Fiery Hands: Designing Thermal Glove through Thermal and Tactile Integration for Virtual Object Manipulation

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Figure 1: Concept diagram of Fiery Hands. A user wearing Fiery Thermal gloves interacting with a fireball.

ABSTRACT

We present a novel approach to render thermal and tactile feedback to the palm and fingertips through thermal and tactile integration. Our approach minimizes the obstruction of the palm and inner side of the fingers and enables virtual object manipulation while providing localized and global thermal feedback. By leveraging thermal actuators positioned strategically on the outer palm and back of the fingers in interplay with tactile actuators, our approach exploits thermal referral and tactile masking phenomena. Through a series of user studies, we validate the perception of localized thermal sensations across the palm and fingers, showcasing the ability to generate diverse thermal patterns. Furthermore, we demonstrate the efficacy of our approach in VR applications, replicating diverse thermal interactions with virtual objects. This work represents significant progress in thermal interactions within VR, offering enhanced sensory immersion at an optimal energy cost.

CCS CONCEPTS

• **Human-centered computing** → *Interaction design theory, concepts and paradigms*; **Haptic devices**.

KEYWORDS

Thermal Gloves, Thermal Referral, Thermal Illusions, Thermal and Haptic Interfaces, Virtual Reality

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1 INTRODUCTION

Thermal gloves are an exciting area of growth in wearable technology, especially in immersive virtual reality (VR) [9, 23, 37, 45]. As the demand for more engaging VR experiences increases, integrating thermal feedback into gloves has become a promising way to make interactions feel more real and immersive. These gloves typically come with thermal actuators and sensors, allowing users to feel sensations like temperature changes, making virtual interactions more meaningful and lifelike [22]. This emerging technology has many potential applications, from gaming and entertainment to healthcare and training, where realistic thermal feedback can greatly enhance user experiences and task performance.

Designing thermal gloves for VR presents a significant challenge due to the bulky components required for generating and managing heat, such as heat sinks, heat spreaders, and cooling systems [14, 22, 25]. Integrating these components into a single glove design is particularly difficult because of their size and weight. These bulky elements limit the wearer's hand dexterity and range of motion and make it challenging to ensure a comfortable and ergonomic fit [9, 23]. Moreover, heavy or cumbersome gloves can restrict hand and finger movements, leading to discomfort and usability issues when interacting with virtual objects. As a result, users may experience hindered interactions, impacting the overall immersion and usability of the VR experience.

Another primary challenge in designing thermal gloves for VR is the high power consumption associated with thermal actuators, making scalability difficult [22, 23]. This increased power demand can lead to challenges in achieving localized thermal feedback for rendering various thermal patterns effectively. The need for continuous power supply and management adds complexity to the design and operation of thermal gloves, potentially limiting their practicality and usability. Moreover, this complexity may result in shorter battery life or the inclusion of larger, bulkier batteries, which can hinder mobility and user comfort. These challenges highlight the urgent need for innovative solutions to ensure reliable and efficient delivery of thermal feedback, thereby enhancing the overall user experience in VR environments.

Our approach focuses on integrating thermal and tactile actuators to create thermal referral illusions at specific tactile locations, leveraging the interaction between these actuators to generate thermal sensations without the need for actual thermal actuators. This perception-based approach addresses key challenges in thermal glove design, including virtual object interaction and manipulation, engineering complexity, and difficulties in achieving localized and global thermal feedback. When both the vibrotactile actuator and thermal actuator are activated at separate locations, a strong thermal illusion occurs at the vibrotactile site [44]. This phenomenon, known as vibrotactile-induced thermal referral or *thermal masking*, enables the creation of illusory thermal sensations using simpler vibration mechanisms. Consequently, this reduces the need for multiple thermal actuators and can potentially lower costs. By strategically placing tiny vibrotactile actuators on the palm and fingers and thermal actuators at peripheral locations, we ensure minimal interference with virtual object interactions while effectively providing diverse thermal patterns for enhanced user experiences in VR.

We present Fiery Hands, a pair of innovative thermo-tactile gloves specifically designed to provide thermo-tactile sensations through thermal and tactile integration, creating thermal referral illusions. Fiery Hands are strategically equipped with thermal and tactile actuators designed to minimize obstruction during virtual object manipulation. They can deliver both localized and global thermal feedback with various dynamic thermal effects that vary spatially and temporally through their thermal and tactile integration. The main contributions of this work are (i) a unique, perception-based approach to designing thermal gloves that strategically arrange and integrate thermal and vibrotactile actuators to minimize obstruction during virtual object manipulation; (ii) providing localized thermal illusions through thermal and tactile integration, allowing users to feel realistic thermal sensations in specific areas of their hands, and (iii) offering various dynamic thermal effects that spatially and temporally to enhance immersion and interaction in VR.

2 RELATED WORKS

2.1 Thermal Perception

Thermal perception plays a vital role in sensory cognition, allowing individuals to distinguish between sensations of warmth and coldness triggered by the response of thermoreceptors to stimuli that exceed or fall below the skin's temperature [21, 40, 43, 48]. These thermal sensations are detected by warm or cold thermoreceptors located within the epidermis and dermis layers of the skin. These sensory inputs are then transmitted to the brain and undergo processing within the insular cortex [12, 21]. While warm receptors are sparsely distributed across the skin compared to cold receptors, this difference in receptor density explains the heightened sensitivity of human skin to cold temperatures relative to warm temperatures [1, 3]. The thermal thresholds for detecting warmth and heat-induced pain range from 30°C to 34°C and 39°C to 50°C, respectively, while those for cold and cold-induced pain detection range from 12°C to 31°C and 0°C to 28°C [4, 6, 13, 27, 28]. The response time of thermoreceptors typically falls within the range of 0.5 to 2 seconds, which is slower compared to the millisecond-level response of mechanoreceptors [18, 34].

2.2 Thermal Referral

Thermal referral is a phenomenon in which thermal sensations are referred to nearby areas due to interactions between thermal and tactile stimuli. When the skin receives both types of stimuli simultaneously, the thermal sensation can be felt not only at the location of the thermal stimulus but also at adjacent tactile sites. Green [15] observed this effect, noting that applying a neutral-temperature tactile stimulator on the middle finger could induce a thermal sensation if thermal and tactile stimuli were applied to the index and ring fingers. The exact mechanism behind this concurrent perception of thermal and tactile stimuli is not fully understood, but hypotheses suggest that it may involve thermal redistribution and spatial summation, causing the thermal sensation to be perceived across the tactile contact area [10, 20].

Several studies have explored various aspects of thermal referral, highlighting its spatial limitations on the hand and the diminishing intensity of sensation as the distance from the stimulus increases [19]. Notably, thermal referral tends to be less pronounced in colder conditions compared to warmer ones, possibly due to the prevalence of cold receptors in the skin [15, 20, 24]. Thermal referral has been observed on other body parts, such as the hand [10], forearm [25, 47], and back [38]. Liu et al. [25] have demonstrated that combining pressure with thermal stimuli can mimic the sensation of moving heat. Recently, researchers discovered that thermal referral illusions could be elicited through vibration when integrated with thermal actuators, revealing a new dimension of vibrotactile-induced thermal referral [38, 44]. This vibrotactile-induced thermal referral illusion is much more perceptible compared to existing tactile means such as pressure. Since vibration is easier and cheaper to create, this finding is scalable and offers significant engineering benefits. This discovery opens up new possibilities for creating cost-effective and efficient thermal feedback systems.

2.3 Wearable Thermal Devices

Wearable thermal devices primarily provide thermal feedback through convection [33, 36, 46] and conduction [14, 16], offering the flexibility to be placed on various body parts for a more immersive user experience. Different thermal approaches have been explored to generate thermal sensations. For example, water pipe-based systems can create a wide thermal area and adapt to anatomical shapes, but they face challenges related to complexity, weight, and obstructed movement due to the pipes [16]. Peltier-based systems are also popular in wearables due to their expandability and fast temperature response, making them suitable for enhancing realism in VR scenarios [14, 30, 31]. Peltier-based systems, when combined with other modalities such as vibrotactile and wind, can enhance the experience [11, 32] and even induce a wetness sensation [29, 35]. However, maintaining the performance of Peltier requires a relatively large heatsink, making it difficult to achieve a compact wearable form factor. Other approaches include chemical-induced methods [26], where the skin absorbs the Methyl to generate thermal sensations, and olfactory-stimulated temperature illusions [7].

