Thermal Masking: When the Illusion Takes Over the Real

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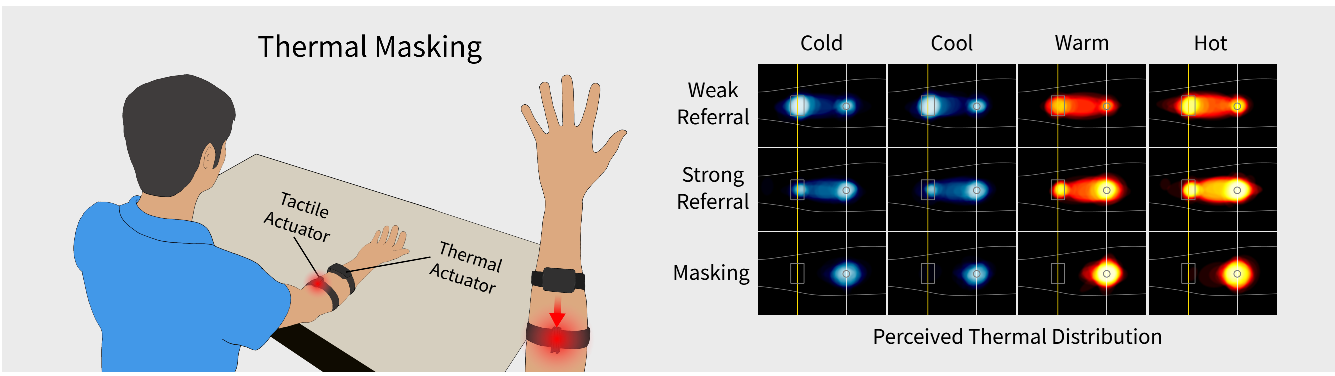

Figure 1: Illustration depicting the thermal masking phenomenon. When both the actuators are activated simultaneously the referred illusion could take over the real, resulting in the perception of the illusory thermal sensation only at the tactile actuator.

ABSTRACT

This paper reports on a thermal illusion called thermal masking. Thermal masking is a phenomenon induced by thermal referral to completely mask the original thermal sensation, providing thermal sensation only at the tactile site. Three experiments are conducted using thermal and vibrotactile actuators to investigate the nature of thermal masking on human arms. The first experiment investigates the effects of different temperatures on masking. The results show a higher percentage of thermal masking occurs in warm than hot or cold conditions. The second experiment examines how far the thermal masking can be perceived. The results show that masking can reach up to 24 cm from the thermal site. The third experiment explores the interaction space by placing the tactile actuators on the opposite side of the thermal actuator. The results confirm that thermal masking can reach the other side of the arm, and the performance was higher in warm conditions.

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CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**.

KEYWORDS

Thermal perception, tactile masking, multisensory feedback, thermal illusion, forearm

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1 INTRODUCTION

We introduce a novel concept called *thermal masking*, a newly observed thermal illusion demonstrating apparent masking properties in thermal referral. In thermal referral, when thermal and tactile stimuli are simultaneously applied to nearby locations of the skin, an illusory thermal sensation is also perceived at the location where the tactile stimulation occurs [20, 21]. We argue that a strong intensity of the tactile signal can affect the redistribution of thermal sensation and dominate the original thermal sensation, exhibiting masking properties. That is, the masking effect will take place so that the original thermal sensation can be sufficiently attenuated and completely masked by the elicited thermal illusion created from the tactile location, perceiving the thermal sensation only at the tactile location.

Thermal masking is a phenomenon that exhibits masking effects in thermal referral through tactile and thermal interactions. Unlike existing sensory masking (i.e., vision [19], auditory [22], and tactile [57]) that shows a stronger stimulus dominating the perception of a weaker stimulus within the same type of sensory stimuli, thermal masking shows that illusory thermal sensation could dominate the original thermal stimulus through thermal and tactile integration. Previous thermal referral studies have suggested that this phenomenon was based on spatial summation and thermal redistribution, resulting in a uniform distribution of temperature sensation across the thermal and tactile locations. When the thermal stimulus is applied, the amount of thermal sensation would be summed and uniformly redistributed to both the thermal and tactile locations, perceiving thermal sensations at both locations [28]. However, our finding of the thermal masking phenomenon extends this theory, demonstrating several referral states of *weak*, *strong*, and *masking* with non-uniform thermal redistribution.

Although the underlying mechanism needs further investigation, we believe that our finding of thermal masking has significant implications that potentially impact various human-computer thermal interfaces. Leveraging thermal masking could achieve localization in a large-scale thermal display with a minimum number of thermal actuators. That is, we can perceptually turn vibrotactile actuators into thermo-tactile actuators by transferring thermal sensation to the tactile location through the masking effect. Because thermal actuators and devices are generally more expensive and require more power to activate than vibrotactile actuators, adopting a cost-effective masking approach with a minimum number of thermal actuators could simplify the interface design and engineering complications. Thermal motion illusions from one location to another could be designed to provide rich thermal sensation. We can deliver thermal moving experiences throughout the user's body to create various thermal effects for better thermal experiences in immersive environments such as VR and AR. Such new illusions could bring huge engineering benefits by bridging the gap between human sensory capabilities and device limitations, benefiting designers and engineers to make effective thermal interfaces. Furthermore, our efforts to investigate thermal masking and its property of non-uniform redistribution of thermal sensations can accelerate scientific research in understanding thermal perception.

In this study, we investigate the properties of thermal masking by interplaying thermal and vibrotactile actuators. We placed one thermal actuator and one or more vibrotactile actuators on the user's arm to explore the effects of thermal masking in several aspects: temperature, distance, and the placement of opposite sides. The first study focuses on the occurrence of masking in different temperature conditions to investigate the temperature effects on thermal masking and thermal referral. The second study explores the effective distance range of thermal masking on the entire arm. The third study investigates its spatial features to explore the design space of thermal masking. The main contributions of this paper are i) new findings of masking effects in which the thermal sensation can be attenuated and completely weakened, exhibiting non-uniform thermal redistribution; ii) promoting the scientific research in thermal perception through new aspects from existing sensory masking and thermal referral; and iii) engineering benefits of employing perceptual approaches of thermal migration and thermal motion for various thermal displays and interfaces.

2 RELATED WORKS

2.1 Thermal Perception

Thermal perception is a fundamental aspect of sensory perception that allows humans to perceive warmth and coldness when their thermoreceptors respond to a stimulus above or below the skin temperature [31, 50, 52, 56]. In contrast to vibrotactile information detected by mechanoreceptors, triggering the human brain's somatosensory cortex, thermal sensations are perceived through the warm or cold thermoreceptors found in the epidermis and dermis skin layers. These sensory signals are then transmitted to the brain and processed within the insular cortex. [7, 31]. Warm receptors are sparsely distributed on our skin in comparison to cold receptors. This discrepancy in receptor density is responsible for the heightened sensitivity of human skin to cold temperatures rather than warm ones [1, 2]. Still, the process by which simultaneous thermal and tactile sensations are processed and interact remains uncertain. The thermal thresholds for detecting warmth and heat-induced pain span from 30°C to 34°C and 39°C to 50°C, respectively, while those for cold and cold-pain detection range from 12°C to 31°C, 0°C to 28°C [3, 4, 9, 39, 41]. The response time of thermoreceptors falls within the range of 0.5 to 2 seconds, and it is typically slower compared to mechanoreceptors, which typically respond within a few milliseconds [26, 45].

