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RESEARCH-ARTICLE

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Thermal In Motion: Designing Thermal Flow Illusions with Tactile and Thermal Interaction

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Figure 1: The illustration shows thermal motion. Precise activation of tactile actuators induces tactile motion, and simultaneous activation of the thermal actuator creates the perception of moving thermal cues.

ABSTRACT

This study presents a novel method for creating moving thermal sensations by integrating the thermal referral illusion with tactile motion. Conducted through three experiments on human forearms, the first experiment examined the impact of temperature and thermal actuator placement on perceived thermal motion, finding the clearest perception with a centrally positioned actuator under both hot and cold conditions. The second experiment identified the speed thresholds of perceived thermal motion, revealing a wider detectable range in hot conditions (1.8 cm/s to 9.5cm/s) compared to cold conditions (2.4cm/s to 5.0cm/s). Finally, we integrated our approach into virtual reality (VR) to assess its feasibility through two interaction scenarios. Our results shed light on the comprehension of thermal perception and its integration with tactile cues, promising significant advancements in incorporating thermal motion into diverse thermal interfaces for immersive VR experiences.

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CCS CONCEPTS

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

KEYWORDS

Thermal Motion, Thermal Feedback, Haptics, VR, Thermal Referral, Thermal Masking, Vibration-induced Thermal Illusions

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1 INTRODUCTION

The integration of thermal feedback in VR environments represents an emerging frontier in the field of sensory simulation. While visual and auditory feedback has long been established in VR systems, the inclusion of thermal sensations has gained increasing attention in recent years. Thermal feedback has the potential to add a new dimension of immersion and realism to VR experiences, enhancing the user's sense of presence and engagement. By simulating temperature changes and thermal stimuli, VR applications can provide users with a more comprehensive and multisensory experience, allowing them to interact with virtual environments more naturally and intuitively. As VR technology continues to advance, the exploration and development of thermal feedback systems hold promise for expanding the boundaries of immersive virtual experiences.

While thermal feedback in VR has the potential to significantly increase realism and enhance user immersion, current thermal interfaces face significant limitations in presenting thermal feedback effectively. One major challenge is the difficulty in achieving localized thermal feedback, meaning that users cannot feel specific thermal sensations in particular areas of their hands or bodies. Additionally, existing interfaces lack the capability to provide dynamic patterns or animations of thermal sensations, which are crucial for creating more engaging and realistic experiences in VR. As people demand more dynamic and richer multisensory experiences in virtual environments, the inability to deliver diverse and interactive thermal feedback hinders the full potential of thermal interfaces in enhancing VR realism. These challenges highlight the need for innovative solutions that can overcome the limitations of current thermal interfaces and provide users with more nuanced and immersive thermal experiences in VR.

We introduce thermal motion, which creates a compelling illusion of flowing thermal sensations by integrating thermal and a series of tactile actuators (Figure 1). This innovative technique continuously generates dynamic thermal referral illusions across multiple tactile points, resulting in the perception of moving thermal cues. By strategically activating thermal and tactile actuators near each other on the skin, we can create a strong thermal illusion at specific tactile actuator locations, leading to a more nuanced and immersive experience for users. We believe that this advancement not only overcomes current limitations in thermal feedback in VR but also unlocks new possibilities for creating more engaging and meaningful interactions within virtual environments.

Our approach offers several noteworthy advantages. Firstly, by capitalizing on thermal and tactile illusions, we can achieve the perception of thermal motion with a minimal number of thermal actuators. Unlike traditional methods that may require a large array of actuators to simulate dynamic thermal feedback, our approach strategically utilizes thermal and tactile illusions to create the sensation of movement with efficiency and economy. Moreover, the foundation of our approach to thermal referral allows us to achieve precise movement of thermal cues. This precision enables us to convey nuanced thermal sensations, enriching the user experience and increasing the fidelity of thermal feedback in virtual environments. By leveraging thermal referral, we can accurately direct thermal sensations to specific locations on the body, enhancing the realism and immersion of VR experiences. In essence, our approach offers a cost-effective and resource-efficient solution for integrating thermal motion into VR environments. By combining thermal and tactile illusions with precise thermal referral, we can create compelling and immersive sensory experiences while minimizing hardware requirements and optimizing user engagement.

The main contributions of this paper include: i) the introduction of a novel perception-based approach to induce moving thermal cues, ii) the adaptation of existing tactile motion methods to provide a scalable thermal motion algorithm, and iii) the definition and establishment of key parameters for optimal thermal motion generation. Through these contributions, we aim to advance the understanding and implementation of thermal feedback systems in VR environments.

2 RELATED WORKS

2.1 Thermal Perception and Referral

Thermal perception is a crucial aspect of daily human perception. Given temperature changes relative to skin temperature, humans perceive thermal sensations through thermoreceptors in the skin, activating the insula cortex region of the cerebral cortex. [8, 25, 45, 48, 54]. Thermoreceptors can be heat-sensitive or cold-sensitive and exhibit a response time between 0.5s to 2s [9, 24]. Warm and heat-pain detection threshold range from 30°C to 34°C and 39°C to 50°C respectively, and cool and cold-pain thresholds detection thresholds ranging from 31°C to 35°C and 9°C to 12°C respectively. [3, 6, 11, 32, 49]. The processing of simultaneous thermal and tactile stimuli is still unknown, but the benefits of this cross-modal interplay, such as thermal referral [2, 7, 17, 18, 22], thermal sharpening [42, 43], and thermo-tactile identification [33, 38–40, 52] are currently being explored. A recent study has also shown that visual cues strongly impact the perception of thermal sensations [19].

The thermal referral is a thermal perception phenomenon in which the thermal sensations can be referred to a nearby location through thermal and tactile interaction. This illusion was first discovered by Green through experiments on cross-modal interactions between thermal and tactile stimuli [17, 18], and it has also been observed with cold stimuli as well as without tactile information [7]. Ho et al. [22] and Watanabe et al. [53] further explored the properties of the thermal referral intensity distribution. Liu et al. [29] demonstrated moving thermal illusions through pressure stimulation and thermal sensations produced by water systems. In recent studies [41, 50], researchers discovered that strong thermal referral illusions can be created by activating thermal and vibrotactile actuators together at a distant location. These vibration-induced thermal referral illusions allow the simulation of various thermal sensations through simple vibration. This finding simplifies the design of haptic interfaces, particularly in VR and AR environments, by reducing the need for multiple thermal actuators while still providing rich thermal feedback, enhancing user interaction and immersion.

2.2 Tactile Illusions and Motion

Mechanoreceptors in our skin detect vibrotactile stimuli to produce perceived tactile sensations. Compared to thermoreceptors, mechanoreceptors exhibit a significantly shorter response time of a few milliseconds and activate the somatosensory cortex of the human brain. Several illusions have been observed regarding vibrotactile perception and tactile motion.

Tactile masking is a phenomenon where stronger tactile signals dominate weaker tactile signals, thus rendering the strongest signal as the only perceivable one [13–15, 20, 47]. The phenomenon is commonly exploited in masking techniques, such as forward masking, backward masking, simultaneous masking, and sandwich masking, but its underlying mechanisms are still inconclusive beyond controlling the signal-to-noise ratio [16].