Haptic and thermal gloves are essential in VR because they provide a rich sensory experience, allowing users to feel and interact with virtual objects and environments. This feedback significantly enhances the sense of immersion and realism in VR, making the overall experience more engaging and fun. Haptic gloves are equipped with multiple feedback mechanisms, including vibrotactile, pressure, and kinesthetic feedback. These gloves are widely used in both commercial and academic settings [8, 42]

On the other hand, developing thermal gloves presents significant challenges due to the larger size of thermal actuators and the complexity of their setup. These challenges make it difficult to integrate thermal elements seamlessly into glove designs without compromising comfort and usability. The added bulkiness can restrict natural hand and finger movements, making it harder to manipulate virtual objects effectively. Various approaches have been explored to address these challenges. For example, Cai et al. [9] used a pneumatic glove with airbags beneath each finger connected to a temperature chamber for thermal sensation, but this resulted in a bulky and energy-intensive system. Kim et al. [23] proposed a flexible Peltier-based thermal glove covering the entire hand, but this required numerous Peltiers and limited hand movement due to the silicone cover. Weart introduced a thermal glove capable of providing force, texture, and thermal feedback, although its effective area was restricted to the fingertips [39].

3 APPROACH

3.1 Challenges in Designing Thermal Gloves

Designing thermal gloves for VR environments comes with a set of significant challenges that must be carefully addressed to ensure optimal performance and user satisfaction.

Challenge 1: Obstruction of Virtual Object Manipulation. Conventional thermal actuators tend to be bulky due to their dependence on heat generation and management. This reliance necessitates the inclusion of bulky components like heat sinks, heat spreaders, and cooling systems to prevent overheating. Additionally, these actuators often integrate mechanical components crucial for converting thermal energy into mechanical motion, further adding to their overall size and bulkiness. Consequently, heavy or cumbersome gloves can restrict hand movement, leading to discomfort and usability issues, especially when interacting with virtual objects. Additionally, this bulkiness can limit hand-tracking capabilities to vision-based head-mounted display (HMD) tracking systems.

Challenge 2: Engineering Complexity. Thermal actuators consume considerable energy to generate heat, resulting in significant power consumption. It is crucial to effectively manage heat levels within the glove to prevent user discomfort or overheating. Incorporating effective heat regulation mechanisms into the design is essential to maintain a comfortable and safe thermal environment. However, integrating these mechanisms adds a complex engineering burden to the design process.

Challenge 3: Difficulties in Achieving Localized and Global Thermal Feedback. Achieving both localized and global thermal feedback poses challenges because of the size, weight, and power consumption of the actuators. Integrating multiple thermal actuators becomes difficult due to their bulkiness, resulting in limited customization and adaptability for creating different temperature levels and patterns that enhance immersion and user satisfaction.

Challenge 4: Limited tactile interaction. Integrating thermal feedback with tactile feedback is essential for providing a comprehensive sensory experience. However, achieving this integration in a single glove design without interference presents significant challenges. The thermal actuator is relatively larger than the tactile actuator, and Peltier-based systems typically require a bulky heatsink to maintain performance. This leaves limited space for the tactile actuator [14, 23, 49].

3.2 Strategies

Our approach is based on the integration of thermal and tactile actuators to generate thermal referral illusions at specific tactile locations [38]. When these actuators are activated near each other on the skin, the perception of stronger thermal referral illusions occurs at the tactile actuator's location instead of the original thermal site. This means that by leveraging the interaction between thermal and tactile actuators, we can create thermal sensations without the need for actual thermal actuators. This has significant benefits, especially in addressing challenges related to designing thermal gloves. This offers significant advantages in tackling key challenges in thermal glove design. Vibrotactile actuators are smaller, more energy-efficient, and less complex than thermal actuators, facilitating integration with thermal actuators and scalability to larger displays. This integration enables seamless provision of localized and global thermal feedback with diverse patterns, enhancing user experiences in the virtual environment and enabling advanced tactile interaction possibilities.

In this perception-based approach, we strategically place multiple tiny vibrotactile actuators on the palm and fingers while situating thermal actuators at peripheral locations to avoid interference with interactions involving virtual objects. We study how these actuator placements can minimize the virtual object interactions and impact the thermal perception to effectively create localized and global thermal feedback with various thermal patterns.

Our research focuses on determining the optimal locations for thermal and vibrotactile actuators on the hand and fingers to generate thermal sensations effectively. We also delve into delivering various thermal patterns using our method, aiming to comprehend the formation and perception of these patterns and accurately replicate thermal sensations with virtual objects. Lastly, we present the design of our thermal gloves based on our approach and assess their performance in VR scenarios involving user interactions.

3.3 Setup

We combined thermal and vibrotactile actuators to produce thermal referral illusions on the palm and fingers consistently across all experiments. The configuration of the actuator setup varied in terms of numbers and locations, customized to meet the specific goals of each experiment.

Thermal Actuators. A flexible Peltier-based thermal actuator (TEGWAY, S017A026026)[1] paired with heatsinks (Assmann WSW Components, V5619A) was used, as shown in Figure 2 (a). The heatsinks efficiently dissipate heat, maintaining the non-actuation side at ambient temperature and ensuring a clear contrast with the activated side. The size of the thermal actuator and its heat sink is 26 mm (width) × 26 mm (height) × 2.3 mm (depth) and 6.35 mm (width) × 19 mm (height) × 4.83 mm (depth), respectively. Two heat sinks were placed at the back side of the thermal actuator for heat dissipation. The maximum temperature difference between the two sides of the thermal actuator is 64°C when supplied with a voltage of 2.2V and a current of 6A. The Peltier provides the same heat flow to the hand under a fixed voltage level. It takes approximately 1 second to reach the target temperature and about 20 seconds to return to normal temperature.

Vibrotactile Actuators. We used small coin-shaped vibrotactile actuators (JIEYI, JYC0827, ERM type) to induce tactile sensations (see Figure 2 (a)). These actuators have a diameter of 8mm and a height of 2.7mm. We set the vibrotactile actuators to deliver 5.7 mN of force at 166 Hz based on preliminary studies showing their effectiveness in achieving a higher occurrence rate of thermal referral on the palm and fingers. Digital power supplies (Korad KD6005P) were employed to power both the thermal and vibrotactile actuators. Arduino UNO was used in the company with the relay (SRD-05VDC-SL-C) to control all the actuators.

Attachment Mechanism. Adjustable Velcro straps were used in user studies 1 and 2 to securely attach the actuators in their designated positions. We designed 3D-printed structures with holes to support the actuators and allow for strap insertion, ensuring a secure attachment to the skin (see Figure 2 (b) and (c)).

Other Setup. An Alienware R13 desktop PC was utilized in both user studies 1 and 2. Participants were provided with a Samsung S9 tablet equipped with an active stylus pen to follow instructions and store raw data.

4 USER STUDY 1: OPTIMAL THERMAL ACTUATOR PLACEMENT

The goal of this study is to explore the effective positions of thermal actuators to be placed and integrated with vibrotactile actuators to provide localized thermal feedback and minimize obstructions for virtual object manipulation. We tested 12 potential locations on both sides of the hand and fingers, dividing the study into two sections: one for the fingers and another for the palm. Participants completed both sections of the study with a one-week gap in between. We recorded data on the frequency of occurrence, response time, and perceived thermal coverage of the referred thermal sensation across various placements of the thermal actuators.

4.1 Participants

Sixteen participants (8 females, mean age 22.1, SD = 3.9) completed this study. All participants were right-handed, and they were compensated with a $10 gift card for their participation. We proceeded with a screening procedure with a questionnaire form to exclude individuals with any illness or injuries related to the skin of the hand. The mean size of the hands were 75.8±6.7mm (width) × 95.6±5.6mm (length). All experiments were approved by the author's institution's Institutional Review Board.

4.2 Fingers

Thermal Actuator Placement. Ten thermal actuators were strategically positioned in the center of the proximal phalanx for the thumb and middle phalanges for the other four fingers, on both the ventral (inner) and dorsal (outer) sides (see Figure 3 (a)). The ventral placement aimed to study thermal referral sensations within the finger, while the dorsal placement explored alternative locations to avoid obstruction during virtual object manipulation.