2.2 Thermal Referral

The thermal referral is a phenomenon in which the thermal sensations can be referred to a nearby location through thermal and tactile interaction. When both thermal and tactile stimuli are applied to the skin, thermal sensation can be perceived at both thermal and tactile locations. In the work by Green [20], when thermal stimuli were presented on the index and ring fingers, and the tactile stimulus was presented on the ring finger, all three fingers felt the thermal sensations. This phenomenon has been demonstrated to occur with both warm and cold stimuli. It was observed that the illusion ceased when the neutral tactile stimulus was eliminated by raising the middle finger, suggesting a strong association between thermal and tactile sensations. However, Cataldo et al. [5] demonstrated that thermal referral still occurred when a purely thermal stimulus was applied without any accompanying tactile information. The underlying mechanism of this cross-modal perception remains unclear. One of the hypotheses grounded on this phenomenon is spatial summation and thermal redistribution. Due to the low thermal spatial resolution, the amount of thermal cues could be summed and redistributed along with the tactile contact area, resulting in an increased thermal perception area [5, 28]. Many studies showed different aspects of thermal referral. It was found the thermal referral has a spatial limit on hand, and the perceived sensation becomes weaker with the increase in distance [27]. The perception of thermal referral tends to be less magnitude in cold conditions when contrasted with warm sensations [21, 28]. This could be attributed to the increased sensitivity of the skin to cold stimuli, likely stemming from the abundance of cold receptors present in the skin's surface [33]. In addition to the fingers, the thermal referral has occurred on various body parts, including hand [5], forearm [35, 54] and back [49]. Recently, Liu et al. [35] demonstrated that thermal referral can be expanded to create an illusion of moving thermal sensations when combined with pressure and thermal sensations generated by a water system. Son et al. [49] proposed a perception-based approach to achieve localized thermal sensations by eliciting thermal referral through thermal and tactile interaction for thermal vests in VR. The majority of thermal referral studies have illustrated its occurrence and explored various applications in diverse contexts. Nevertheless, the precise mechanism governing its function within the human sensory system remains obscure.

2.3 Tactile Masking

Tactile masking is a limited perceptual ability to detect the target signal in the presence of another tactile stimulus. A weaker tactile signal can be masked by a stronger tactile signal, perceiving only the stronger one [15–17, 24]. Various masking techniques are commonly used in sensory perception experiments to investigate how one stimulus affects the perception of another. These techniques include forward masking (the masking stimulus precedes the test stimulus) [8], backward masking (the masking stimulus follows the test stimulus) [12], and simultaneous masking (both stimuli start and end at the same time) [34]. Pedestal masking [51] involves the test stimulus occurring during a continuous masking stimulus, while sandwich masking [11] places the test stimulus between two masking stimuli. Extensive research has been conducted to investigate a broad spectrum of vibrational frequencies, cue sizes, and various locations on the skin [16, 17]. These studies aim to gain insights into the neural and psychophysical underlying mechanisms of this phenomenon.

The identification of tactile cues depends on one of four specific types of mechanoreceptors: the Pacinian corpuscle, Meissner's corpuscle, Merkel's disk, and Ruffini ending. Each of these mechanoreceptors is responsive to distinct types of stimuli. The Pacinian corpuscle is sensitive to high-frequency vibrations (80-450 Hz), Meissner's corpuscle detects touch and pressure, Merkel's disk responds to light touch, and the Ruffini ending is activated by stretch and deformation [14, 55]. Typically, masking is observed when the target and the mask signal both activate the same channel [51]. Vibrotactile masking has also been utilized to explore the underlying mechanisms for texture and speed in human perception. Hollins et al. [37] observed that vibrotactile adaptation hinders the discrimination of fine textures but does not significantly impact the discrimination of coarse textures. It has also been used to attain perceptual localized tactile feedback. Kim et al. [32] explored how key-click feedback signals produced masking effects on a flat surface with two fingers. In their research, users perceived localized key-click feedback on their active fingers while a notably weaker signal was applied to passive fingers. However, the exact mechanism of how sensory masking works remains unknown.

2.4 Thermal User Interfaces

Thermal user interfaces have been widely investigated in Human-Computer Interaction to provide realistic and rich sensory feedback. Thermal sensations can be achieved in single or combined heat transfer methods, including conduction, convection, and radiation. The contact-based thermal device provides thermal sensation via conduction or convection directly attached to the human skin, with sufficient contact area and a high heat transfer rate. The Peltier (thermoelectric) device is commonly used due to its fast temperature-changing characteristics and capability of expanding its heat coverage on the human body [10, 42]. Another common contact-based approach is to use a water pipe. It can deliver thermal sensation quickly because of water's high thermal conductivity and flexibility. It is also suitable for complex surfaces on the human body where the rigid body thermal actuators cannot fit [23, 25]. The non-contact-based thermal devices commonly use heat convection or radiation to achieve thermal sensation. Since these devices would be placed outside the body and have no skin contact, they can provide users with a more natural and seamless experience. The airflow with the target temperature is commonly used to deliver an ambient thermal sensation while the effective range is short due to the high diffusion rate of air [44, 47, 48]. The radiation-based infrared [29, 30] or laser [43] were also used to provide thermal sensation. A recent study [53] presented a fabric-based thermal interface using an ultrasound haptic display.

3 THERMAL MASKING

3.1 Definition

Thermal masking is a newly discovered phenomenon that shows masking properties in thermal referral. In previous literature on thermal referral [20], the thermal sensations can be referred to a nearby body location through thermo-tactile interaction, perceiving thermal sensations at both thermal and tactile locations. In thermal masking, we discovered that thermal sensation could be felt only at the tactile location when the simultaneous presentation of thermal and tactile stimuli is present. That is, thermal stimulus can be completely masked by induced thermal illusion, perceiving thermal sensation at the tactile location, but no thermal sensation would be felt at the thermal location.

Several studies reported that thermal referral is due to the spatial summation and thermal redistribution, yielding a uniform distribution across thermal and tactile locations [5, 28]. This means that thermal sensation can be felt at both original and referral locations, and the intensity of thermal feedback is the same. We hypothesize that a strong intensity of tactile signal can affect the redistribution of thermal sensation and dominate the thermal sensation. That is, if the thermal stimulus is sufficiently attenuated with a strong tactile signal, the thermal stimulus can be weakened, perceiving only the illusory thermal sensation at the tactile location. This is an interesting finding, as the property of thermal masking shows non-uniform thermal distribution across thermal and tactile locations. This thermal perception of the masking phenomenon can be significant and impact various thermal user interfaces as thermal sensation could be completely *migrated* from one location to another or even controlled to demonstrate the *thermal motion*.

In this study, we define four referral states: *No Referral*, *Weak Referral*, *Strong Referral*, and *Masking*. The thermal referral demonstrates apparent masking effects that exhibit non-uniform thermal redistribution, yielding different thermal perceptions at both thermal and tactile locations. Since the concept of thermal referral was

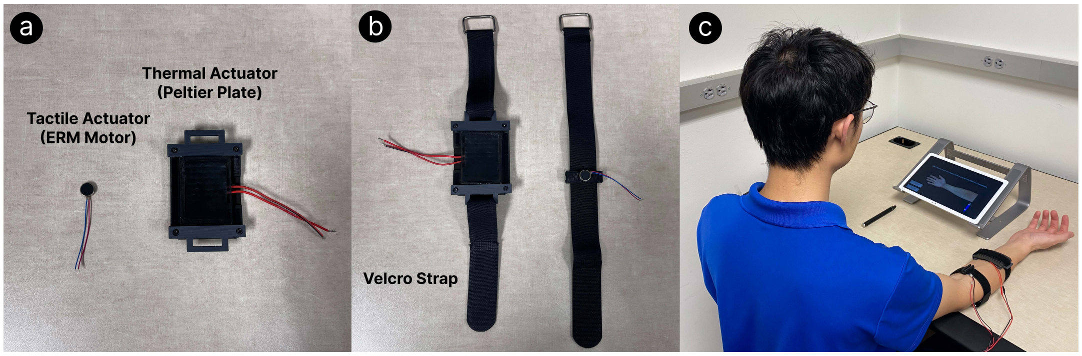

Figure 2: Experiment setup: (a) thermal actuator and a tactile actuator, (b) actuators with straps, and (c) a participant wearing straps with both thermal and tactile actuators.

defined based on the phenomenon only being observed at both thermal and tactile locations in the previous literature [20], there is a need to extend the definition in terms of strength of referral to explore the thermal masking phenomenon. Here, we define referral state as follows:

- **No Referral:** thermal sensation only perceived at thermal location
- **Weak Referral:** thermal sensation perceived at both thermal and tactile locations, with weaker thermal sensation at the tactile location
- **Strong Referral:** thermal sensation perceived at both thermal and tactile locations, with a stronger thermal sensation at the tactile location
- **Masking:** thermal sensation perceived only at the tactile location

These four referral states will be used as dependent variables to investigate several aspects of thermal masking and support our hypothesis.