Israr and Poupyrev designed an algorithm called Tactile Brush, [23] to produce tactile moving strokes in 2D spaces based on two tactile illusions: apparent tactile motion and phantom sensation. Apparent tactile motion occurs when two tactile actuators activate in close temporal and spatial proximity [26, 37]. Rather than perceiving two separate sensations, subjects perceive a single sensation moving between the actuators. The speed of this motion could be controlled by adjusting the stimuli's duration and inter-stimulus onset asynchrony (SOA), or the time interval between activations.

Phantom sensation entails the formation of illusory tactile stimuli in between two activated actuators [1]. Though static, this phantom actuator can be controlled by configuring the associated physical actuators. The intensity of the phantom actuator can be controlled by adjusting the physical actuators' absolute intensities, and the phantom actuator's location can be controlled by adjusting the physical actuators' relative intensities to each other. By strategically manipulating actuator duration, SOA, and intensity, smooth and continuous tactile motion strokes can be produced through the Tactile Brush algorithm.

2.3 Thermal Interfaces

Thermal devices can be categorized as contact-based and non-contact-based with thermal transfer methods of conduction, convection, or radiation. Contact-based devices utilize conduction or convection and scale transfer rates based on their contact with the human body. The Peltier device is a standard contact-based device that quickly generates heat through the thermoelectric effect. By adjusting the size and number of Peltier pack devices, the size of a thermal cue can be controlled [10, 12, 34]. Along with the flexibility and modularity of Peltier devices, various wearable interfaces can be designed for thermal stimulation.

As VR grows and becomes popular among consumers, designing wearable interfaces has become very important. Different headsets, gloves, vests, etc., have been developed to explore multi-sensory experiences without inhibiting movement or accessibility [41, 51]. ThermoCaress is a wearable sleeve that could deliver moving thermal sensations to the forearm by inducing thermal referral through airbags and heated water [29]. PneuMod is a modular wearable designed to deliver a variety of thermo-pneumatic patterns and motions in varying body sites through pneumatic bubbles and Peltier devices [55]. The skin-like wearable interface designed by Sun et al. [44] offers various tactile and thermal sensations through flexible arrays of mechanical, electrotactile, and thermoelectric actuators.

Thermal interface design has already advanced beyond early limitations into an era of exploration. For the next stage of innovation, we envision diverse emulation at low production costs. The cost and power draw of advanced components raises concerns for scalability, so we explore methods of reducing dependence on hardware.

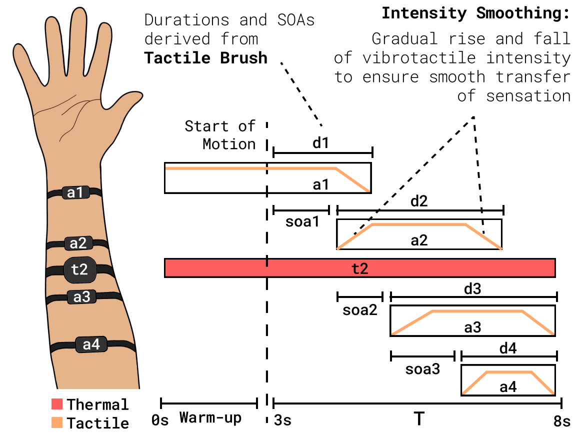

Figure 2: Concept diagram explaining the updated algorithm to generate thermal motion.

Thus, to reimagine interface design, we propose a novel wearable thermal interface based on tactile and thermal illusions.

3 THERMAL MOTION

We introduce the concept of thermal motion, an illusion of flowing thermal sensations achieved by integrating thermal and tactile actuators. Our approach continuously generates dynamic thermal illusions across multiple tactile points, creating the perception of moving thermal cues. This approach is based on integrating thermal and tactile actuators to generate thermal referral illusions at specific tactile locations [41]. When thermal and tactile actuators are activated simultaneously near each other on the skin, the perception of stronger thermal sensations occurs at the tactile actuator's location rather than the original site. We propose extending this illusory technique to create a dynamic moving thermal sensation by incorporating tactile motion illusion [23] through the interaction of a thermal actuator with multiple tactile actuators.

3.1 Algorithm

Our algorithm builds upon the existing tactile motion technique [23, 36], which induces smooth and continuous tactile strokes without actual physical movement through controlled activation of tactile actuators or vibrators strategically placed on the skin. This perceived tactile motion is commonly achieved through two well-established tactile illusions: Apparent Tactile Motion and Phantom Sensations. Apparent Tactile Motion suggests that when two vibrotactile stimuli are placed closely together and activated in quick succession, they are perceived as a single actuator moving between them [5]. Phantom Sensations occur when simultaneous stimulation of two vibrotactile actuators positioned closely together creates the perception of an illusory vibrating actuator located between the actual actuators [46]. By manipulating the timing of Apparent Tactile Motion and intensities of Phantom Sensations, one can control the speed and pattern of perceived tactile motion. We utilized the algorithm mentioned in [23] to calculate the SOAs. Our setup includes four tactile actuators with a fixed motion duration of 5 seconds. Each actuator has a different duration, and we have three

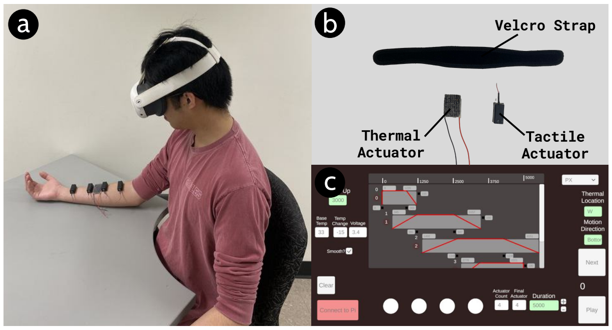

Figure 3: Figure describing (a) Actuator placement on a participant's hand, (b) thermal and tactile actuators, and (c) the interface of the application

SOAs for the four actuators. The algorithm solves for these seven variables. The direction of motion was controlled by the order of activation of tactile actuators. Playing the tactile actuators in the order (a1, a2, a3, a4) results in Wrist to Elbow motion, while playing them from a4 to a1 results in Elbow to Wrist motion (see Figure 2).

While their approach was adaptable to different tactile stroke durations and patterns, its suitability for fulfilling the specific temporal and localization requirements of thermal referral may potentially be limited due to the slower response time of thermal receptors. Thermal feedback is not instantaneously perceived, primarily because thermal receptors have a slower response time compared to mechanoreceptors, which respond within a few milliseconds [21, 31, 35]. Thermoreceptors, on the other hand, have a response time ranging from 0.5 to 2 seconds [9, 24]. To address the challenge of creating smooth and continuous thermal motion while accommodating thermal referral illusions, we have enhanced the previous algorithm with the following modifications.

Warm-up Period. We introduced a warm-up period to allow for the time required for thermal referral to take effect before initiating motion. This phase aims to direct the thermal cue to the initial actuator before motion begins. The warm-up period refers to the duration during which thermal referral occurs. During this phase, the thermal actuator is activated along with the first tactile actuator. This simultaneous activation allows the thermal actuator to reach its target temperature and induce thermal referral at the initial tactile location. By establishing thermal referral before motion starts, participants become familiar with the upcoming thermal sensations. In a preliminary study involving four participants, we tested warm-up durations ranging from 0s to 10s and determined that a warm-up period of 3 seconds yielded the most favorable results (see Figure 2).