Vibrotactile Actuator Placement. Nine vibrotactile actuators were placed at the center of the distal phalanx for the thumb and distal and proximal phalanges for the other four fingers, exclusively on the ventral side. This placement accommodated the presence of thermal actuators on the middle phalanges and facilitated the creation of thermal illusions through interaction with thermal actuators on the ventral or dorsal side.

Thermal and Tactile Integration. We activate the tactile actuator and its corresponding thermal actuator (i.e., within the same finger) together to elicit thermal illusions at the tactile location.

[1] TEGWAY, S017A026026

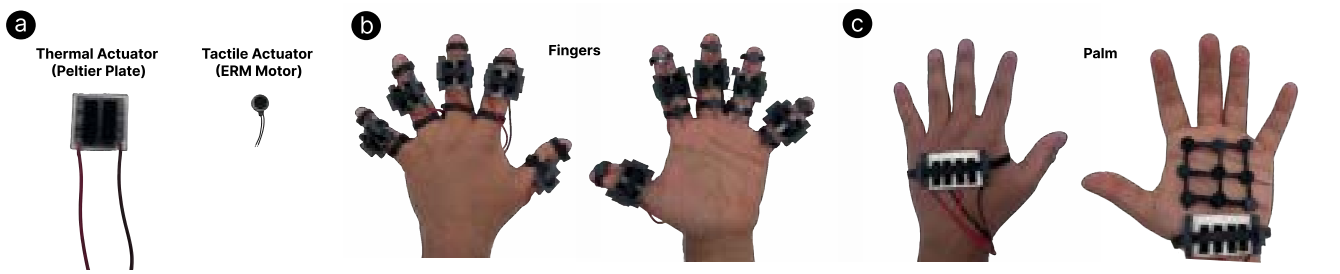

Figure 2: Experiment setup: (a) thermal actuator and a tactile actuator, (b) experiment setup for finger section, and (c) experiment condition for palm section.

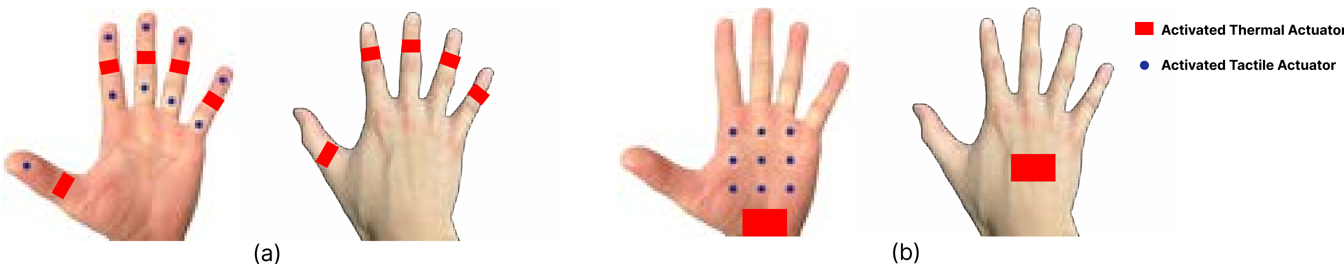

Figure 3: Experiment conditions for User Study 1: (a) Finger, (b) Palm.

Thermal actuators were activated to increase surface temperature by 3°C above the participant's skin temperature using supply voltage control. At the same time, vibrotactile actuators were consistently stimulated at 2.5V to deliver a stimulus of 5.7 mN and 166 Hz to create thermal referral illusions at the tactile location. Each trial involved simultaneous stimulation of thermal and vibrotactile actuators for 5 seconds.

Experimental Conditions. A single factor varies the placement of thermal actuators between the ventral and dorsal sides. This variable was designed to investigate the perceived thermal regions on the fingers and compare the two placements to determine the optimal locations. A total of 72 trials were conducted (9 vibrotactile actuator locations × 2 thermal actuator locations × 4 repetitions).

4.3 Palm

Thermal Actuator Placement. Two larger-size thermal actuators were strategically positioned for the palm. One was placed at the center of the palm's lower edge to avoid interference with virtual object manipulation. Another thermal actuator was positioned at the center of the dorsal side of the hand for the same reason.

Vibrotactile Actuator Placement. Nine vibrotactile actuators were arranged in a 3×3 array on the palm (see Figure 3 (b)). This design could cover the whole palm surface and also maintain a high number of combinations in thermal pattern rendering. The array was anchored by the metacarpophalangeal joints (MCP joints) of the index and ring fingers, representing the top left and right corners of the array, respectively. The remaining seven points of the array were equally distributed along lines parallel to the lower edge of the palm, maintaining symmetry and equal spacing within the array. For each participant, the placement is adjusted based on their hand size.

Thermal-Tactile Integration. Similar to the fingers, we activated the tactile actuator simultaneously with one of the thermal actuators (either at the center of the palm's lower edge or the center of the dorsal side of the hand, depending on the experiment condition) to induce a thermal illusion at the tactile location. The same configuration was maintained for both thermal and tactile actuators as used for the fingers.

Experimental Conditions. The experimental design employed a single-factor approach focusing on the placement of thermal actuators with two levels: either at the center of the palm's lower edge or the center of the dorsal side of the hand. This design allowed for a comparison between these two placements to determine the optimal thermal placement. A total of 72 trials were conducted, involving 9 locations for the vibrotactile actuators, each repeated 4 times across the two thermal actuator locations (9 vibrotactile actuator locations × 2 thermal actuator locations × 4 repetitions).

4.4 Procedure

Participants were seated at a table and instructed to carefully read the provided instructions before signing a consent form. To prevent any biases, participants were not informed about thermal referral information. The skin temperature of the hand was then measured using a thermal camera (Optris PI450). Following this, the experimenter assisted participants in attaching straps with thermal and vibrotactile actuators to their non-dominant hands and positioning their hands comfortably on the table. In each trial, thermal and vibrotactile stimuli were simultaneously activated for 5 seconds.

An audio cue marked the end of the trial, followed by a question displayed on a tablet screen, asking if participants felt thermal sensations on their fingers. If participants responded 'yes,' they were then prompted to freely draw the perceived thermal area on an image of a hand displayed on the tablet screen using a stylus pen. Each trial time was set to 30s to ensure the participant's skin temperature reached to a steady state after the trial. A two-minute break was given after every 24 trials, and the entire study took approximately 60 minutes to complete.

4.5 Results and Discussion

For the finger conditions, the occurrence rate of perceived thermal sensations at the tactile location was notably high, regardless of whether the thermal actuator was placed on the dorsal or ventral side, exceeding 80% for each side (refer to Figure 4). For each finger, the results between two phalanges showed no statistical difference and were aggregated by the mean occurrence rate. This finding suggests that generating localized thermal sensations on the ventral side is feasible by positioning the thermal actuator on the dorsal side of the finger.

The thermal distribution perceived on the finger with the thermal actuator placed at the ventral (denoted as V) and dorsal (denoted as D) sides, as illustrated in Figure 6 (Row 1 and 2), aligns with the position of the vibrotactile actuator, indicating the potential for achieving localized thermal sensations. Interestingly, the distribution pattern on each finger position, whether on the ventral or dorsal side, was quite similar, implying the effective thermal perception can be achieved regardless of the thermal actuator's placement. The larger area depicted in the heatmap compared to the size of the vibrotactile actuators may be attributed to the skin's low thermal resolution [21]. It could also be due to the vibrations spreading out, where the thermal and tactile integration creates a wider perceived thermal distribution around the actuator. Statistical analysis using two-way repeated measures (RM) revealed no significant difference in thermal actuator location across different fingers.

In contrast, the palm conditions exhibited a substantial discrepancy in the occurrence rate of thermal referral between the dorsal (46.5%) and ventral (92.4%) sides (see Figure 4). This discrepancy indicates that while localized thermal sensation can be achieved on the ventral side, placing the thermal actuator on the dorsal side may not effectively generate thermal sensations on the palm.