3.2 Setup

We used a set of thermal and vibrotactile actuators to create thermal and tactile stimuli on the forearm. We selected the skin of the forearm as a target region due to its sparse distribution of thermal receptors in its skin [36]. Across all experiments, we placed the thermal actuator at the central location on the ventral side of the forearm to deliver thermal stimulus (see Figure 2). This location was chosen based on the preliminary study demonstrating a higher probability of thermal masking occurring than in other skin areas on the forearm. The referral occurrence rate at the central location was approximately 20% and 10% higher than at the wrist for hot and cold conditions, respectively.

A Peltier-based thermal actuator with a curved shape surface (Tegway ThermoReal) is used for our study (see Figure 2 (a)). The Peltier dimension of the thermal actuator is 30 mm (width) × 40 mm (height) × 2.3 mm (depth). The bending radius of the Peltier is set to 7.5 mm for a better fit of the skin surface. The maximum temperature difference across the Peltier is 64°C under a current of 6 A and voltage of 5.7 V. The thermal actuator can reach the target temperatures in the current studies with a short response time of approximately 1 second.

We used off-the-shelf ERM vibrotactile actuators (Tatoko B07-Q1ZV4MJ) to generate tactile stimuli onto the forearm (see Figure 2 (a)). The vibrotactile actuator has a coin shape with a diameter of 10 mm with a depth of 3 mm. Based on a series of preliminary studies with hot and cold temperatures, we chose 10mN (2.68V) with 175Hz for warm and hot temperatures and 14 mN (3.19V) with 225 Hz for cool and cold temperatures (see their characteristics in Figure 3), respectively. During these studies, we confirmed that the vibration intensities of 10 mN and 14 mN achieved the highest probability of thermal masking for warm and cool conditions, respectively, demonstrating that cool conditions require stronger vibration intensity to elicit thermal masking. These parameters are within the Pacinian corpuscle detection range that can achieve a guaranteed perception of the vibrotactile stimulus [55] and showed the highest probability of thermal referral and masking.

We used adjustable velcro straps to fasten the thermal and vibrotactile actuators on the forearm. A 3D-printed structure was used to attach the vibrotactile actuator and hold the strap, ensuring tight contact with the skin (see Figure 2 (a)). Both thermal and vibrotactile actuators were powered by a programmable digital power supply (Korad KD6005P). The power supply was controlled through the serial port and operated under constant voltage mode as all actuators functioned by the input voltage. We also used a desktop PC for the experimenter to run the experiments and a tablet with a stylus pen for the participants to show the instructions and record the data.

4 STUDY 1: THERMAL MASKING ON TEMPERATURE

The main goal of this study is to investigate masking effects on temperature. The occurrence rates of *No Referral*, *Weak Referral*, *Strong Referral*, and Masking are measured under four different temperature conditions on the ventral side of the forearm to explore redistribution of the perceived thermal regions under different temperatures.

4.1 Participants

Twenty participants (mean age 22.1 (SD = 3.1), eight females) completed this study. They were recruited via online advertisements at the authors' institution and received a $10 gift card as compensation.

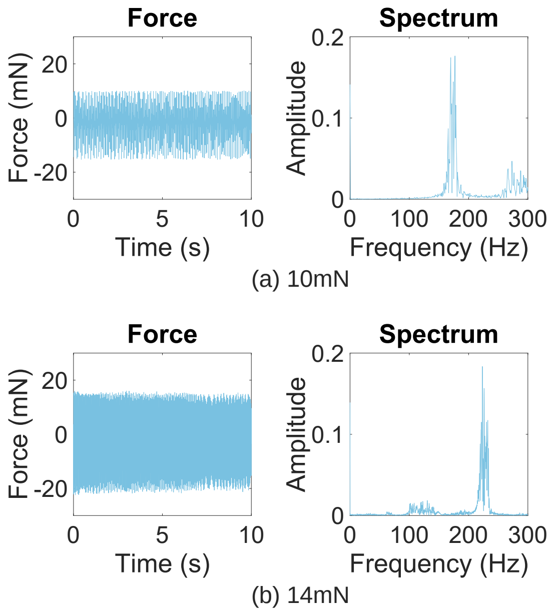

Figure 3: Characteristics of tactile actuator: intensity and frequency.

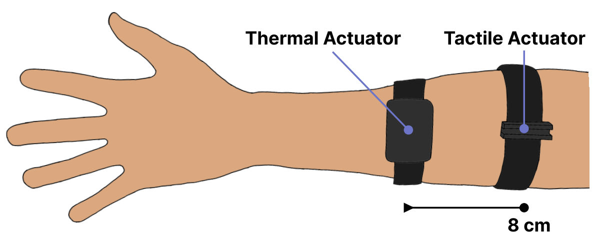

Figure 4: Concept diagram depicting the placement of the actuators for study 1. One thermal actuator was placed in the middle of the forearm. One tactile actuator was placed 8cm apart from the thermal actuator.

A screening procedure with a questionnaire form was preceded to exclude individuals with neuropathy or any injuries to the skin of the forearm. All experiments were approved by the author's institution's Institutional Review Board.

4.2 Study Design

Actuators Placement. We placed one thermal actuator at the center of the forearm and one tactile actuator 8 cm apart from the thermal actuator towards the center of the arm (see Figure 4). The duration of thermal and tactile stimuli was set to five and seven seconds, respectively, and they were activated at the same time. We provided an additional two seconds of duration for the vibrotactile stimulus to prevent any perceptual confusion due to the recession time of thermal sensation from the Peltier.

Experimental Conditions. We designed a single variable with four temperature levels: cold (-8°C), cool (-5°C), warm (+3°C), and hot (+6°C) temperatures from participant's neutral skin temperature, to examine thermal masking on the different types of thermal receptors. Four temperatures were selected based on the pain threshold of thermal stimulus [4, 39] and our preliminary study. The vibration intensity that we set was 14 mN for cool and cold temperatures with a frequency of 225 Hz, and 10 mN for warm and hot temperatures with a frequency of 175 Hz, respectively.

Three questions (see Figure 5) were provided to determine the referral state (i.e., *no referral*, *weak referral*, *strong referral*, and *masking*). The response to each question was collected by checking one of two checkboxes for binary answers.

- Q1) I felt the thermal sensations.
- Q2) Please select the region where you felt strong (hot/warm) sensations.
- Q3) Did you also feel (hot/warm) sensations in the other region?

The Q1 validates the success of thermal stimulus delivery with yes/no answers. The combination of Q2 and Q3 confirms the *referral state*, as shown in Table 1.

Table 1: Referral State.

	Q2 response	Q3 response
No Referral	Thermal location	No
Weak Referral	Thermal location	Yes
Strong Referral	Tactile location	Yes
Masking	Tactile location	No

Each block was composed of a set of trials in one temperature group. Trials were delivered in a random order. The order of the cold and hot temperature groups was balanced among participants. Participants conducted ten trials for each temperature condition. In total, 800 trials were retained (20 participants by four temperature levels by ten repetitions) over the study.

