 0.05$. Post-hoc test showed significant differences between the Gas and Solid states (p < 0.05). No significant variations were observed in the general *Presence* score across different object states.

4.5 Perceived Channel Contribution to The Overall Experience

As the data did not follow a normal distribution, we applied the *Wilcoxon signed-rank test* to assess differences between paired questions: Q1 vs. Q2 and Q3 vs. Q4. Statistical analysis indicated a significant difference between questions Q1 and Q2 (V = 311.5; $p < 0.05$) and between questions Q2 and Q4 (V = 35.5; $p < 0.05$), see Figure 9.



(a) Object State



(b) Temperature

Fig. 9. Reported contribution to Object State and Temperature perception per channel: Participants rated that the visual channel had a bigger contribution to their perception of the material state, while haptics had a bigger impact on the perceived temperature than the visual channel.

5 Discussion

Our analysis showed that Presentation, Hue-Temperature Association, and the target Object State serve as significant predictors for both Perceived Object Congruency and Temperature. Notably, the observed effects of Hue-Temperature and Presentation diverged from our initial hypotheses. This section elaborates on these findings.

5.1 Effects of Visuo-Haptic Presentation on Object Congruency Perception

Simulating the haptic characteristics of virtual objects in VR remains a challenge. Yet, our findings indicate that Ultrasound Haptics can substantially improve the perceived congruency across all evaluated object states. While simulating solid objects poses particular difficulties, we observed that the mere presence of tactile stimuli via Ultrasound Haptics significantly enhances users' perception of congruency. We also found that Gas and Liquid VR objects are already perceived as more congruent in the Visual Presentation modality; however, even the lower-rated Visuo-Haptic Object State already outperforms the best Visual Object State. This supports the importance of considering multisensory experiences in VR and not relying only on visual information as a feedback channel.

5.2 Effects of Visuo-Haptic Presentation on Physiological Responses to Object Consistency

Our physiological measures were in line with self-reported experience metrics. Specifically, in the event-related potentials (ERP) data, Solid objects demonstrated a larger shift in negativity compared to Gas and Liquid objects, which remained relatively consistent. In a visual-only setup, the negativity associated with Solid objects was low, however, this value increased significantly when tactile stimuli were introduced through visuo-haptic interaction. It is important to approach these physiological findings with caution, as the ERP correlate for experience congruency is a recent addition to the literature and lacks extensive validation. Nevertheless, our results are consistent with the initial findings reported in the original study.

5.3 Effects of Visuo-Haptic Presentation on Thermal Perception

Our data revealed that the incorporation of tactile cues did not amplify the Hue-Temperature association, as initially hypothesized. Instead, it led to an overall shift in the perceived temperature of the objects. This effect was consistently observed across all states of matter and color conditions. This suggests that UMH may influence temperature perception, even though there is currently no empirical evidence to show that it specifically stimulates thermoreceptors.

An additional observation was that, within the context of visuo-haptic presentation, objects in the Gas state received higher warmth ratings compared to those in the Liquid and Solid states. This implies that the perceived temperature of an object could be influenced by its state. Literature has reported an effect of specific visualizations impacting temperature perception, including objects in gas states such as rain clouds [29] and steam [10]. However, due to these explorations targeting very specific objects, the concrete effect of an object's state on perceived temperature requires further investigation.

5.4 Per channel contribution to Temperature and Congruency

Our findings reveal that participants placed greater sensory importance on UMH when evaluating the temperature of virtual objects. In contrast, they relied more on visual cues for determining the objects' state (e.g., Solid, Liquid, or Gas). Although our modeled data supports these observations, it's noteworthy that both UMH and visual cues significantly influenced the perception of object state congruency.

5.5 Limitations

This study is subject to several limitations. One limitation is that we did not manipulate the *ambient temperature* in the real environment to assess the robustness of our findings. Our aim was to maintain a controlled setting for both real and virtual environments. While previous research has investigated the influence of virtual environments on temperature perception, our study did not extend its scope to include these variables. We are aware that there is a variety of descriptive research on potential illusions referenced in the literature that together with ultrasound haptics is able to enrich Object properties, however, in this work, we only focused on the Hue-Temperature association. Another limitation of this study is that we explored the perceived temperature and congruency using two 9-point questions per interaction paradigm. While this method successfully describes the phenomenon, a psychophysical paradigm could have potentially elucidated thresholds of perception values or the exact shift in temperature. Finally, this study only covered haptic and visual feedback; other sensory modalities such as audition may play an important role in congruency and temperature perception.