Interestingly, as shown in Figure 5 (Rows 3 and 4), there was a significant difference in thermal referral occurrence rates on the dorsal side between male (19.5%) and female (73.5%) participants. This difference may be influenced by the smaller palm size of female participants, leading to a reduced spatial summation effect for thermal sensation compared to male participants [20]. Additionally, the higher thermal sensitivity of females may contribute to a greater likelihood of perceiving subtle thermal sensations [5].

Statistical analysis using two-way repeated measures ANOVA revealed significant results for gender and thermal locations under palm sections ($F(1,63) = 28,271, p < 0.01$ for gender and $F(8,63) = 40.873$, $p < 0.01$ for thermal locations). These results support the feasibility of generating thermal sensations on the palm's ventral side across all genders. The larger distribution area of thermal sensation on the palm, as observed in Figure 6, can be attributed to spatial summation effects, redistributing thermal sensations over a broader area [10, 20]. However, the uneven thermal redistribution between the thermal actuator and the vibrotactile actuator may result in variations in perceived thermal sensations.

5 USER STUDY 2: THERMAL PATTERNS

The aim of this user study is to investigate how various thermal patterns are perceived on the hand's ventral side when activated by multiple vibrotactile actuators, utilizing the optimal placement of thermal and vibrotactile actuators identified in user study 1. Our focus is primarily on understanding the formation and perception of different thermal patterns to efficiently reproduce thermal sensations with virtual objects. A total of 52 distinct thermal patterns were examined on the fingers and palm of the hand.

5.1 Participants

Sixteen participants (8 females, mean age 24.4, SD = 2.03) who did not participate in the first user study were recruited in this study. We followed the same recruitment and screening procedure as in the previous user study. All participants were right-handed, and they were compensated with a $15 gift card for the approximately 90-minute experiment.

5.2 Experimental Design

We made the following changes in the experiment setup and conditions from user study 1.

Thermal Actuator Placement. Five thermal actuators were strategically positioned on the dorsal side of the fingers: one at the center of the proximal phalanx for the thumb and one each at the center of the middle phalanges for the remaining four fingers. Additionally, a larger thermal actuator was placed at the center of the palm's lower edge to ensure it did not obstruct virtual object manipulation. These placements were determined based on the findings of user study 1.

Vibrotactile Actuator Placement. Fourteen vibrotactile actuators were positioned on the ventral side of the finger, each centered on a finger phalanx. Additionally, a 3×3 array of nine vibrotactile actuators was placed on the palm (consistent with user study 1), yielding a total of 23 vibrotactile actuators covering the hand's ventral side effectively. The arrangement of vibrotactile actuators was also validated using insights from user study 1.

Thermal-Tactile Integration. The integration of thermal and tactile stimuli remained unchanged from the previous user study. Vibrotactile actuators for the fingers were synchronized with corresponding thermal actuators within each finger, while vibrotactile actuators for the palm were activated alongside the thermal actuator at the center of the palm's lower edge.

Experimental Conditions. A total of 52 thermal-tactile patterns were evaluated, as shown in Figures 7 and 8. These patterns encompassed various interaction areas, aiming to examine perceived thermal regions under different thermal-tactile integrations to determine the effective regions of each pattern. Each pattern required simultaneous activation of corresponding actuators. For example, the top-left pattern in Figure 8 required activation of the

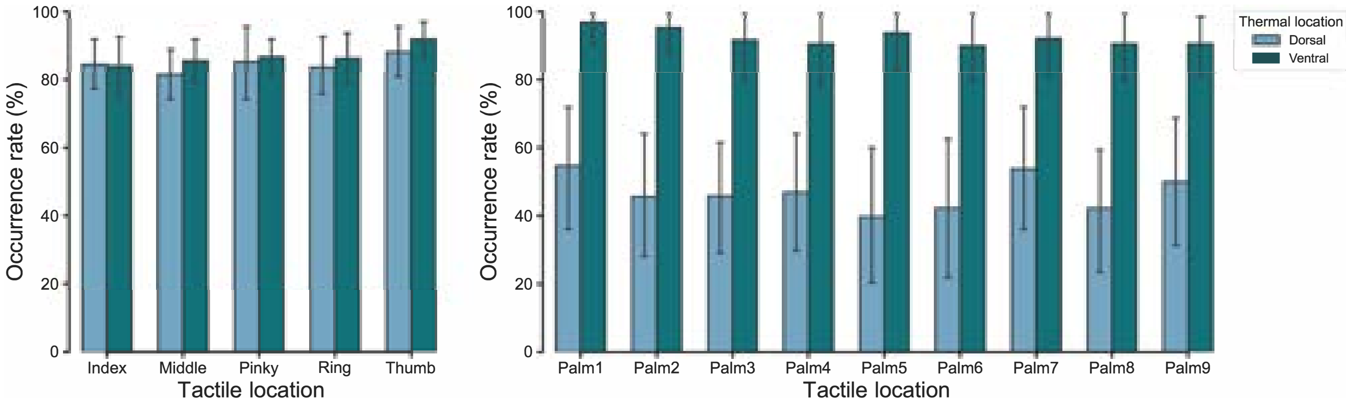

Figure 4: Occurrence rate of perceived thermal sensation on the fingers (left) and palm (right).

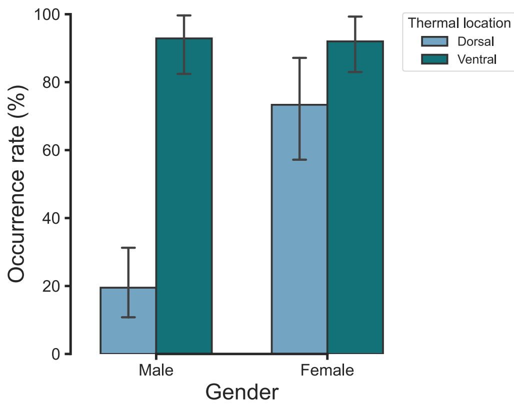

Figure 5: Occurrence rate of perceived thermal sensation on the palm (gender effect).

thermal actuator and the top three tactile actuators on the palm.) The experiment consisted of 156 trials (52 thermal-tactile patterns $\times$ 3 repetitions).

5.3 Procedure

Similar to user study 1, participants were instructed to report if they experienced thermal sensations in the tactile locations and to draw the perceived thermal area on a hand image displayed on the tabletop screen using a stylus pen. The rest of the procedure was the same as user study 1. The entire study took approximately 90 minutes to complete.

5.4 Results and Discussion

Figures 7 and 8 illustrate the perceived distribution of thermal sensations for each pattern, with purple dots highlighting the activated vibrotactile actuators. From top to bottom, they are labeled as Row 1 to Row 4 for better understanding. The concentration of thermal sensation distribution on the fingers appears to be more focused compared to that on the palm.

5.4.1 Fingers. Examining the perceived thermal patterns in Figure 7, it's clear that the distribution closely aligns with the activated vibrotactile patterns, indicating the perception of thermal patterns on the fingers.

Row 1. Notably, the distribution for the simple pattern (Row 1) maintains a high concentration, albeit relatively more dispersed compared to other positions on each finger and even across different sections of the thumb (compare Figure 7 Row 1 Column 1 with Figure 6 Row 1 Column 2). This dispersion could be attributed to spatial summation, where the middle phalanx disperses the thermal distribution in multiple directions, unlike the distal and proximal phalanges that spread in one direction only. The variability in the thumb's distal phalanx could stem from participants' tendencies to draw larger areas within the pattern stimuli.

Row 2. In more complex patterns involving two activated vibrotactile actuators per finger, the perceived thermal distribution tended to center around the middle phalanx, possibly due to phantom tactile sensations creating an illusory vibrating stimulus between two vibrotactile stimuli [2, 41]. Additionally, the placement of the Peltier device in the middle and the evenly distributed tactile noise might impact the perceived thermal location.

Row 3. For patterns involving three vibrotactile actuators (Row 3), a similar centralized distribution effect was observed, particularly on fingers other than the thumb. In Columns 2, 3, and 4, the perceived thermal sensation clustered more at the middle phalanx compared to patterns in Row 2. This indicates that middle phalanx placement enhances localized thermal perception while skewing the overall thermal distribution.

Row 4. The full-finger patterns cover each finger with varying numbers of tactile actuators. For fingers other than the thumb, these patterns show more concentration at the middle phalanx compared to the single-finger patterns in Rows 1, 2, and 3. Patterns involving only one vibrotactile actuator activated at the thumb (Row 4 Columns 1, 2, and 3) exhibit perceptual clustering around the vibrotactile positions.