4.3 Procedure

Participants were seated in front of a desk and asked to read the instructions and sign a consent form. They received detailed information about the experiment's procedures and instructions. However, no information about the referral phenomenon was presented to the participants to avoid any preconceived notions. A ten-minute rest time was given to ensure the participants' skin temperature became a steady state. The initial skin temperature was measured using the thermal camera (Optris PI450) during this time. The length of the participant's dominant forearm was also measured using a measuring tape to place the actuators precisely. After the experimenter confirmed that participants clearly understood the study instructions, they were asked to wear the straps with thermal and vibrotactile actuators on their forearms and place them on the desk with a comfortable posture (see Figure 2(c)). In each trial, we asked participants to close their eyes. After five seconds, both tactile and thermal stimuli were delivered to the forearm. After each trial, they took off the strap of the thermal actuator to neutralize the skin temperature. Participants were then asked to answer three questions

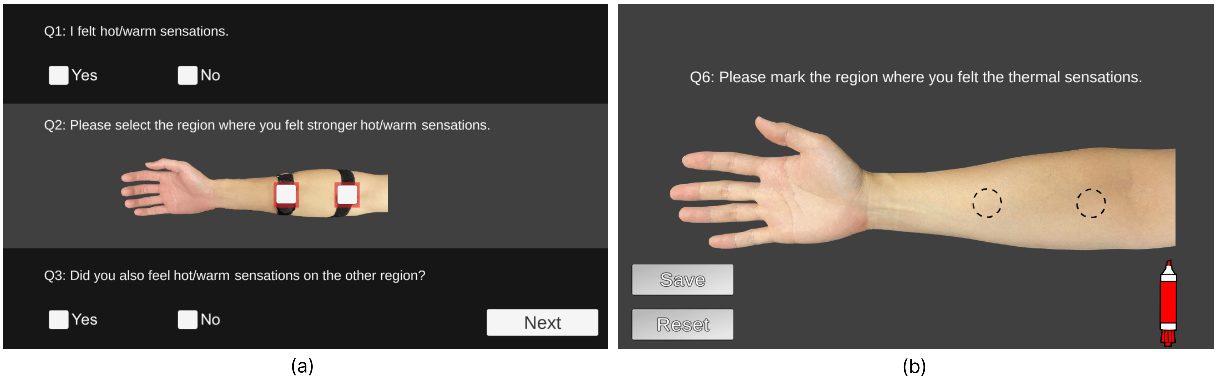

Figure 5: (a) Three questions in study 1 were provided to determine the referral state and (b) one image of an arm was provided to allow users to draw the perceived thermal area (the circle contour indicates the center location of the actuators by avoiding any bias from the shape)

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about the referral state (see Figure 5 (a)). Participants were then presented with an image of an arm on a tablet to freely draw any contours that fit their perceived thermal regions using a stylus (see Figure 5 (b)). A two-minute break was given after every ten trials, and the study took approximately 50 minutes to complete.

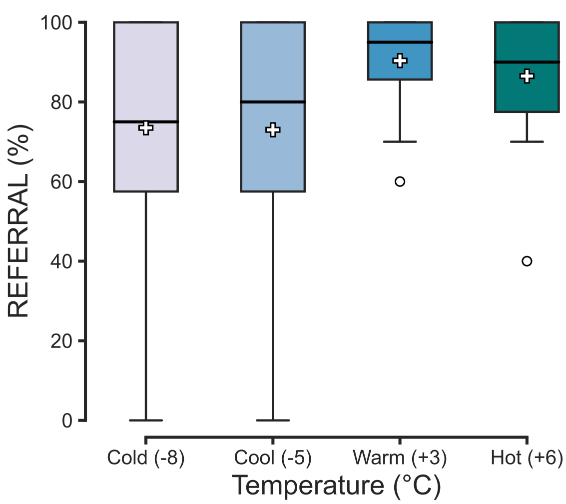

Figure 6: Mean occurrence rates of REFERRAL on four temperatures.

4.4 Results and Discussion

Figure 6 shows the occurrence rate of *REFERRAL* (i.e., a combination of *weak referral*, *strong referral*, and *masking*) in four temperature conditions. The overall mean of *REFERRAL* was 80.8%, showing a uniformly high referral rate with all participants. The warm condition showed the highest mean rate of *REFERRAL* (90.4%). The mean thermal detection rate was 99.1% (Q1 response).

Figure 7 shows the breakdown of *REFERRAL* that shows the occurrence rates of *no referral*, *weak referral*, *strong referral*, and *masking* for each temperature condition. In cold and cool conditions, *weak referral* was presented most frequently, followed by *strong referral* and *masking*. In warm conditions, the occurrence rate of *masking* was the highest, followed by *strong referral*. In hot conditions, the occurrence rates of *strong referral* were higher than that of *masking*. The results clearly show the variation of the referral state at different temperatures.

To statistically analyze data from all studies, we adopted Repeated-Measures (RM) ANOVA with Greenhouse-Geisser corrections for sphericity violations and post-hoc t-tests with Bonferroni corrections. The effect size for an ANOVA was reported by a partial-eta squared (η_p^2). In this study, we analyzed data with one-way RM ANOVA on the temperature for the different referral states. A significant result is reported ($F(3, 57) = 5.84$, $p < 0.05$, η_p^2=0.24) for *REFERRAL*. Post-hoc t-tests showed no significant differences for cold/warm ($p = 0.136$) and cool/warm ($p = 0.088$). While the results have the likelihood of a Type I error, the results in Figure 6 suggest that the *REFERRAL* presented more frequently at the warm temperature generally than at other temperatures. Only *masking* showed a significant difference ($F(3, 57) = 11.84$, $p < 0.001$, η_p^2=0.38) among *weak referral*, *strong referral*, and *masking*. Post-hoc testing revealed that the *masking* in warm conditions showed a higher occurrence rate than in the cool and cold conditions ($p < 0.05$), implying that the masking phenomenon likely appears more often when the temperature is warm.

Figure 8 shows the perceived thermal distribution on the forearm for each condition. The results show that the perceived area of thermal illusion in *strong referral* and *masking* is generally larger than the actual size of the vibrotactile actuator, while *weak referral* shows similar size of perceived area to the actuator. It indicates that the illusory thermal sensation could be more dispersed as the thermal illusion becomes stronger. Particularly, the perceived thermal area in warm and hot conditions is larger than that in cool and cold conditions, following the higher occurrence rate of *masking* in warm temperatures. In *masking* for all temperature conditions, apparent thermal migration from the thermal actuator to the vibrotactile actuator is clearly observed.

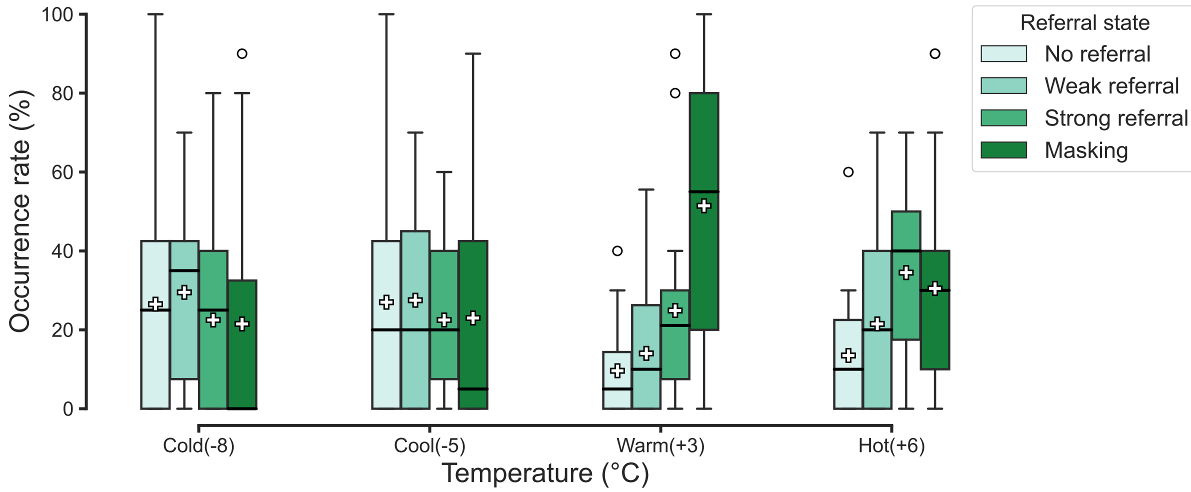

Figure 7: Mean occurrence rates of no referral, weak referral, strong referral, and masking on four temperatures.