Intensity Smoothing. Thermal referral needs to be maintained throughout the entire tactile motion as a smooth and continuous experience. Considering the temporal lag in thermal perception, the durations of actuator activations and inter-stimulus onset asynchronies (SOAs) need significant extension. However, extending tactile motion into the temporal range conducive to thermal perception compromises the smoothness and continuity of the motion, leading to noticeable gaps in the flow of sensation. To address this, we introduced an intensity smoothing feature that promotes seamless transfer of sensation throughout the motion. Intensity smoothing involves gradually increasing and decreasing an actuator's intensity at the beginning and end times, respectively, to create blurred transitions of sensation akin to the phantom sensation illusion. In our algorithm, an actuator gradually ramps up from zero intensity to peak intensity within a starting sub-period known as the peak start offset, maintains peak intensity, and then gradually ramps down from peak intensity to zero within a final sub-period called the peak-end offset. The specific pattern for intensity increase and decrease can be configured; in our preliminary study, we compared linear and exponential patterns and found that linear smoothing produced the smoothest motions.

3.2 Setup

We arranged thermal actuators and tactile actuators in a linear series along the ventral side of the forearm, as shown in Figure 3. We chose the forearm skin as the target region due to its relatively sparse distribution of thermal receptors. We used Velcro bands and sleeves to attach the actuators firmly to the ventral side of the forearm, ensuring direct contact between all actuators and the skin. The apparatus and its components were controlled by a Raspberry Pi microcontroller, which received actuator activation instructions from applications we developed using the Unity game engine.

Thermal Actuators. We utilized flexible Peltier-based thermal actuators (S043A030040, TEGWAY), as shown in Figure 3 (b) to deliver thermal sensations. Each thermal actuator was paired with a heatsink using adhesive thermal tape for efficient heat dissipation and temperature control. By reversing the polarity of the thermal actuators, we can alternate between hot and cold conditions. The dimensions of the thermal actuator and its heatsink were 30 mm (width) × 40 mm (height) × 2.3 mm (depth) and 20 mm (width) × 20 mm (height) × 10 mm (depth), respectively. The maximum temperature difference between the two sides of the thermal actuator is 64°C when supplied with a voltage of 5.7V and a current of 6A. It takes approximately 1 second to reach the target temperature and about 20 seconds to return to normal temperature. All thermal actuators were connected to a programmable power supply (KD6005P, Korad) through a relay (SRD-05VDC-SL-C). Thermal actuator activation was controlled by the relay according to a boolean signal received from the Raspberry Pi, which sent the desired voltage to the programmable power supply and activated the desired actuators. To control the temperature, we used an open-loop system to generate the thermal stimulus. In a preliminary study, a temperature sensor was used to determine the thermal characteristics of the Peltier device and the equilibrium skin temperature. We created a mapping table that linked the Peltier supply voltage to the equilibrium skin temperature under various initial conditions. Temperature conditions were subsequently controlled using this voltage mapping.

We decided not to measure the temperature on different parts of the forearm separately. Initial testing showed that temperature varied by only 0.25°C across regions. Thus, we measured the mean skin temperature of the entire forearm using a thermal camera. The Peltier device reaches thermal equilibrium with the skin within a

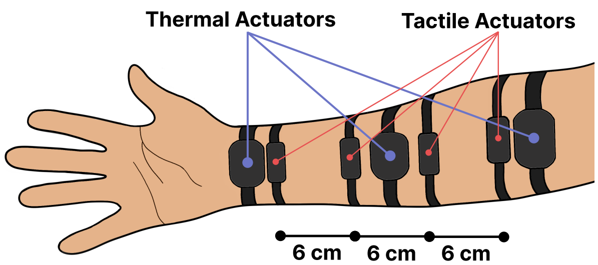

Figure 4: Concept diagram depicting the placement of the actuators for Study 1. Three thermal actuators were placed at the Wrist, Middle and Elbow locations. Four tactile actuators were placed 6cm apart from each other.

second, altering the temperature for the trial's duration. When it is turned off, the skin quickly returns to its initial temperature.

Vibrotactile Actuators. ERM vibriotactile actuators (Tatoko, B07PXZSP7J), as shown in Figure 3 (b) were used to provide vibrotactile sensations. Each tactile actuator had a dimension of 3 cm (length) × 1.8 cm (width) × 1.2 cm (height) and could provide a maximum force of 1.5N and a frequency of 125Hz at a peak voltage of 3V. Each tactile actuator was connected to a MOSFET trigger switch drive module (ANMBEST) to control its input voltage and intensity. A single power supply (Korad, KD6005P) provided a constant voltage of 2.2V to all the modules. We used a PWM controller to vary the intensity over time.

Controller. A Raspberry Pi 4 Model B was used to control the actuators and electrical components. One set of GPIO pins was configured to output PWM signals for the tactile actuators, and another set was configured to output boolean signals for the thermal actuators. The Raspberry Pi sent signals to the programmable power supply to control voltage. The Raspberry Pi also received communications containing motion information through TCP.

4 USER STUDY 1: TEMPERATURE EFFECTS

The main aim of this study is to investigate the viability of thermal motion and analyze how temperature affects its incidence. We evaluate the probability of thermal motion occurring on the ventral side of the forearm at different temperatures, thermal positions, and motion orientations.

4.1 Participants

Sixteen participants, with a mean age of 22.8 years (SD = 3.16), including eight females, participated in the experiment. Two participants identified their left hand as dominant. None of the participants reported any disorders affecting their hand sensations. Each participant received a $10 gift card as compensation for their involvement and provided written informed consent. The study protocols were approved by the Institutional Review Board (IRB) of the University of Texas at Dallas (IRB-21-194).

4.2 Study Design

Actuator Placement. Three thermal actuators were placed on the ventral side of the forearm: one at the wrist, one at the elbow, and one at the center of the forearm. In our preliminary tests, we evaluated thermal motion perception with two to eight tactile actuators, determining that at least four actuators were needed to create continuous motion. Therefore, we placed four tactile actuators evenly spaced 6cm apart in a straight line, as illustrated in Figure 4. Velcro straps were used to secure the actuators.

Stimuli. We provided thermal motion by referring thermal cues to tactile motion. For each trial, one of the thermal actuators and all tactile actuators were activated in sequence based on our algorithm. The motion duration was established at 5 seconds, preceded by a 3-second warm-up period, based on findings from pilot testing. Our algorithm computed all the essential parameters, including actuation start and end times, as well as actuation duration for both thermal and tactile actuators. Subsequently, it relayed this information to the control board through the TCP protocol.

Experimental Conditions. We designed a three-factor study to explore how temperature, the location of thermal actuator placement, and motion direction impact thermal motion perception. Four temperature levels were chosen: *Cold* (-15°C), *Cool* (-12°C), *Warm* (+6°C), and *Hot* (+9°C), relative to participants' neutral skin temperature. These temperatures were determined based on the detection thresholds in thermal stimuli [4, 32]. Three locations were chosen to determine the optimal thermal actuator placement location: emphWrist, *Middle*, and *Elbow*. Two motion directions, *Elbow to Wrist* and *Wrist to Elbow*, were also considered. This led to 24 conditions (4 Temperature levels × 3 Placement locations × 2 Motion directions). Each condition was repeated four times, yielding a total of 96 trials. While we did not specifically study tactile intensity, our preliminary testing showed that clear and continuous motion requires a certain intensity threshold. Additionally, the timing of stimulus onset asynchrony (SOA) and relative actuator intensities are crucial for generating tactile motion [23]. We created smoother motion by gradually increasing and decreasing the tactile intensities.