5.4.2 Palm. In the thermal patterns for the palm (Figure 8), the perceived thermal sensation distribution covers the activated vibrotactile actuator positions but exhibits dispersion across a wider range of area.

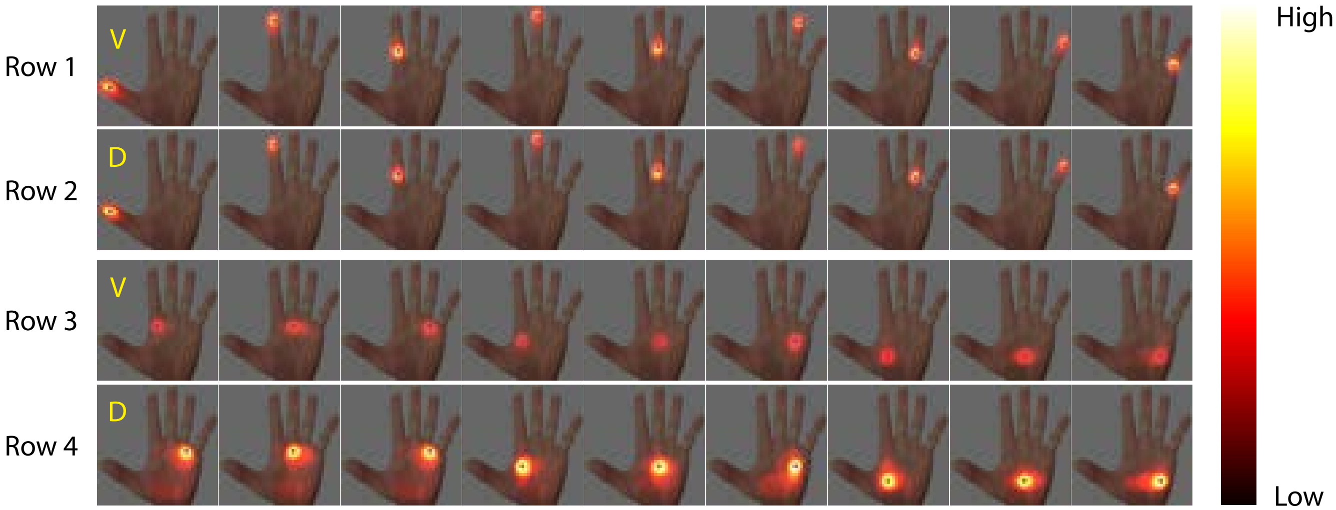

Figure 6: Perceived thermal distribution on the finger (Row 1 and 2) and palm sections (Row 3 and 4). From top to bottom row: ventral side of finger section, dorsal side of finger section, ventral side of palm section, and dorsal side of palm section. V and D denote the thermal actuator placed on the ventral and dorsal sides, respectively. The purple dot denotes the tactile actuator location. The brighter region in the figure indicates a higher occurrence rate of perceived thermal sensation.

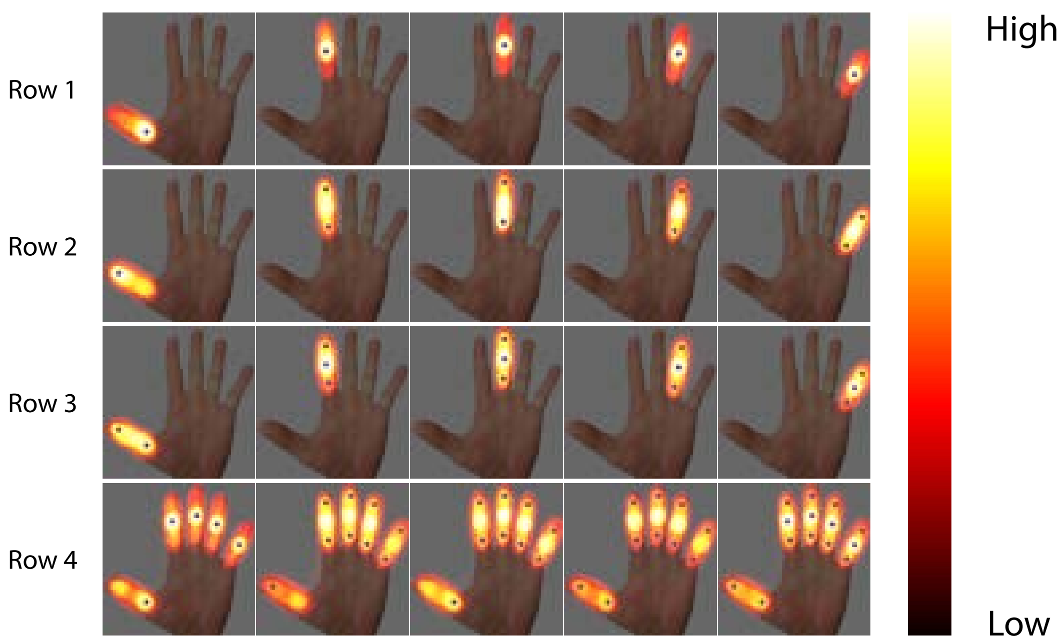

Figure 7: Perceived thermal distribution on the finger. The complexity of the pattern gradually increased from the top (Row 1) to the bottom (Row 4). The purple dot denotes the tactile actuator location. The brighter region in the figure indicates a higher occurrence rate of perceived thermal sensation.

Row 1. Less complex patterns (e.g., Row 1 patterns with three vibrotactile actuators) demonstrated a more accurate thermal distribution when closer to the thermal actuator. For instance, Row 1 Column 3 showed a close match between the thermal and vibrotactile patterns, whereas Row 1 column 1 exhibited significant dispersion. This discrepancy suggests that thermal sensations perceived on the palm have relatively lower resolution when vibrotactile patterns are activated farther from the thermal actuator, aligning with spatial summation principles that redistribute sensations over larger areas [10, 20].

Row 2. Similarly, in more complex patterns, the proximity effect was evident, with closer vibrotactile patterns to the thermal actuator resulting in better matches in perceived thermal sensations. Additionally, the perceived thermal sensation at locations without tactile actuators indicates spatial summation under complex patterns (e.g., Row 2 Columns 3, 4, 5).

Row 3. It's interesting to see that when the complexity of the pattern is further extended, a full-hand thermal perception appears. It could be due to the increased number of vibrotactile actuators covering a relatively larger area that the thermal redistributed among that region and formed a sense of full-hand thermal perception.

Row 4. Combination patterns (Row 4) showed a high match between perceived thermal sensations and activated vibrotactile areas, with the perception of areas with more vibrotactile actuators being more uniform and resulting in a larger perceived area. Interestingly, patterns with fewer activated vibrotactile actuators within this category (e.g., patterns Row 4 Columns 1, 2, 3 and columns 4, 5, 6, 7, 8) exhibited similar perceived thermal sensations, suggesting that full-hand thermal sensation rendering could be achieved with patterns involving fewer activated vibrotactile actuators.

6 FIERY HANDS

We present Fiery Hands, a pair of wearable gloves strategically equipped with thermal and tactile actuators to create localized thermal illusions through thermal and tactile integration (see Figure 9). Our extensive exploration into the development of these gloves involved intricate design and implementation strategies aimed at reducing obstruction on the palm and inner sides of the fingers for virtual object manipulation. Fiery Hands leverages insights from our prior user studies, delivering various thermal effects that dynamically vary in both spatial and temporal dimensions within its thermal and tactile integration.

6.1 Glove Design

Actuator Placement and Design. To create a wearable glove, we integrated the same thermal and tactile actuator configuration as in user study 2, covering the entire hand with thermal sensations. We selected an off-the-shelf leather glove (HydraHyde, R3267M) for comfort and stability during hand tracking. The actuators were embedded into the glove, with the driving module and controller housed in a 3D-printed box on the forearm to minimize wire interference.