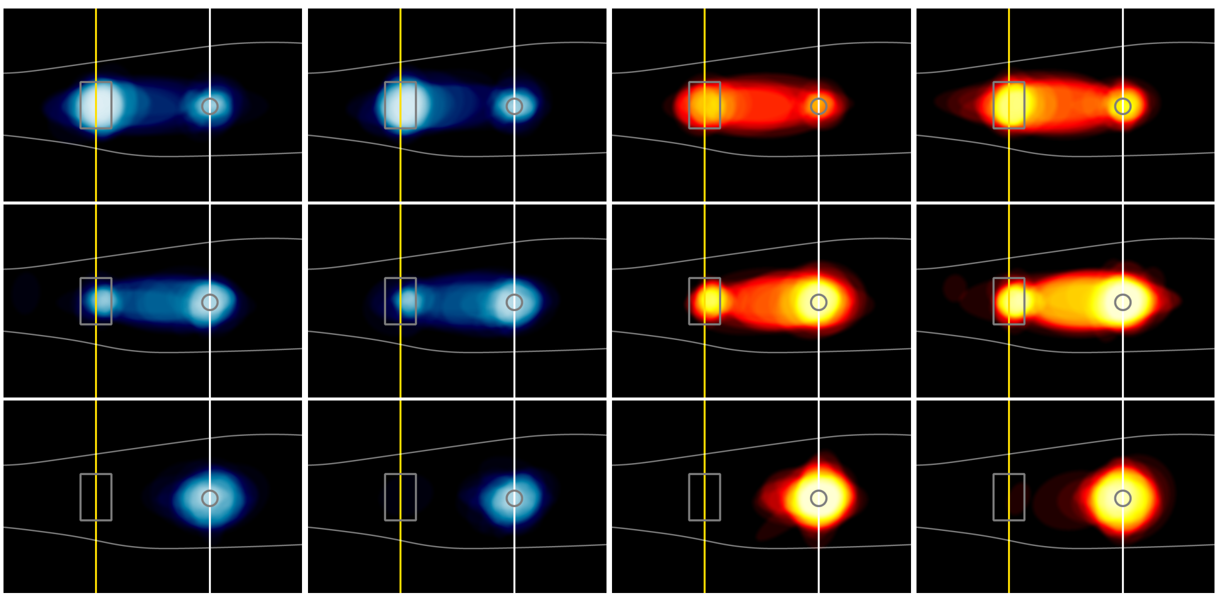

Figure 8: Perceived thermal distribution by weak referral, strong referral, and masking with four temperatures. Drawings from all participants were overlaid to obtain perceived thermal distribution. Red hues represent warm and hot conditions, while bluer shades represent cool and cold conditions. The brighter regions in the figure indicate higher drawing frequency. From top row to bottom row: *Weak Referral, Strong Referral, Masking*. From left column to right column: -8°C, -5°C, 3°C, 6°C. Rectangle contour = Thermal actuator, Circle contour = Tactile actuator, Yellow line = Center of the thermal actuator, and White line= Center of the tactile actuator.

It seems evident that warm temperatures are significantly more effective for masking compared to cool and cold temperatures. This can be attributed to the greater abundance of cold receptors on our skin, outnumbering the warm receptors [36]. The high density of cold receptors may cause a less spread of thermal redistribution among the area between two actuators, which may result in less frequent thermal illusions on the tactile location [28]. On the other hand, the temperature conditions with a high-temperature gap from the neutral skin temperature could yield a lower occurrence rate than the low-temperature gap. This could be caused by the stronger magnitude of the thermal sensation, which weakens the thermal redistribution [20, 28].

5 STUDY 2: THERMAL MASKING ON DISTANCE

This study aims to explore the effective distance range of thermal masking in the entire arm. The occurrence rates and the perceived thermal regions for the four referral states were measured to study the distance effect.

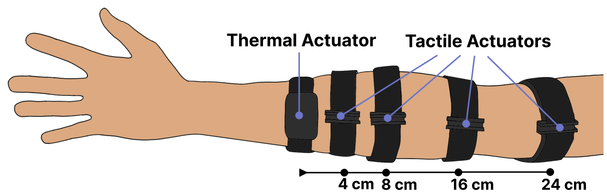

Figure 9: Concept diagram depicting the placement of the actuators for study 2. One thermal actuator was placed in the middle of the forearm. Four tactile actuators were placed at 4cm, 8cm, 16cm, and 24cm apart from the thermal actuator. All actuators were placed on the ventral side.

5.1 Participants

Twenty-two participants (mean age 23.7 (SD=3.6), nine females) who did not participate in the first user study participated in this study. We followed the same procedure of recruitment, compensation, and screening as in the previous study.

5.2 Study Design

Actuators Placement. In this study, we varied the location of the vibrotactile actuators with four distance levels. They were placed at 4 cm, 8 cm, 16 cm, and 24 cm apart from the thermal actuator. One thermal actuator was placed at the same location (the middle of the forearm) as in the previous study (see Figure 9). The four tactile actuators and a thermal actuator were worn together to reduce any perceptual bias by the setup. The onset time and duration for both thermal and vibrotactile actuators were the same as in our previous study.

Experimental Conditions. This study involved two independent variables: temperature and distance. Two temperature levels of cool (-5°C) and warm (+3°C) were selected based on the results from the first user study. Four distance levels of 4cm, 8cm, 16cm, and 24cm were determined for short and long distances based on the average human arm length. To explore the ceiling of thermal masking distance, we chose those 16cm and 24cm to reach the upper arm. The intensity and frequency of vibrotactile actuators were the same as in the first study for cool and warm conditions. The same three questions were provided to determine the referral state.

A block consisted of the randomized trials of four distances to avoid any bias. The order of the cool and warm conditions was balanced among participants. Each condition, by the temperature and distance, has five trials. We gathered a total of 880 trials with the combination of 22 participants by two temperatures by four distances by five repetitions.

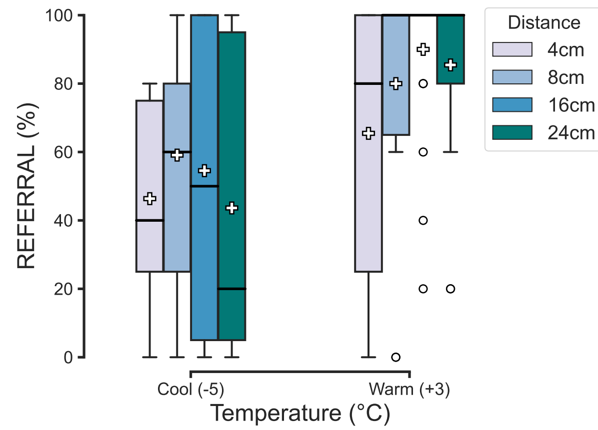

Figure 10: Mean occurrence rates of REFERRAL by two temperatures and four distances.

5.3 Procedure

Participants were asked to wear five straps on their arms. The rest of the procedure was the same as the first user study.