The trials were divided into two blocks based on temperature groups: the *Cold Group*, including *Cold* and *Cool* conditions, and the *Hot Group*, comprising *Hot* and *Warm* conditions. Within each block, the trials were randomized. The sequence of temperature groups was balanced across participants.

4.3 Procedure

Participants were seated in front of a desk and instructed to read the provided instructions thoroughly before signing a consent form. Detailed information regarding the experiment's procedures and instructions was provided. A five-minute resting period was allotted to allow participants' skin temperature to stabilize. Subsequently, the initial skin temperature was measured using a thermal camera (Optris PI450). After confirming the participants' understanding of the study instructions, the experimenter placed the straps containing the thermal and vibrotactile actuators on their forearms. Participants were then instructed to position their arms comfortably on the desk, as shown in Figure 3. Participants were also instructed

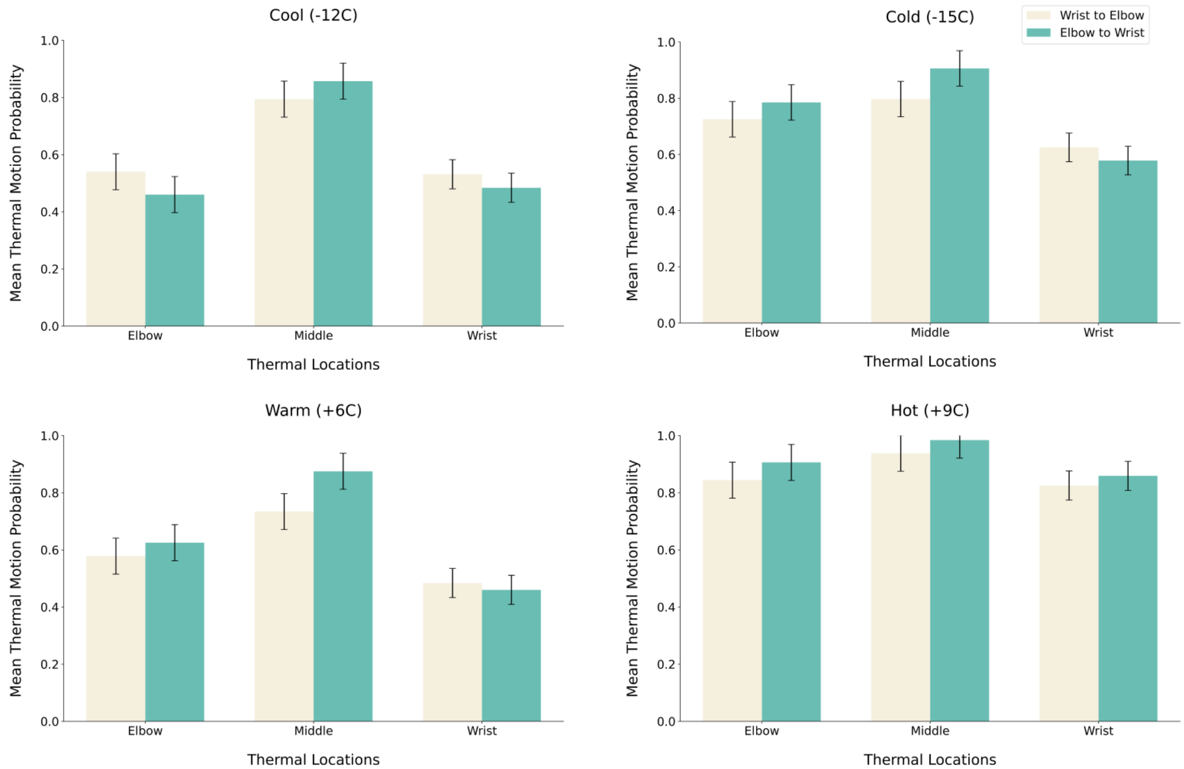

Figure 5: Mean thermal motion perception probability across four temperature conditions, three locations, and two directions.

to wear noise-cancellation headphones to mitigate any sound interference from the tactile actuators and environmental noise. During each trial, participants were instructed to close their eyes while the experimenter initiated the trial, delivering the tactile and thermal stimuli to the forearm. Subsequently, participants were asked if they perceived a single continuous moving stroke. It was explicitly stated that participants should respond affirmatively only if they perceived a continuous movement. Participants recorded their responses on a tablet (Samsung Galaxy A7) with a pen. Each trial lasted approximately fifteen seconds, including the time taken to mark responses. A 20-second inter-trial interval was provided to ensure participants' skin temperature returned to a stable state. Additionally, a 60-second break was provided after every quarter of the total trials. The study duration was approximately one hour.

4.4 Results and Discussion

Figure 5 displays the average probability of thermal motion perception across all participants for three locations and both directional conditions corresponding to *Cool*, *Cold*, *Warm*, and *Hot* temperature conditions. Overall, the *Hot* temperature condition demonstrates the highest performance, with thermal motion perceived 89.3% of the time. Moreover, extreme temperatures are associated with a higher likelihood of perceived thermal motion. Specifically, the mean motion probability for *Cold* (73.6%) exceeds that of *Cool* (61.1%), while *Hot* (89.3%) exhibits a higher mean probability as compared to *Warm* (62.6%).

Positioning the thermal actuator in the center of the forearm yielded the highest likelihood of perceiving clear and continuous thermal motion, with the *Middle* resulting in an 86.1% likelihood of thermal motion. Conversely, placing the thermal actuator at the *Wrist* yielded the lowest probability, with only a 60.5% chance of inducing thermal motion, while the *Elbow* placement offered a probability of 68.4%. Additionally, playing the motion from *Elbow to Wrist* resulted in slightly higher chances of inducing thermal motion compared to the *Wrist to Elbow* direction, with probabilities of 72.8% and 69.6% respectively.

The normality of the data was assessed using the Shapiro-Wilk test, revealing a normal distribution ($p > 0.05$) for all three independent variables. We employed Repeated-Measures (RM) ANOVA with Greenhouse-Geisser corrections for sphericity violations and conducted post-hoc t-tests with Bonferroni corrections. The effect size for the ANOVA was reported by a partial-eta squared (η_p^2).

A significant effect of temperature conditions was observed ($F(3, 90) = 36.38$, $p < 0.001$, η_p^2=0.067), indicating that temperature plays a significant role in inducing thermal motion. Post-hoc tests revealed that both *Hot* and *Cold* conditions exhibited significant differences with all other temperature conditions ($p < 0.001$ for all combinations). Conversely, no significance was found between the *Warm* and *Cool* conditions. These findings further underscore the notion that extreme temperature conditions are significantly more likely to induce thermal motion perception.

Thermal actuator location showed a significant effect ($F(2, 90) = 48.95$, $p < 0.001$, $\eta_p^2 = 0.061$), highlighting that the placement location is vital for providing effective thermal motion perception. Post-hoc tests revealed significant differences between all three conditions *Middle*/*Elbow* = ($p < 0.001$), *Middle*/*Wrist* = ($p < 0.001$), and *Elbow*/*Wrist* = ($p = 0.011$). This further highlights that placing thermal actuator in the center of the forearm results yields a higher probability of thermal motion perception. We did not find any significance for the motion direction ($F(1, 90) = 2.001$, $p = 0.157$, η_p^2=0.001). However, placing the thermal actuator in the middle of the forearm leads to a clearer perception of motion direction compared to the wrist or elbow, though these differences are not statistically significant. This may be due to the lower thermal sensitivity of the middle forearm area [30]. The higher sensitivity at the wrist and elbow might cause a more distinct perception of the thermal stimuli at the actuator sites, affecting the illusion of motion.