Precise actuator placement was determined based on data from previous user studies, using mean values for optimal usability. We drilled twenty-three 6mm holes on the glove's inner side for the vibrotactile actuators. Each vibrotactile actuator was housed in a 10mm diameter 3D-printed cylinder, varying in height based on placement: 5mm for the finger phalanx and palm-side columns and 10mm for the palm's center column. The housings were inserted from the palm side to maintain a smooth exterior and glued to the glove's surface for stability. Velcro straps were employed to secure the finger actuators, allowing for flexible positioning to accommodate different finger sizes. Thermal actuators were strategically positioned to conform to finger curves and were also fastened with straps. Wiring was managed along the glove's inner edge to avoid any interference.

On the palm, tactile actuators were attached to 3D-printed cylinders, while the thermal actuator was affixed to a cuboid at the palm's center. A 50mm cut on the glove allowed a wire connection for the pinky finger's vibrotactile actuator.

Circuit Design. Actuator control utilized N-channel MOSFETs, with each actuator connected to a MOSFET. A total of fifty-eight MOSFETs (forty-six for vibrotactile and twelve for thermal actuators) were used for both hands, managed by an Arduino MEGA microcontroller. Separate power sources were employed for thermal and vibrotactile actuators.

6.2 Sensation Rendering

The glove enables thermo-tactile perception by combining thermal and vibrational stimuli, facilitating localized and pattern-based rendering. The sensation rendering technique was developed based on insights from previous user studies. Localized thermal feedback follows a precise mapping of the corresponding actuators. For the finger pattern, tactile actuators were activated at the distal and proximal phalanges, adequately covering the target area (see Figure 7). For the palm pattern, three or four actuators were used to partially cover the palm area. For full-hand rendering, the center actuator was activated along with randomly selected peripheral actuators (see Figure 8).

Localized rendering involves real-time stimulation of corresponding actuators on each finger phalanx and nine designated palm locations marked by the array of vibrotactile actuators, alongside corresponding thermal actuators on fingers and palm. This approach creates a continuous, seamless localized thermal cue across the hand. In contrast, pattern rendering synthesizes intricate interactions using localized rendering principles, replicating real-world experiences and imaginative scenarios with diverse shapes and random stimulation sequences.

To implement this rendering technique in a VR environment, we developed a series of sphere colliders corresponding to the vibrotactile actuator locations on a virtual hand model in Unity3D, mimicking the arrangement on the thermal glove. Interacting with a virtual object triggers the relevant collider, configured as spheres matching each finger's phalanx diameter and cuboids reflecting the segmented sizes of the 3×3 array on the palm. In our software framework, collision detection for all vibrotactile actuator colliders forms the foundational layer for rendering. The virtual object's attributes determine the rendering strategy, choosing between localized rendering and pattern-based rendering. The real-time status of all vibrotactile positions is conveyed through a quest link cable, ensuring users receive immediate tactile feedback consistent with the virtual environment.

6.3 VR Setup

Our VR setup utilizes a Quest 3 headset and Unity3D for running VR applications. We employed vision-based hand-tracking from the Quest 3 platform to accurately track glove movements within the VR environment. We implemented two distinct scenes to explore the capabilities of Fiery Hands and how users interact with virtual thermal objects while wearing the gloves. A pinch gesture

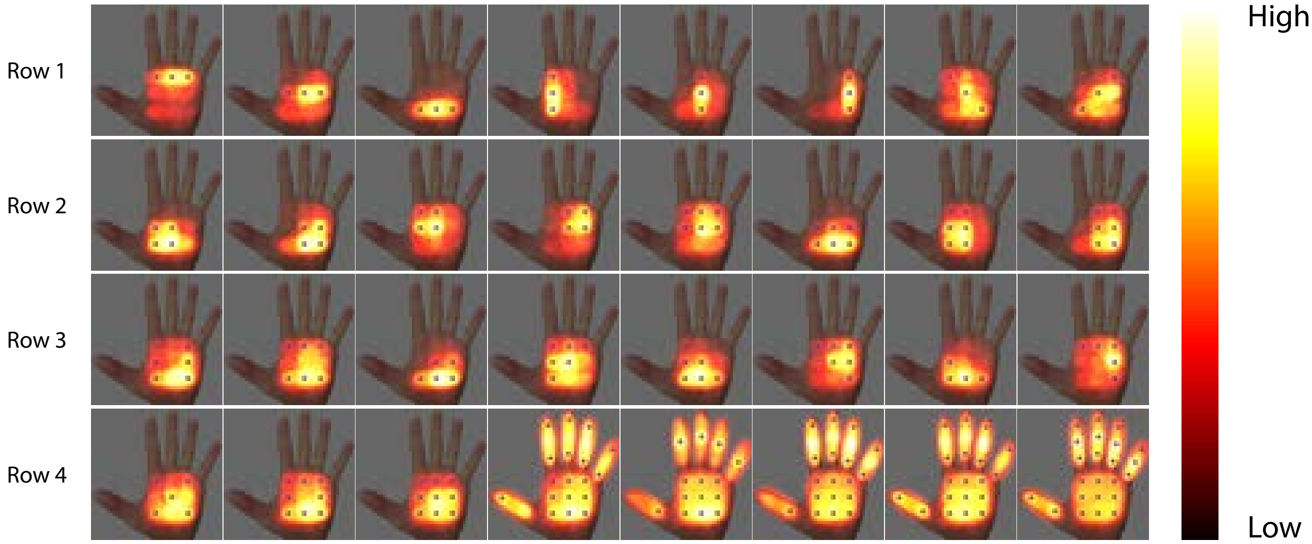

Figure 8: Perceived thermal distribution on the palm. The complexity of the pattern gradually increased from the top (Row 1) to the bottom (Row 4). The purple dot denotes the tactile actuator location. The brighter region in the figure indicates a higher occurrence rate of perceived thermal sensation.

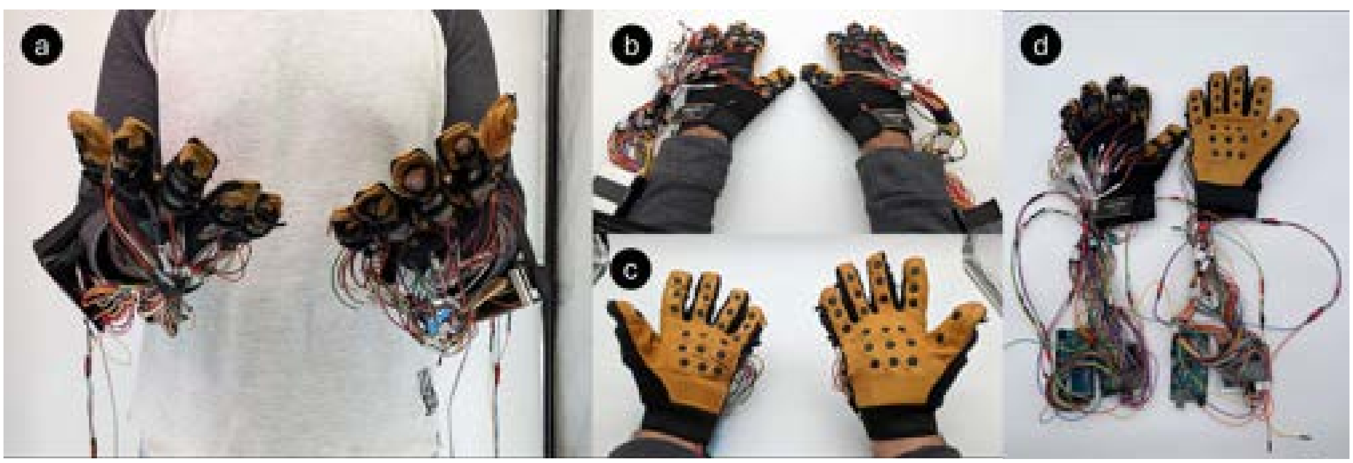

Figure 9: Fiery Hands. (a)A user wearing the thermal glove, (b) the dorsal side of the glove, (c) the ventral side of the glove, and (d) the full system setup with the circuit board and microcontroller.

calibration was required when entering the scene to re-center the participant at the correct position.

Magic Fireball. This scene was designed to assess the rendering of patterned thermal sensations with virtual object manipulation. Upon entering the virtual scene, users experience a magic fireball initiated at the center of their palms. Users can adjust the fireball's size by pulling or stretching their fingers while wearing gloves that simulate the hot sensation of the fireball. Once holding a fireball, the participants will be presented with vibrotactile stimulus at the center and a thermal stimulus at the lower center of the palm. Randomized spatial patterns would be rendered on the participants' hands every 2s within the contact area between their hands and the fireball. They can also transfer the fireball to the other hand by bringing both hands closer and continuing to resize it, enhancing the fun and immersive experience.