5.4 Results and Discussion

Figure 10 shows the mean rates of *REFERRAL* (i.e., a combination of *weak referral*, *strong referral*, and *masking*) at each distance level in cool and warm conditions. It shows a generally higher rate and lower variances with warm conditions than cool conditions over four distance levels. The low occurrence rates of *REFERRAL* were observed at the shortest distance (4cm) at both temperatures. The mean occurrence rates of warm conditions were 90% and 85% at 16cm and 24cm, respectively, showing higher rates at long distances. The results indicate that the thermal referral could be reached to the upper arm with a higher chance. The mean thermal detection rate was 99.9% (Q1 response).

Two-way RM ANOVA for the temperature and distance variables was conducted for data analysis. There was only one significant main effect of temperature ($F(1, 21) = 20.72$, $p < 0.001$, η_p^2=0.50). Post-hoc t-tests revealed that *REFERRAL* at the warm condition led to a higher occurrence rate on the distances of 8cm (p<0.01), 16cm (p<0.01), and 24cm (p<0.001). This result suggests that the warm temperature better generated thermal referral with the vibrotactile stimulus over long distances.

The individual occurrence rates of *weak referral*, *strong referral*, and *masking* are shown in Figure 11. Both *masking* and *strong referral* accounted for high occurrence rates in warm conditions at all distances. It shows that the strength of the thermal illusion was likely to be stronger than the actual thermal sensation from the thermal actuator when thermal referral occurred.

The three referral states were analyzed using two-way RM ANOVA with the temperature and distance variables. Only *masking* showed significant main effect on temperature ($F(1, 21) = 18.23$, $p < 0.001$, η_p^2=0.46) and interaction effect ($F(3, 63) = 8.99$, $p < 0.001$, η_p^2=0.30), indicating the strongest effect of *masking* on temperature. We also note that the interaction effect involves the distance variable. It

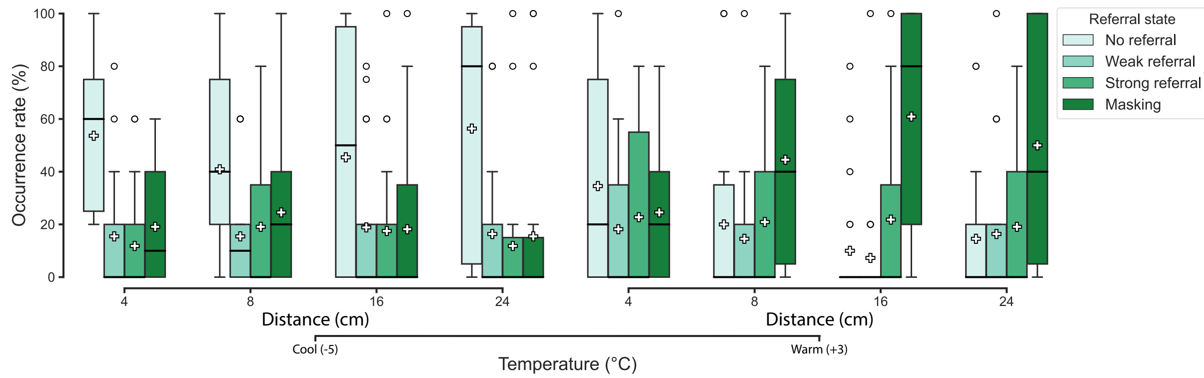

Figure 11: Mean occurrence rates of no referral, weak referral, strong referral, and masking by two temperatures and four distances.

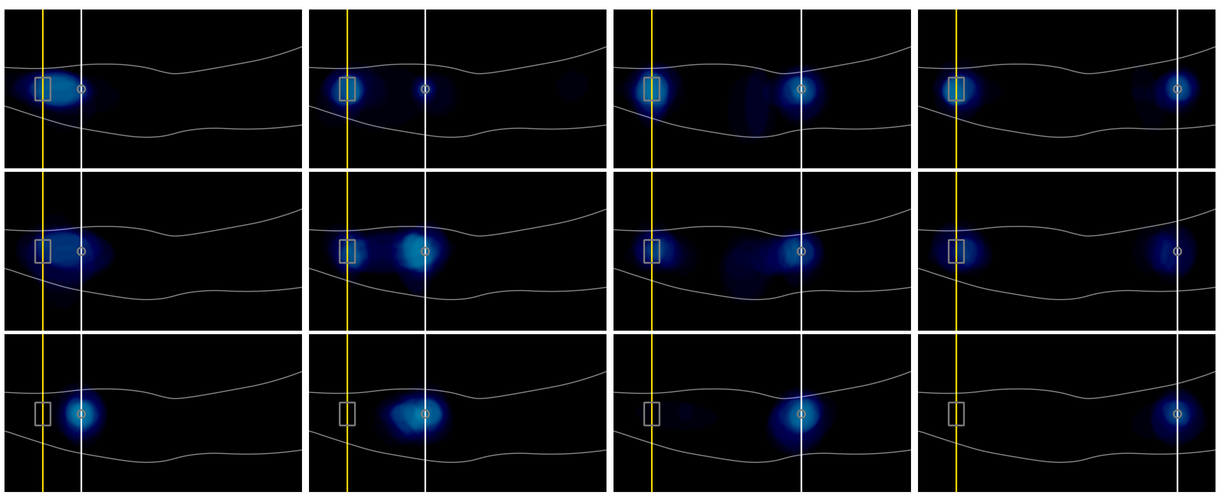

Figure 12: Perceived thermal distribution by weak referral, strong referral, and masking with the cool temperature. From top to bottom row: *Weak Referral, Strong Referral, Masking*. From left column to right column: 4cm, 8cm, 16cm, 24cm. Rectangle contour = Thermal actuator, Circle contour = Tactile actuator, Yellow line = Center of the thermal actuator, White line= Center of the tactile actuator.

can be demonstrated with the results of post hoc t-tests as the high occurrence rates of *masking* at the distances of 16 cm and 24 cm impacting the overall occurrence rate of *masking* at the warm condition. This suggests that the warm temperature can yield a higher masking rate than the cool temperature as the distance increases. It may be due to the difference in density of the warm and cold receptors, which is similar to the results from Study 1.

The thermal distribution of the perceived regions on the two temperatures and four distances are shown in Figure 12 and Figure 13. Three types of thermal referral showed similar trends compared to Study 1: a larger and denser region from the stronger thermal illusions. In addition, we observed that the area of illusory thermal sensation is generally larger than the contact area of the tactile actuator over all distance levels. Specifically, in warm conditions, the strong thermal illusions with high occurrence rate formed more dispersed thermal sensations regardless of the distance. At the shortest distance (4 cm), *weak referral* and *strong referral* were likely to form a unified thermal region at both locations. This demonstrates that the more dispersed single sensation was perceived rather than two separated thermal sensations due to the close distance. This might be due to poor tactile spatial resolution for close distances and may result in a low occurrence rate of thermal referral at 4 cm. At the distance of 16 cm, the thermal sensation was likely to be redistributed around the elbow joint. This may indicate that the thermal referral can be generated by the vibration conveyed to joints through the skin. It is also interesting to see clear *masking* at 24 cm, indicating thermal masking is feasible for larger distances. One possible interpretation is that the afferent nerve signals from two thermal and tactile locations far apart can be transmitted to the brain cortex within the acceptable time for sensory masking [38, 46].