5 USER STUDY 2: TEMPORAL THRESHOLDS

This study aims to determine the minimum and maximum durations for perceiving thermal motion in both hot and cold conditions. Our initial investigations have shown that the duration of the motion plays a crucial role in creating the thermal motion illusion. If the duration is too short, the thermal illusion breaks, and participants only sense thermal sensations at the starting point. Conversely, if the duration is too long, only tactile motion is felt, without any thermal motion effect. An optimal duration range exists where a clear and continuous thermal motion illusion is experienced, possibly varying between hot and cold sensations. This leads to the following research questions for this study:

- **RQ1**: What are the minimum and maximum durations needed for a smooth and continuous thermal motion illusion?
- **RQ2**: How do these duration thresholds differ between hot and cold temperatures?

Through this user study, we aim to establish temporal thresholds for perceiving thermal motion in hot and cold environments, addressing the research questions outlined above.

5.1 Participants

Sixteen new participants, not previously involved in User Study 1, took part in this study. Their average age was 22.1 years (SD = 2.27), with eight being female. All participants were right-handed and had no reported hand sensation disorders. Each participant received a $10 gift card as compensation and provided written consent. All the experiments were approved by the Institutional Review Board (IRB) of the University of Texas at Dallas (IRB-21-194).

5.2 Study Design

Actuator Placement. We positioned a single thermal actuator at the central point of the ventral side of the forearm, as determined by the results of User Study 1, which showed the highest likelihood of thermal motion perception. Alongside, we arranged four tactile actuators evenly spaced in a straight line with 6cm intervals between each actuator (refer to Figure 6). We used Velcro straps to secure the actuators on the forearm.

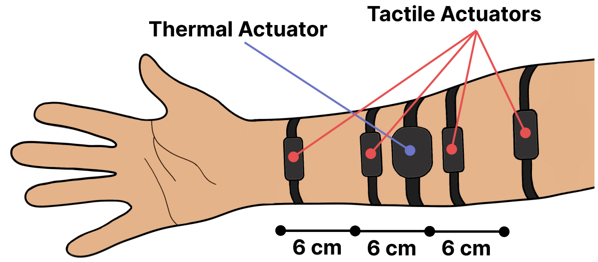

Figure 6: Concept diagram depicting the placement of the actuators for Study 2. One thermal actuator was placed at center of the forearm. Four tactile actuators were placed 6cm apart from each other.

Stimuli. Thermal actuators and all tactile actuators were activated based on our algorithm to generate thermal motion. The duration of motion varied according to the conditions.

Experimental Conditions. We employed a one-interval two alternative forced-choice (1I2AFC) paradigm along with one-up two-down adaptive procedures to determine duration thresholds [23, 28]. This method provides an estimation of the 70.7% point of the psychometric function [27]. We calculated lower and upper thresholds for both hot and cold temperatures, resulting in a total of four staircase procedures (2 temperatures × 2 thresholds). The order of these procedures was balanced using Latin squares.

5.3 Procedure

Participants were seated at a table and were instructed to carefully read and understand the provided instructions before signing a consent form. Detailed information regarding the experiment's procedures and instructions was comprehensively provided to ensure participants' understanding, following the same protocol as the previous study. A five-minute break was given, during which their skin temperature was recorded.

When measuring the upper threshold of duration, we deliberately chose an initial value of 12 seconds, ensuring it was sufficiently large to prevent participants from perceiving clear thermal motion. When determining the lower threshold of duration, we opted for an initial value of 0.5 seconds. These choices were based on our observation from the preliminary pilot study involving four participants, confirming that these values effectively precluded any discernible thermal motion. Participants were asked if they could feel a single clear continuous thermal stroke. For every "No" response, the duration value decreased until participants responded with a "Yes". At this point, the duration of the motion was increased. The change of decreasing to increasing duration, and vice versa, is referred to as a "reversal". The experiment continued until reaching six reversals.

Each experiment series started with a duration step size of 1 second, and after the first reversal, the step size decreased to 0.5 seconds. An average duration threshold was computed from the average of the six reversals. A 20-second inter-trial interval was provided to ensure participants' skin temperature returned to a stable state. Each staircase lasted approximately 10 minutes, and a 60-second break was provided after every staircase. The study duration was approximately one hour.

5.4 Results and Discussion

Figure 7 displays the mean upper and lower thresholds for *Hot* and *Cold* temperatures. To create this figure, we first plotted the mean probability of perceiving thermal motion for each motion duration and then applied a second-order quadratic function to smooth the curve. We used a one-interval, two-alternative forced-choice paradigm combined with one-up, two-down adaptive procedures to determine duration thresholds. This method estimates the 70.7% point of the psychometric function, allowing us to identify the 0.707 probability duration as the threshold. The mean lower threshold for perceiving thermal motion under hot temperature conditions was found to be approximately 1.9 seconds, while under cold temperature conditions, it was approximately 3.6 seconds. Conversely, the mean upper threshold for perceiving thermal motion was higher under hot temperature conditions (10 seconds) compared to cold temperature conditions (7.5 seconds) as shown in Figure 7. Since we had a fixed end-to-end distance of 18cm between the first and the fourth actuator, we can also obtain the optimal range of speed for both temperature conditions. The optimal ranges of speed to perceive clear and continuous thermal motion are (1.8 cm/s to 9.5cm/s) for *Hot* and (2.4cm/s to 5.0cm/s) for *Cold* respectively.

The results indicate notable differences in the lower and upper duration thresholds for perceiving thermal motion between hot and cold temperatures. Under hot temperature conditions, participants exhibited a lower mean lower threshold and a higher mean upper threshold compared to cold temperature conditions. This suggests that individuals may be more sensitive to thermal motion at lower durations under hot temperatures, potentially due to increased sensory receptivity or heightened physiological responses to heat stimuli. Conversely, under cold temperature conditions, participants displayed a higher mean lower threshold and a lower mean upper threshold, indicating decreased sensitivity to thermal motion at lower durations and heightened sensitivity at higher durations.

6 USER STUDY 3: VR APPLICATIONS

The goal of this study is to evaluate our method for implementing thermal motion in VR applications. Two specific VR applications were created to enable participants to engage with virtual thermal objects. They interacted with these objects while using sleeve interfaces that incorporate our approach. Following these interactions, participants were interviewed to gather their feedback and insights regarding their experiences.

6.1 Study Design

Participants. Eight new participants (3 females; the average age was 23.5 years (SD = 2.44)) who had not previously been involved in previous user studies participated in this study. One participant was left handed and everyone reported no hand sensation disorders. Each participant received a $10 gift card as compensation and provided written consent. The Institutional Review Board approved the study protocols of the author's institution.

Sleeve Interfaces. We designed a pair of wearable thermal sleeves as the experimental apparatus for bimanual interaction. Each sleeve comprises four tactile actuators evenly spaced 6 cm apart in a linear arrangement, accompanied by a thermal actuator positioned at the midpoint of the tactile actuators. Thermal actuator polarities were configured such that the left arm sleeve provided cold feedback while the right arm sleeve offered hot feedback. Motion duration was set to 5 seconds with a 3-second initial warmup time. All actuators are connected to a microcontroller (Raspberry Pi 4) to communicate with VR applications using TCP protocol.