Water Faucet. This scene was specifically designed to showcase the advantages of rendering localized thermal sensations. It replicates a bathroom scenario with a hot water basin, visually enhanced with steam to indicate the water's temperature. Upon entering the virtual environment, users discover their hands covered in ink stains. They can then use the virtual faucet's flushing water to wash away these ink stains. When the user's hand touches the water stream, the collision area will be rendered with a constant vibrotactile sensation at the nearest vibrotactile actuator location

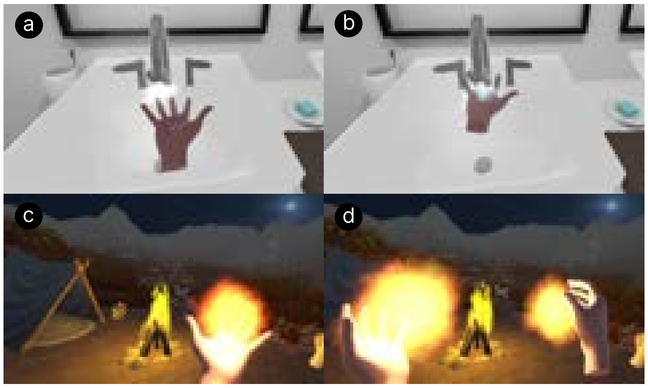

Figure 10: Interaction with VR Scenes. Water Faucet: (a) Cleaning finger, (b) cleaning palm. Magic Fireball: (c) Respawn on one hand, (d) respawn on two hands.

along the corresponding thermal sensation. Also, a visual splash would be presented on the collision position. In that case, the localized thermal sensation was presented to the finger, and localized or clustered thermal sensation was presented to the palm. The thermal actuators were activated to increase the surface temperature by 3°C above the user's skin temperature. The tactile actuators were stimulated at 2.5V to deliver a stimulus of 5.7mN and 166Hz.

7 USER STUDY 3: VR APPLICATIONS

We tested our Fiery Hands in VR applications to assess the impact of thermal and tactile sensations during interactions with virtual thermal objects. Our goal was to evaluate how this approach influences the user experience in immersive virtual environments.

7.1 Study Design

Participants. Ten new participants (4 females, mean age 23.6, SD = 2.61) were recruited for this study. They followed the same recruitment process as previous user studies and were compensated with a $10 gift card. We also audio-recorded the study proceedings with their consent.

Apparatus. Participants wore a pair of Fiery Hands gloves and a Quest 3 headset with a Quest link cable connected to the PC. Two power supplies were used to power the actuators.

Tasks. Participants were engaged in two VR scenes: the magic fireball and the water faucet, completing tasks within each scene (see Figure 10). The task in *Water Faucet* scene was to wash the ink stains using flushing water from the water faucet. The task in *Magic Fireball* scene was to initiate the fireball by pinch gesture, control the size of the fireball by stretching or grasping hands, and pass the fireball to another hand by touching two hands together. The order of scene presentation was randomized and balanced.

User Interview. After each scene, participants were interviewed to gather their feedback and insights regarding their experience. The interview format was semi-structured and open-ended, with prepared questions focusing on comparing their virtual experiences to real-life, their interaction experiences, enjoyment, engagement, and other related aspects. The questions were intentionally open-ended to encourage detailed responses.

Procedure. Participants were given detailed instructions about the experiment, including hand measurements and signing consent forms. The experimenter then helped them wear the headset and thermal glove tightly, ensuring optimal hand-tracking performance by facing their hands toward the headset's field of view. Each participant experienced two VR scenes in a counterbalanced order, completing tasks specific to each scene. After completing all tasks, the experimenter assisted participants in removing the equipment for an interview. The interview began with a common question about the virtual object's sensation. Additional questions were tailored to each scene, such as comparing the VR experience to real-life interactions and describing specific sensations. General questions about immersion, comfort, responsiveness, and overall experience were also asked. The study lasted around one hour, including reception, calibration, and interview.

7.2 Interview Insights

Overall, participants were highly enthusiastic about both VR scenes, praising the immersive and realistic experiences they encountered. Notably, not a single participant reported any discomfort with the thermo-tactile feedback from the Fiery Hands gloves. They enjoyed interacting with virtual thermal objects and appreciated the rich and clear sensory experiences that complemented their visual experiences.

Distinct Thermal Sensations and Illusions. All participants reported that they were able to feel different types of thermal sensations in both the water faucet and fireball scenes. In the fireball scene, participants distinguished the spawning sensation of the fireball and the transfer of heat as they moved the fireball between their hands. P2 remarked, "When the fireball spawned, I felt the heat spreading from my palm to my fingers," while P7 noted, "When I transferred the fireball, the heat traveled from one palm to the other." These varying thermal renderings contributed to a more convincing and immersive experience for participants while engaging with the fireball.

In the water faucet scenario, participants perceived thermo-tactile feedback targeted to specific areas based on their spatial interactions with the faucet. P3 remarked, *"I could discern strong vibrations accompanied by heat precisely where the water made contact with my hand."* Similarly, P5 noted that while the water faucet's heat was *"less intense compared to a fireball, the vibrations were more pronounced"*, closely resembling the sensation of a water stream. This nuanced rendering of thermo-tactile feedback enriched user interactions in both scenes.

Interestingly, three participants also experienced the illusion of wetness on their hands. Participants experienced wetness only on their fingers while interacting with water P1 stated, *"I felt some moisture on my fingers while washing my hands."* and P5 highlighted, *"I don't know how it is possible, but I feel like my fingers are wet."* Participants also highlighted as they moved closer to the faucet, they felt the illusion of increasing intensity, just like a real-life faucet. P4 emphasized, *"I felt more intense water pressure when I moved closer to the faucet".* The illusion of wetness with the water faucet could be due to the combined visual, thermal, and pressure feedback [17], which wasn't reported in the fire scene, highlighting the unique interplay of these cues in creating sensory illusions.

Virtual Object Manipulation. Participants were delighted and pleasantly surprised by their ability to control the fireball's size and transfer it between hands, all while experiencing the thermo-tactile feedback. P6 remarked, *"When I transferred the fireball, I could feel the heat moving from one hand to the other, which was surprisingly realistic,"* while P9 observed, *"As I decreased the size of the fireball, the area of heat also changed."* These subtle variations in feedback contributed to participants' sense of immersion and realism. Participants highlighted how the intensity of heat concentrated on their fingers increased when they curled them up while holding the fireball, contributing to a heightened sense of agency in their interaction with the virtual fireball. P10 remarked, *"I noticed a surge in heat on my fingers when I curled them up,"* while P4 observed, *"The sensation of heat on my hands varied while manipulating the fireball."* Participants attributed these convincing feelings to the precise alignment of thermo-tactile feedback with visual cues, resulting in a more engaging interaction with the virtual objects. P8 mentioned, *"Controlling the fireball felt even more convincing, as both the visuals and the heat sensations complemented each other."* This shows that the combination of multimodal interactions significantly heightened user engagement and agency.

Localized vs. Global Thermal Feedback. All participants appreciated how the thermo-tactile feedback varied depending on the specific area of interaction on the hand and the spatial positioning of the hand itself. They reported experiencing convincing illusions due to the accurate localized thermal feedback, with P10 stating, *"I tried cleaning just the tips of my fingers, and I could immediately feel the heat in that specific area."* P8 also noted that *"As I switched hands, I immediately sensed the transfer of heat corresponding to the point of contact with the water."* These experiences vividly demonstrate that precise localized thermal feedback provided by the gloves significantly enhanced the overall user experience.

Participants also lauded the global thermal feedback experienced during the magic fireball scene. They praised the distinct sensation of the fireball surrounding their hand, offering feedback in a larger area. Participants were impressed by the seamless synchronization between thermal-tactile sensations and visual cues all over their hands. P8 emphasized, *"I could sense the heat spreading from my fingers to my palm,"* as the fireball increased in size. P9 stated, *"Feeling the heat and subtle vibrations on both hands truly felt like touching fireballs."* This highlights the Fiery Hands gloves' ability to provide both localized and global thermo-tactile feedback to participants.