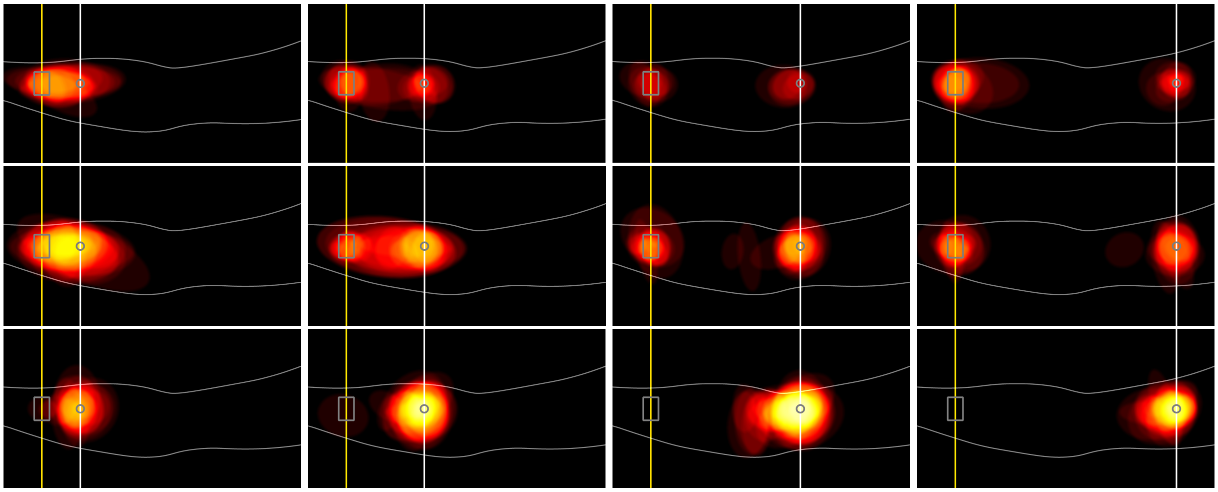

Figure 13: Perceived thermal distribution by weak referral, strong referral, and masking with the warm temperature. From top to bottom row: *Weak Referral, Strong Referral, Masking*. From left column to right column: 4cm, 8cm, 16cm, 24cm.Rectangle contour = Thermal actuator, Circle contour = Tactile actuator, Yellow line = Center of the thermal actuator, White line= Center of the tactile actuator.

6 STUDY 3: THERMAL MASKING ON THE OPPOSITE SKIN SIDE

This study aims to explore the interaction space of masking effects by placing the tactile actuators on the opposite side of the thermal actuator. We measured the referral states on both the dorsal and ventral sides of the forearm to observe the thermal redistribution over the arm in two different temperature conditions.

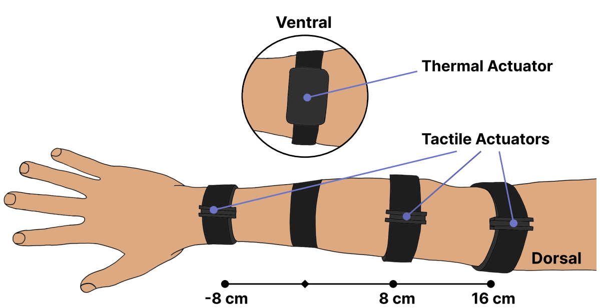

Figure 14: Concept diagram depicting placement of the actuators. A thermal actuator was placed at the middle of the forearm on the ventral side. Three tactile actuators were placed at -8cm, 8cm, and 16cm apart from the thermal actuator on the dorsal side.

6.1 Participants

Eighteen participants (mean age 23.4 (SD=3.4), nine females) who did not participate in the previous two studies completed this study. We followed the same procedure of recruitment, compensation, and screening as in the previous two studies.

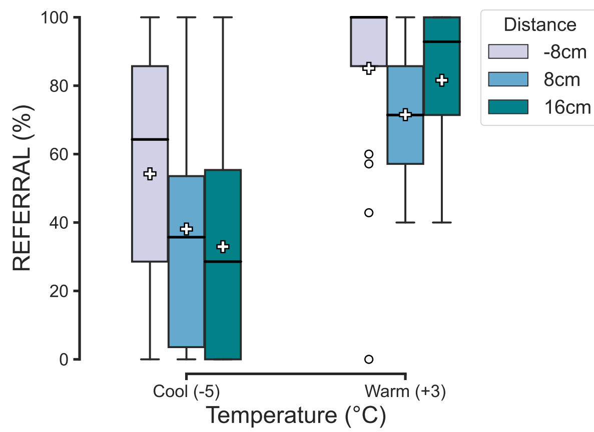

Figure 15: Mean occurrence rates of REFERRAL by two temperatures and three distances at the dorsal side of the arm.

6.2 Study Design

Actuators Placement. Three tactile actuators were placed on the dorsal side of the forearm, while one thermal actuator was placed at the same location as in our previous two studies (i.e., the middle of the forearm on the ventral side of the forearm). The locations of tactile actuators were -8cm (8cm toward the wrist), 8cm, and 16cm (8cm and 16cm toward the upper arm from the thermal actuator) (see Figure 14). Participants wore the three tactile actuators along with the thermal actuator at the same time to minimize the perceptual bias. The methods of presenting stimuli were the same as in our previous studies.

Experimental Conditions. We explored the thermal masking on the effects of temperature and placement on the opposite side of

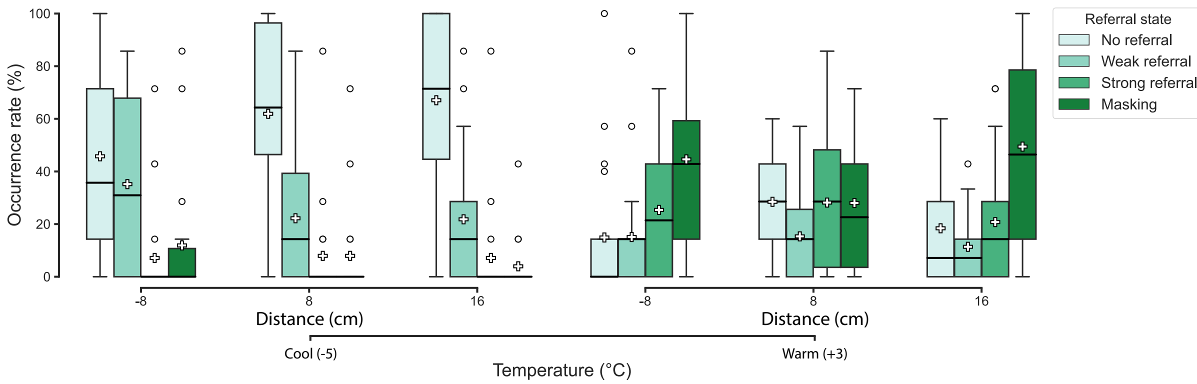

Figure 16: Mean occurrence rates of no referral, weak referral, strong referral, and masking by two temperatures and three distances at the dorsal side of the arm.

the forearm. We chose the distance of -8cm as it is a popular place for the wristwatch. We kept 8cm and 16cm distances to maintain consistency with the distance condition in Study 2. The temperature conditions were cool and warm, as in the second user study, and we used the same intensities and frequencies as in the previous studies. The thermal and tactile stimuli were delivered in the same way as in the previous studies. All trials were randomized, and the order of cool and warm conditions was balanced. Each condition by temperature and distance has seven repetitions. In total, we retained a total of 756 trials throughout the study, with the combination of 18 participants by two temperature levels and three distance levels by seven repetitions. The same three questions were provided to determine the referral state.

6.3 Procedure

Four straps were placed on the participants' arms. Besides this, we used the same procedures as in the previous studies.

6.4 Results and Discussion

As shown in Figure 15, the mean occurrence rates of *REFERRAL* at -8cm, 8cm, and 16cm with the warm conditions were relatively higher than in cool conditions, indicating that the thermal referral is likely to occur at the opposite side of the forearm with a higher rate with warm temperatures. A two-way RM ANOVA was conducted for statistical analysis. There were two significant main effects for both temperature ($F(1, 17) = 34.49$, $p < 0.001$, η_p^2=0.67) and distance ($F(2, 34) = 4.70$, $p < 0.05$, η_p^2=0.22) and interaction effect ($F(2, 34) = 6.35$, $p < 0.01$, η_p^2=0.27). Post-hoc t-tests for the distance explicitly showed that the distance of -8cm had a significantly higher occurrence rate than the distance of 8cm ($p < 0.05$). It suggests that the wrist is suitable for generating thermal referral on the dorsal side of the forearm. The interaction effect can be interpreted with the results of post-hoc t-tests as thermal referral is presented with a higher rate in warm conditions at all distances of -8cm ($p < 0.01$), 8cm ($p < 0.001$), and 16cm ($p < 0.001$). The mean thermal detection rate was 98.1% (Q1 response).