5.6 Future Work

The observed shift in perceived temperature offers multiple avenues for future research. Key research questions include a precise quantification of the temperature shift and an exploration of its physiological underpinnings. Specifically, future studies could investigate whether the observed effects are a result of the interplay between tactile mechanoreceptors and visual cues, or whether ultrasonic stimulation directly activates thermoreceptors.

Additionally, it may be useful to examine the relationship between acoustic radiation intensity and the magnitude of temperature perception shifts. For example, one could assess whether higher ultrasound intensities lead to greater shifts in perceived temperature compared to lower intensities. Another intriguing area for future research is the exploration of implicit temperature associations related to the different states of matter, particularly during phase transitions such as melting, evaporation, solidification, and condensation.

Finally, empirical evaluations involving real temperature changes could be conducted, possibly utilizing acoustically transparent interfaces as suggested by Howard et al. [34].

5.7 Implications for Design

In this section, we present new insights into how UMH rendering affects how users perceive the congruency and temperature of objects. These insights offer practical guidance that haptic designers and researchers can apply. Here's a summary of our key takeaways:

Enhanced Congruency with Visuo-Haptic Presentation: Our results indicate that integrating UMH in visuo-haptic presentations improves the perceived congruency of virtual objects.

Optimal Rendering Scenarios For Ultrasound Mid-air Feedback: The efficacy of this haptic feedback is more pronounced for objects in gaseous or liquid states. This suggests that designers should tailor the choice of haptic feedback based on the specific type of object being rendered. Alternatively, they might opt for attributing gaseous or liquid properties to virtual objects and interfaces to maximize the congruency effect.

Shift in Perceived Temperature: Our study strongly indicates that ultrasound haptic feedback alters the perceived temperature of virtual objects. Designers should take this into account, especially in scenarios where accurate temperature perception is crucial.

Design Opportunities with Temperature Shift: The observed shift in perceived temperature also presents an opportunity for designers. Ultrasound haptics can be utilized to intentionally modulate the perceived temperature of virtual objects, thereby adding a new dimension to object rendering without requiring additional hardware.

5.7.1 Implications for VR prototyping. Utilizing UMH enhances the presence and congruency of VR design explorations, particularly in the early stages. This technology allows for the simulation of diverse object properties, such as soft/warm or hard/cold surfaces, within the same virtual model. Such haptic feedback can be coupled with Hue-Temperature associations to offer a more comprehensive sensory experience. This approach has not yet been incorporated into VR industrial design iterations and has the potential to significantly influence design decisions and project directions:

- Seamless Sensory Integration: Facilitates haptic explorations in VR without requiring user-worn devices, creating a holistic experience.
- Enhanced Materiality: Enables industrial designers to explore material affordances in VR, from texture to temperature, broadening the design palette.
- Perceptual Consistency: The introduction of UMH elevates the overall congruency of virtual objects, even outperforming visual-only simulations.
- Tailored Haptic Feedback: Our findings indicate optimal use cases for different object states, allowing for more targeted design choices in rendering gas, liquid, or solid objects.

6 Conclusion

We studied the potential of UMH and HI to enhance the congruency of virtual objects. In our study, 30 participants interacted with virtual objects in VR. These objects appeared in three forms: Solid, Liquid, and Gas, and displayed one of three colors: Blue, White, or Red. Participants experienced these combinations with or without UMH feedback. Our results indicate that UMH notably improved the congruency of objects, especially for Liquid and Gas forms. Additionally, the presence of UMH influenced the perceived temperature of the objects in VR more than the color-temperature relationship did. These results contribute to the body of knowledge in Ultrasound Mid-air Haptic rendering in VR and have implications for haptic designers and researchers.

7 Open Science Statement

We strongly believe in the need for replication within HCI, in order to facilitate this, we openly release the materials used to conduct the study, including source code and assets for the VR environments and data analysis scripts in the following link: https://github.com/mimuc/UltrasonicMaterials

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