Comparison with Real-Life. In the water faucet scene, participants found it straightforward to draw parallels with real-life situations. They were pleased with the responsiveness of the thermal feedback, observing how it dynamically adjusted as they cleaned different parts of their hands. P9 commented, *"When I switched hands, the feedback was immediate—I could feel the hot water on my other hand right away,"* while Participant 2 mentioned, *"While washing my fingers, I could distinctly sense the water on each finger, just like using a real faucet."* P5 also expressed surprise at how closely the sensation of water resembled real-life experiences.

Conversely, in the fireball scene, where a direct comparison to reality was not feasible, 8 participants reported feeling a sense of wielding magical powers. P6 conveyed this feeling by saying, *"I felt like a sorcerer while controlling the fire."* The ability to manipulate the size of the fireball and transfer it between hands, along with the thermo-tactile feedback, seems to contribute to an immersive fantasy experience for users.

Immersion and Realism. Participants consistently reported a high level of realism and immersion in both scenes. Seven out of ten users expressed surprise at the lifelike sensations they experienced while interacting with the water faucet and magic fireball scenes. For example, P9 remarked, *When the fireball spawned on my hand, the sensation of heat spreading across my hands was unbelievable,"* while P10 mentioned, *"I lost track of time while interacting with the fireballs."* In the water faucet scene, P4 emphasized, *"I genuinely felt like I was touching water through the gloves; it was difficult to convince myself it was virtual."* Similarly, P1 stated, *"I could feel the pressure changes of water on my palm and fingers as I moved my hand."* These convincing illusions clearly demonstrate the high degree of realism experienced by users, indicating complete immersion in both VR scenes.

Enjoyment. Based on the participants' feedback provided, they thoroughly enjoyed both the fireball and water faucet scenes in VR. They appreciated the immersive nature of the experiences, particularly when the thermo-tactile feedback closely synchronized with their visual perceptions. In the fireball scene, users expressed satisfaction with the sensation of warmth and vibrations while interacting with the fireball. P7 stated, *"I could play with those fireballs all day; it was fun to transfer them from one hand to another and feel the heat transfer at the same time."* In the water faucet scene, users were also delighted, with 6 out of 10 participants washing their hands multiple times due to sheer enjoyment. P2 mentioned, *"It was satisfying to wash individual fingers and feel the water feedback"*. Overall, participants found both VR scenes engaging and fun, highlighting the potential of VR technology to provide captivating sensory experiences.

Comfort. No participant experienced or reported any sort of discomfort or difficulty while interacting with the VR scene using the gloves. They liked the form factor of the gloves, which enabled them to interact with virtual objects without feeling restricted. Additionally, participants unanimously agreed that both scenes provided a comfortable experience while providing different thermal sensations. For instance, in the fire scene, P5 noted, *"The temperature accurately represented the sensation of a fireball, providing users with a comfortable experience."* This allowed participants to engage with the scene for extended periods without fatigue. Similarly, in the water faucet scene, P3 remarked, *"I have never felt so comfortable while washing my hands,"* while P7 described the experience as therapeutic. Participants found the combination of heat and tactile feedback to be particularly soothing and relaxing.

Applications. Participants offered insightful suggestions for the potential applications of haptic and thermal gloves across diverse fields. They highlighted the capacity for immersive gaming experiences, where the gloves could replicate interactions with fire, water, and ice, intensifying realism and engagement. For example, P3 mentioned, *"When you go down the temperature changes, so you can make that feeling like different along the different height of the lake."* Moreover, participants emphasized applications in physical therapy, envisioning the gloves aiding patients in re-establishing their sense of touch through simulated textures and sensations. As P6 said, *"I could definitely see this being in something like touch therapy or such like that where patients have to learn how to, you know, regain their touch after an incident or a condition."* These insights underscored the adaptability of haptic technology, transcending entertainment to facilitate therapeutic interventions and innovative gaming encounters. Additionally, participants envisaged applications in education and training, proposing simulations for safety training in chemistry experiments, environmental science exploration, and healthcare scenarios. For instance, P10 highlighted *"Interacting with like, chemical experience experiments instead of like actually doing it for the cause of like danger."* This feedback illustrates the vast potential of haptic technology to revolutionize gaming, therapy, education, and training, positioning it as a valuable tool with multifaceted applications.

8 DISCUSSIONS

We presented Fiery Hands, a novel thermo-tactile gloves that utilize the integration of thermal and tactile actuators to render various thermal sensations to the palm and fingers. We showed that our approach to adopting thermal-tactile integration can effectively address significant challenges in designing thermal gloves for immersive VR environments. We also demonstrated that Fiery Hands can deliver enhanced VR experiences with localized and global thermal feedback for interacting with virtual objects, demonstrating the interfaces' ability to produce diverse thermal patterns.

Our strategy of strategically placing thermal actuators to provide localized thermal feedback through integration with vibrotactile actuators is simple yet powerful, addressing numerous design challenges. By using multiple tiny vibrotactile actuators as perceptual heat sources, we achieved precise delivery of localized and global thermal sensations while minimizing interference with hand movement obstruction and improving HMD-based hand tracking accuracy, all without requiring a complex engineering setup.

Fiery Hands also excelled in rendering various thermal patterns, including intricate localized patterns and spatio-temporal sensations. Participants appreciated the distinct thermal sensations, such as feeling a fireball or a hot water stream, enhancing their overall engagement and immersion. They particularly enjoyed the realistic feedback of hot water splashing over their fingers and palms, as well as the seamless synchronization of spatiotemporal thermal rendering simulating a fireball over their hands. This highlighted the significant impact of integrating thermal and vibrotactile technologies in our approach.

We have also identified some challenges and limitations with Fiery Hands. One issue is that the current glove design impedes the ability to make a complete fist, restricting user interaction with virtual objects due to limited hand tracking. This limitation is primarily due to the tension force from the wires, which doesn't hinder single-finger movement but blocks full-fingered fists. To address this, we propose optimizing wire placement by adding an extra layer inside the glove. This adjustment would enable a smoother wire connection and eliminate tension forces for users. Additionally, using a robust yet thinner wire can help minimize space constraints.

Another limitation that we found was rendering resolution. When applying complex vibrotactile patterns to the palm, the upper side of the palm struggles to effectively perceive thermal sensations, resulting in the dispersed perception of the area. This issue may be attributed to the low thermal resolution and the redistribution characteristic of thermal referral [20, 21]. Additionally, the impact of phantom tactile sensation should be considered, as it may distort the perceived thermal area [2]. Further investigation into the spatial effects of thermal referral is necessary to gain a comprehensive understanding of this mechanism and enable precise spatial pattern control implementation.

We plan to further explore thermal referral to achieve thermal rendering across a broader temperature range. Our preliminary study indicated that cold feedback can also be induced in the proposed interface, although it is less prominent compared to hot feedback. We plan to further explore vibration-induced thermal referral illusion with cold temperatures and how it could be integrated into gloves and other user interfaces.

In addition to expanding the temperature range, we aim to investigate the spatial effect range of thermal referral and reduce the number of thermal actuators. For instance, placing thermal actuators only on the thumb, middle, and pinky fingers might be sufficient to cover thermal sensations across all fingers. Factors such as pose and body parts are also of interest for future exploration.

Moreover, we plan to examine the impact of vibrotactile cue intensity and frequency on thermal sensation rendering to enhance user experiences. Investigating spatial-temporal moving patterns could further improve the realism and effectiveness of our thermo-tactile feedback system in VR applications. Exploring multimodal aspects, such as wetness, texture, and temperature variations, and integrating them with other multisensory feedback, holds promising potential for creating immersive and realistic sensory experiences.

9 CONCLUSION

In this paper, we presented Fiery Hands, a pair of novel thermal gloves designed to provide localized and thermal feedback while minimizing bulk and complexity, enhancing immersion and interaction in VR environments. Fiery Hands showed a promising solution to tackle challenges in thermal glove design by strategically combining thermal and vibrotactile actuators, minimizing interference with virtual object interactions. We demonstrated the optimal placements of thermal and vibrotactile actuators and confirmed their ranges and capabilities, creating various thermal patterns with localized and global feedback.

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