Visual Rendering. Visual scenes were presented using a Meta Quest 3 VR headset, with scenes created using the Unity game engine (vers. 2022.3.20f1).

Experiment Design. Participants engaged in tasks within two virtual scenarios: "Social Touch" and "Sci-Fi Effects." They completed tasks for both scenes in a counterbalanced order as part of a within-subject design. Since this is an exploratory study, we chose not to include a non-thermal baseline. Instead, we focused on understanding user interactions and perceptions related to thermal actuation. This design choice allowed us to gain deep insights into users' thoughts, feelings, and experiences. By concentrating on user interviews and exploratory studies, we validated our approach and gathered essential data to understand the prototype's current state.

Social Touch. In this passive interaction scenario, participants were placed in a virtual household setting at a table. They observed their virtual arms from a first-person viewpoint, facilitated by the Meta SDK's avatar features. A virtual human was also present, seated nearby. Participants were instructed to position their right arm on the table to match their real-world placement. The experimenter then aligned the virtual scene with the physical table to synchronize both virtual and physical arm positions. Following calibration, the virtual human initiated an animation where he gently stroked the participants' virtual hand from elbow to wrist using his index and middle fingers (see Figure 8 (a)). Concurrently, the thermal sleeve produced a moving thermal sensation on the participants' real forearm, mimicking the touch's warmth. To create a gentle touch sensation, we applied a tactile force of 0.5N (3.8G). Additionally, we applied the *Warm* temperature condition to evoke a sense of warmth associated with the touch.

Sci-Fi Effects. In this active interaction scenario set in a futuristic environment, users are placed in a futuristic building where they encounter a blue and an orange orb. They also see virtual sleeves with a charging bar design. Users can interact with the orbs by making a closed-fist gesture, absorbing their power to charge their sleeves. This action initiates a visual animation where the orbs shrink as the sleeve charges (see Figure 8 (b)), and upon opening their fist, the sleeve begins discharging, causing the orbs to regenerate on their palm. Once fully charged, users can propel the orbs forward. Each visual animation is complemented by corresponding audio cues. During charging, a thermal motion occurs from the wrist to the elbow, while during discharging, it moves from the elbow to the wrist. Interacting with the blue orb triggers a *cold* temperature, while the orange orb triggers the *hot* temperature. The tactile actuators provide a force of 1N (7.5G) for all conditions.

Procedure. The study commenced with participants providing informed consent and consenting to be recorded during task and

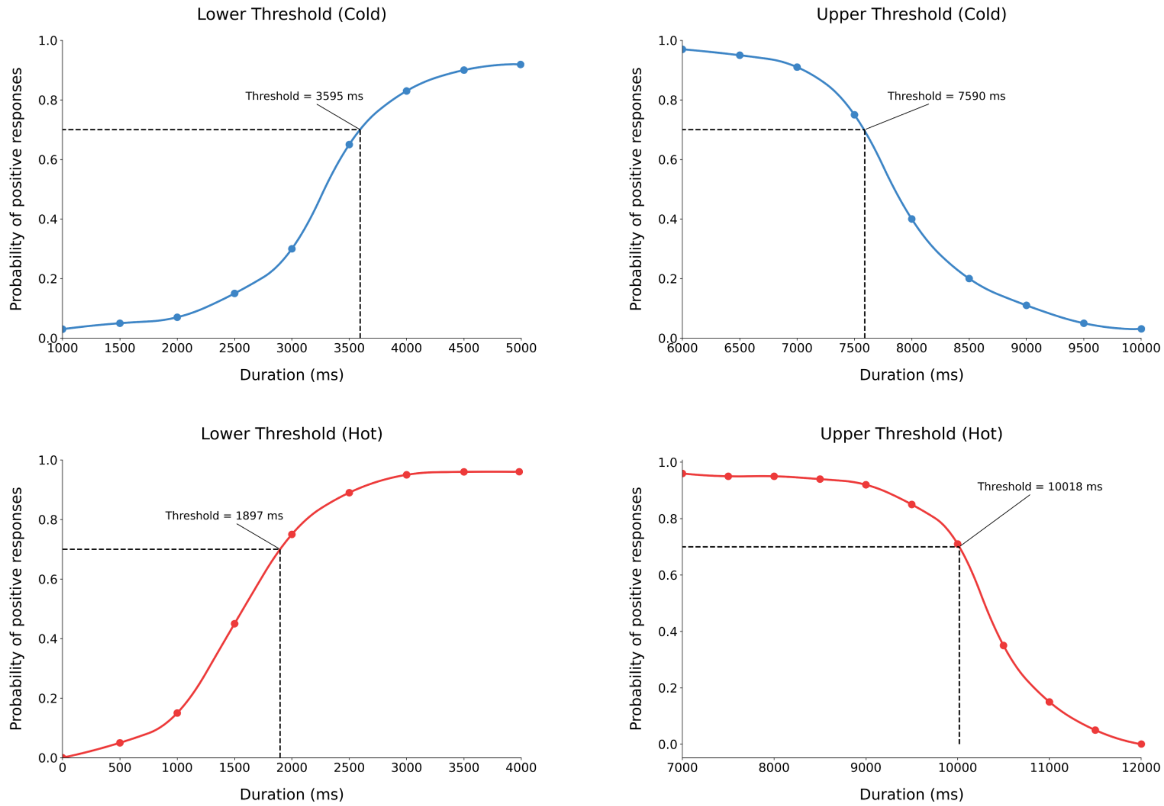

Figure 7: Lower and Upper Thresholds of Thermal Motion with Cold and Hot Temperatures.

interview sessions. Following this, participants received instructions regarding the task within each scene. The experimenter then proceeded to put the thermal sleeve on their arms, after which participants engaged with the initial visual scenario. Upon completion of each scenario, participants underwent a semi-structured interview lasting approximately 12 minutes. Overall, each visual scenario took roughly 20 minutes to complete, with the entire experiment spanning approximately 45 minutes.

6.2 Interview Results

Overall, participants reported that the thermal motion sensations and feedback provided by the sleeve significantly improved their immersion in the VR environment and helped in a better understanding of interactive elements. The introduction of thermo-tactile feedback to each VR scene helped reinforce typically intangible visual information, providing a perceptual anchor for participants within the virtual world.

6.2.1 Overall Experience.

Immersion. Participants unanimously experienced greater immersion in the VR environment when additional thermo-tactile sensations were provided through the thermal sleeve. They expressed that these novel sensations enhance their overall experience and engagement with the virtual surroundings. P6 stated the thermo-tactile sensations "allowed for a more immersive experience", and P4 further described the sensations as "tricking your brain into thinking you're actually in the VR world." P3 stated they believed the virtual arm was indistinguishable from their own and that they could truly feel the *Social Touch* interaction. Similarly, P7 claimed they felt the *Sci-FI Effects* orbs "traveling through their forearm." P8 explicitly attributes their immersion to the temperature changes, as they were "able to immerse myself in that world because I could feel changes in my body." Evidently, the variety of congruent sensory modalities resulted in high immersion in the virtual world.

Clarity of Motion. Most participants found the thermo-tactile sensations smooth and clear. Regardless of realism or expectations, participants identified the intended direction and flow of the thermal motions very clearly. Every participant perceived smooth and continuous thermal motion, experiencing both warm and cold temperatures without discerning individual locations of stimulation. The participants' perceptual resolution even surprised us, where descriptions such as "Movement in a straight line along the direction of my forearm" from P2 and "Medicine slowly traveling up and through the veins in my arm" from P4 reveal deep processing of perceived sensations. Notably, P7 compared the ice orb interaction to a "cold object sliding up and down their arm." Even through illusions, thermal sensations can be perceived as animated with high clarity and understanding.

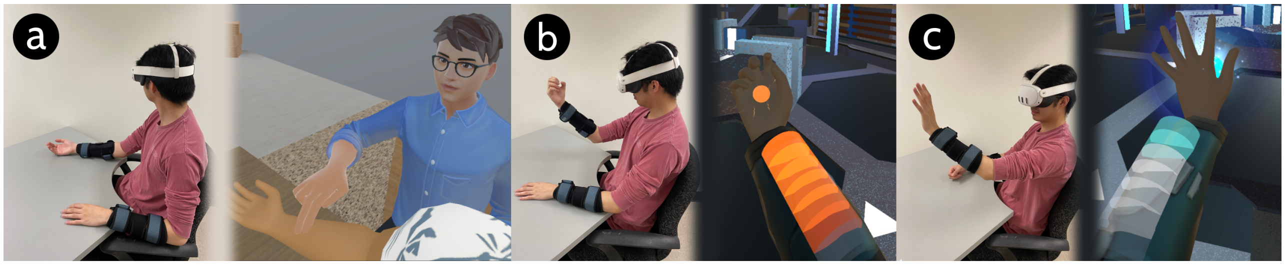

Figure 8: A participant interacts with a) a virtual peer in *Social Touch*, b) a charging fire orb in *Sci-Fi Effects*, and c) a discharging ice orb in *Sci-Fi Effects*

Comparison to Expectations. Generally, the feedback provided through the thermal sleeves matched the participants' expectations built from real-world experience and visual cues. Throughout the participants' experiences with interactions both grounded in reality through the *Social Touch* scene and drawn from fiction in the *Sci-Fi Effects* scene, several participants commented on congruence between the visual cues and animated sensations from the thermal sleeve. For *Sci-Fi Effects*, all 8 participants agreed that the sensations aligned with the visual cues, with 3 of them claiming the realism even "exceeded their expectations". For *Social Touch*, 7 participants agreed the sensation matched the visual location and motion, with 3 of them also comparing it to a real human touch in terms of temperature and texture. P5 stated the sensations were "smooth and continuous" and "aligned with their expectations, especially with the Sci-Fi indicators." For P7, the VR experience was "the first one that felt really immersive and realistic, something unique."

Enjoyment. All participants expressed enjoyment and delight while interacting with the thermal sleeves. They found the novelty of the device exciting and mentioned looking forward to seeing it in the public consumer space. Positive opinions such as "I think this is one of the newest experiences that I have felt inside a VR environment" from P2 and "I really like the experience, I think it would be really fun to continue" from P6 were abundant during the interviews. Amusingly, 6 participants expressed eagerness to repeat the interactions or incorporate the sleeves into existing video games. As such, further development of the thermal sleeves will tap into unexplored spaces of the consumer market.

Comfort. Participants found the sleeve equipment comfortable and non-intrusive. They all mentioned physical wearing of the sleeve was natural and posed no additional exertion. Restriction of movement was not found to be an issue among participants, with 7 participants claiming they felt no limitation on physical range. 7 participants noted the thermal levels provided were indicative but non-painful, and 4 participants even found the thermal stimulation surprisingly pleasant. P8 even suggested the sleeve would be suitable for therapy applications, such as acclimating users to specific sensations before true exposure.

6.2.2 *Sci-fi Effects.*

Interaction with Power Orbs. Responses to the power orb interactions were highly positive and enthusiastic. Even without real-world references for the haptic profiles of the *Sci-Fi Effects* scene, participants claimed they could feel the orbs as if "interacting with real-life objects," as mentioned by P4. P2, P4, and P5 all described feeling power "charge up and down" their forearm as moving thermal sensations. P8 even admitted to a high level of immersion, stating they "felt like they gained those powers and could shoot them their hands." Evidently, the new thermo-tactile sensations exhibited congruency with the visual cues and enhanced the user experience.

Interestingly, some participants claimed they felt increasing tactile and thermal intensity during the charge-up sequence as if "power is being stored in their arms" and decreasing intensity during the discharge sequence as if the power is "leaving" the arm. However, the haptic feedback provided through the thermal sleeve is vibrations with constant average intensity and thermal stimulation of always increasing intensity, regardless of the scenario. We discussed this intriguing contradiction further in Section 7.

Differences between Fire and Ice Orbs. Notably, participants exhibited individual differences and preferences for specific thermal profiles. The perceived thermal clarity varied by the participant as well, with P4 claiming the ice sensation moved slower and P5 stating the thermal intensity increased with proximity to the center of the forearm. More often than not, participants such as P7 felt the cold sensations more clearly, comparable to "ice traveling all the way through the arm." Likewise, these participants claimed the warm sensations were more dispersed "throughout the forearm" and were "harder to pinpoint," as worded by P7. Further exploration of individual thermal perception profiles may reveal insights into human thermal perception as a whole.

6.2.3 *Social Touch.*

Realism. In the more reality-grounded *Social Touch* setting, the decrease in visual spectacle emphasized the significance of the thermo-tactile modality in establishing immersion. By introducing tangible sensations congruent with the visual human's finger, seven participants felt deeper ownership of their virtual arm and environment, such as P8 reflecting on existing "in that world now." However, high immersion was not always indicative of high realism. While most participants stated the thermo-tactile sensations matched the visual cues and reinforced their understanding of the interaction, several participants, like P8, admitted the sensation was "similar to but not quite" realistic. Whether due to temperature or vibration intensity, the thermal sleeves did not fully satisfy these participants' previously established expectations for a human touch. At the same time, 3 other participants actually compared the interaction to a real human touch, such as P5 admitting they "felt the man move his finger across their arm." This shows that there are subtle nuances in thermal and tactile patterns of daily stimuli to further consider.

Emotional Response. Participants reported feeling more connected to virtual peers as they became increasingly immersed in the VR environment. Specifically, six participants mentioned experiencing a deeper connection with virtual characters due to the immersive thermo-tactile sensations. For example, P2 expressed that it felt like a real person was sitting next to them. P1 described "feelings of warmth" throughout the interaction, and P4 suggested integrating these sleeves with physically restricted meetings to feel "more connected with the virtual persons." Recognizing the significance of physical touch in human interactions, our approach represents a promising step toward bridging this sensory gap in virtual environments.

7 DISCUSSION

We clearly demonstrated the feasibility of creating an illusory perception of moving thermal cues by effectively integrating the thermal referral phenomenon and tactile masking illusion. Unlike conventional approaches that primarily offer static thermal cues within multimodal feedback systems, our innovative method introduces a perception-based approach to deliver dynamic thermal feedback. By combining thermal referral and tactile motion techniques, we effectively induced the sensation of thermal motion, creating an enhanced user experience in virtual environments. We conducted several experiments to explore different aspects of our approach.

Our innovative approach involves creating dynamically moving thermal illusions using thermal referral, setting our work apart. While previous research by Son et al. [41] focused on delivering static localized and global thermal illusions at vibrotactile locations, our study pioneers the generation of dynamic moving thermal illusions. We achieve this by integrating thermal referral with apparent tactile motion illusions, producing a continuous flow of moving thermal cues. By adapting existing tactile motion algorithms, we identified the critical factors necessary for translating these into thermal motion and explored the key elements that influence thermal motion generation. This study is the first to investigate thermal motion, and we validate our findings through three experiments. In the first experiment, we examined how temperature variations and the spatial placement of the thermal actuator influenced the perceived thermal motion. The results revealed distinct perceptions of thermal motion under both hot and cold conditions, with the most pronounced effect observed when the thermal actuator was centered on the forearm. In the second experiment, we focused on the temporal aspect of our method by determining the upper and lower thresholds of perceived thermal motion speed in hot and cold conditions. The findings indicated a wider range of detectable thermal motion speeds in hot conditions compared to cold conditions, highlighting the dynamic nature of thermal perception. We also integrated our approach into VR environments to evaluate its feasibility through two interaction scenarios, demonstrating that incorporating thermal motion into VR scenes not only enhanced immersion but also served as a perceptual anchor, reinforcing typically intangible visual information and further engaging participants within the virtual world.

Our main contribution lies in the introduction of a novel approach enabling the perception of thermal motion using a minimal number of thermal actuators, leveraging thermal and tactile illusions to efficiently create the sensation of movement. In this work, we provided moving thermal cues across the entire forearm by utilizing only one thermal actuator and four tactile actuators. This contrasts with traditional methods that often require a larger array of actuators. Furthermore, our study confirms that the perceived motion is experienced as a singular continuous flow, enhancing the realism of thermal feedback in virtual environments. Secondly, rooted in thermal referral, our approach provides precise control over the movement of thermal cues, allowing for the conveyance of nuanced thermal sensations and enriching the user experience in virtual environments. By accurately directing thermal sensations to specific locations on the body, our method enhances the realism and immersion of VR experiences. Lastly, our approach offers a cost-effective and resource-efficient solution for integrating thermal motion into VR environments, minimizing hardware requirements while optimizing user engagement. Overall, our contributions provide a comprehensive framework for enhancing VR experiences with dynamic thermal feedback, paving the way for more immersive and engaging virtual environments.

Several significant findings emerge from our study. We demonstrated that our approach can effectively induce thermal motion perception for both hot and cold temperatures, with a heightened likelihood of perception at extreme temperature ranges. We also identified the optimal location for the thermal actuator on the forearm to clearly perceive the thermal motion illusion. Furthermore, we established the feasibility of generating to and fro thermal motion, with comparable effectiveness observed for both *Elbow to Wrist* and *Wrist to Elbow* directions, suggesting an optimal motion speed range to perceive cleat thermal motion for hot 1.8 cm/s to 9.5cm/s) and cold temperatures (2.4cm/s to 5.0cm/s).

Another intriguing observation from our study is the perceptual distinction in thermal motion illusion between hot and cold conditions. We observed that *Hot* stimuli exhibit a relatively higher probability of inducing thermal motion compared to *Cold* stimuli. We also observed that the range of duration for clear and continuous thermal motion perception was larger for hot temperatures than for cold temperatures. This difference may be attributed to the sparse distribution of warm receptors, resulting in a lower magnitude of thermal stimuli and, consequently, a more pronounced illusion. This observation aligns with previous studies on thermal referral phenomena. It exhibited a comparable observation in the previous thermal referral studies [17, 22].

An unexpected relationship we found was deep visual-thermo-tactile sensory interplay. Interestingly, a common observation from participants was level-based intensity changes in both temperature and vibration while interacting with the *Sci-Fi Effects* orbs. As if to match the step-like visual cues from the charge bar, participants perceived staggered increasing and decreasing levels of intensity, independent of motion smoothness, for the charge and discharge interactions respectively rather than gradual changes over time. While perceiving increasing temperature is reasonable for the charge interaction, perceiving decreasing temperature during the discharge animation is contradictory, as the thermal actuator increases temperature intensity regardless of the scenario. Likewise, the actuators changed intensity in a gradual pattern rather than the perceived step-like pattern. Even the audio cues provided for charging and discharging rose and fell in pitch gradually. This suggests visual perception takes a high priority in multi-sensory compilation with a deep cognitive interplay of visual cues and thermo-tactile sensations. One possible conclusion for the perceived step-like sensations is participants attempt to reconcile their perceived sensation to what they experience visually, thus assuming the segmented structure of the visual bar attached to the location of sensation indicates different predefined levels of intensity. If so, human thermal perception may be more malleable and susceptible to cognitive influence than we expected.

Regardless of individual differences in perception, the animated thermal feedback provided to participants universally enhanced immersion by familiarizing virtual entities. Not only did participants feel part of the virtual world, but they were pleasantly surprised when that previously intangible world enacted change upon them. Several participants commented on the realness of the interaction with the *Social Touch* virtual peer, claiming they truly felt the touch and thus considered its source more "real." Through thermal motion, we can instill animated life into virtual entities, providing them a tangible mean of expression with human users. Humans have long been known as social creatures, reliant on the sensory diversity to connect with each other. Prominent among these is physical touch, which historically demonstrates high significance to human social connection and mental well-being. This form of connection was emulated through the thermal sleeves even without hyper-realism, as users acknowledged the congruency between the thermal sensations and visual cues. Through the thermal sleeves and illusory thermal motion, we have unlocked this method of connection for virtual utilization without physical or spatial limitations.

We acknowledge certain limitations encountered during the study. In Study 3, participants expressed concerns regarding the complexity of the setup due to the presence of numerous wires. Addressing this issue entails streamlining the circuit design and transitioning the sleeve to Bluetooth-powered functionality, which would enhance user comfort and mobility. Additionally, the utilization of ERM tactile actuators restricted our ability to independently vary frequency and intensity. To overcome this limitation, we intend to validate the observed motion phenomena using alternative actuator types such as LRA and piezo, which offer greater flexibility in modulation and control.

Another limitation is the limited number of use cases tested in Experiment 3. We aimed to conduct an in-depth exploration of two distinct scenarios to examine the nuances of thermal motion perception. By testing only two use cases, we were able to thoroughly understand the underlying mechanisms and influencing factors. Although a broader range of applications would have strengthened our findings, focusing on these specific scenarios allowed for a comprehensive analysis and provided a solid foundation for future research. By mitigating these constraints, we can further refine our experimental setup and bolster the robustness of our findings.

In this study, we have demonstrated the feasibility of thermal motion perception on the forearm. Our findings underscore the scalability of our approach, paving the way for its application to various body locations such as the palm, back, and neck in future research endeavors. Furthermore, we aim to explore the viability of thermal motion in a two-dimensional space, thereby investigating the potential to create intricate thermal patterns and animations through this technique. By expanding our investigation to encompass diverse body regions and dimensional spaces, we aim to unlock new avenues for enhancing the sensory realism and immersive potential of virtual reality experiences.

8 CONCLUSION

This study delved into a perception-based approach for generating moving thermal cues. Across three experiments conducted on human forearms, we explored the viability of this phenomenon across various factors. Our findings confirmed that thermal motion can indeed be distinctly perceived through the integration of thermal referral and tactile masking illusions. Furthermore, we validated the efficacy of this approach within virtual reality environments.

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