Figure 16 shows the individual referral state. The results show the majority of *no referral* and *weak referral* at all distance levels in cool conditions, indicating poor referral performance at the opposite side of the arm. In warm conditions, we observed dominant *strong referral* and *masking*.

We statistically analyzed the individual occurrence rate of *weak referral*, *strong referral*, and *masking* with two-way RM ANOVA. We found that *strong referral* shows a significant main effect on the temperature($F(1, 17) = 9.82$, $p < 0.01$, η_p^2=0.37) by the higher rates in warm condition. We also found that *masking* had a significant main effect of temperature ($F(1, 17) = 29.68$, $p < 0.001$, η_p^2=0.64) and interaction effect ($F(2, 34) = 4.58$, $p < 0.05$, η_p^2=0.21). The interaction effect can be interpreted as the higher occurrence rates at all distances of -8cm ($p < 0.01$), 8cm ($p < 0.05$), and 16cm ($p < 0.001$) on the warm temperature by post-hoc t-tests. The results suggest that the forearm's opposite side (dorsal side) tended to have a similar trend in thermal referral and masking to the ventral side of the forearm: the higher occurrence rates on all distances with the warm temperatures.

Figure 17 and 18 shows the thermal distribution on the dorsal side of the forearm. The thermal referral was formed in the dispersed thermal location around the location of the vibrotactile stimulus on the dorsal side and the ventral side of the forearm. The thermal illusion also occurred on the opposite side of the target area on the ventral side of the forearm. This phenomenon was observed particularly on the wrist, the thinnest part of the forearm. It may indicate that the thermal illusions can be spread to both sides of the forearm, and the thickness of the arm can affect the thermal referral on the opposite side. Furthermore, it was noted that positioning actuators on the opposite side of the arm resulted in a more dispersed sensation, in contrast to the findings from Study 2, where actuators were on the same side. The afferent nerves on two sides of the forearm may convey the sensations to the brain cortex with a different modulation process, yielding poor sensory masking [6]. It may even weaken the masking occurrence in cool conditions with a higher density of cold receptors.

7 DISCUSSIONS

We demonstrated apparent thermal masking phenomenon and non-uniform thermal redistribution in thermal referral. Previous studies

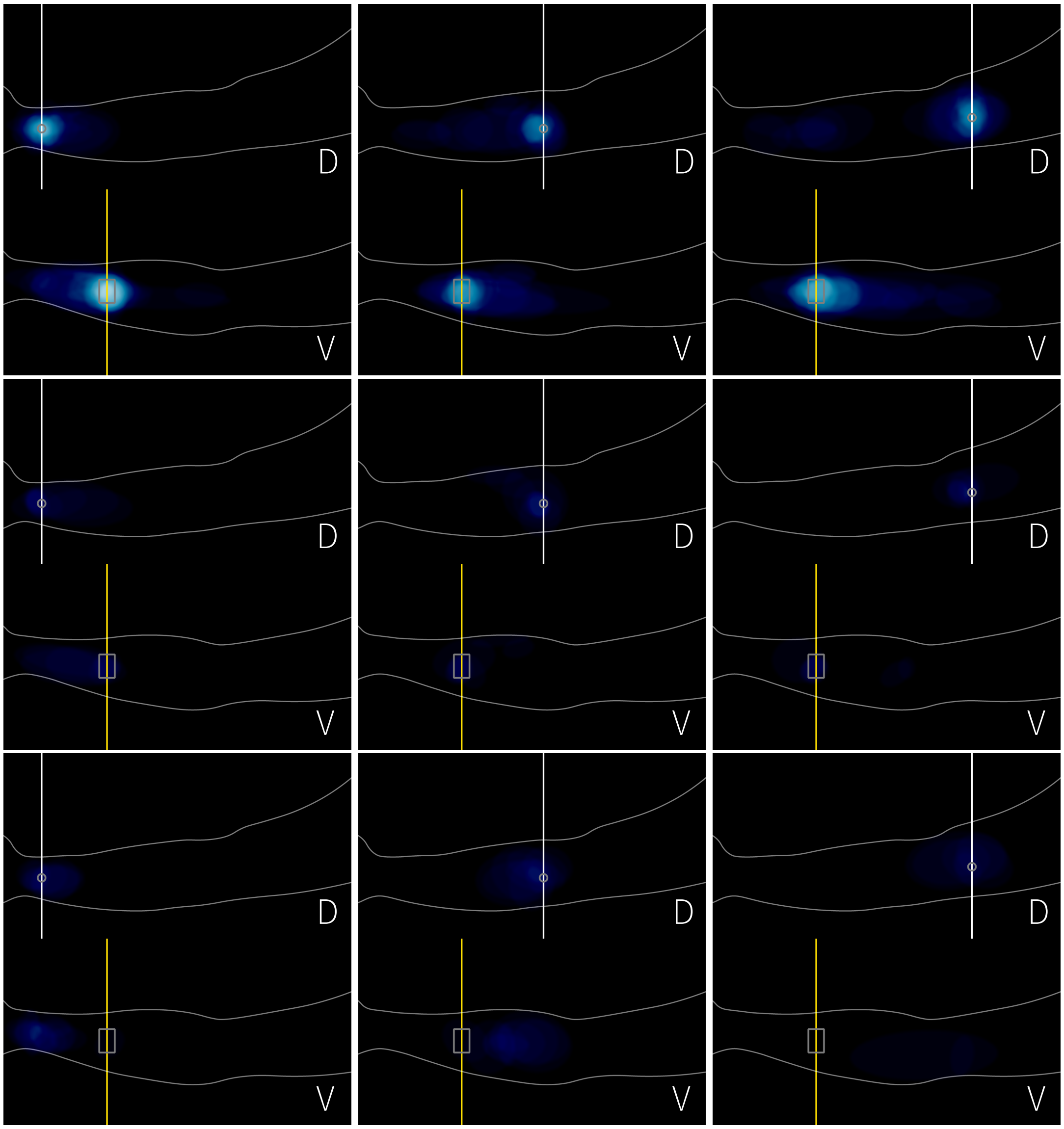

Figure 17: Perceived thermal distribution by weak referral, strong referral, and masking with the cool temperature. From top to bottom row: *Weak Referral*, *Strong Referral*, *Masking*. From left column to right column: -8cm, 8cm, 16cm. Rectangle contour = Thermal actuator, Circle contour = Tactile actuator, Yellow line = Center of the thermal actuator, White line= Center of the tactile actuator. D: Dorsal side of the arm, V: Ventral side of the arm.

have claimed that thermal referral relies on spatial summation and uniform redistribution of thermal sensations between the initial and referred sites. We showed that original thermal sensation can be sufficiently attenuated and dominated by illusory thermal sensation.

Sensory masking has been extensively investigated in auditory, tactile, and visual stimuli, but the discovery of the masking phenomenon in thermal is new. It's a novel phenomenon that extends the concept of thermal referral in that the original thermal sensation can be completely attenuated so that thermal sensation can be only felt at remote locations. To the best of our knowledge, there exists no known thermal masking theory that one thermal stimulus dominates another thermal stimulus in two different sites. That is, there are no "true" masking effects in thermal cues in that we can perceive two distinctive thermal stimuli when applied simultaneously in different locations, regardless of whether they are the same or different temperatures. Our discovery of thermal masking that demonstrates illusory thermal sensation dominating the existence of thermal sensation will present a new aspect of masking and can help advance scientific research in the understanding of thermal perception.

Another aspect of our contribution is engineering benefits. Our finding of non-uniform thermal redistribution in thermal referral

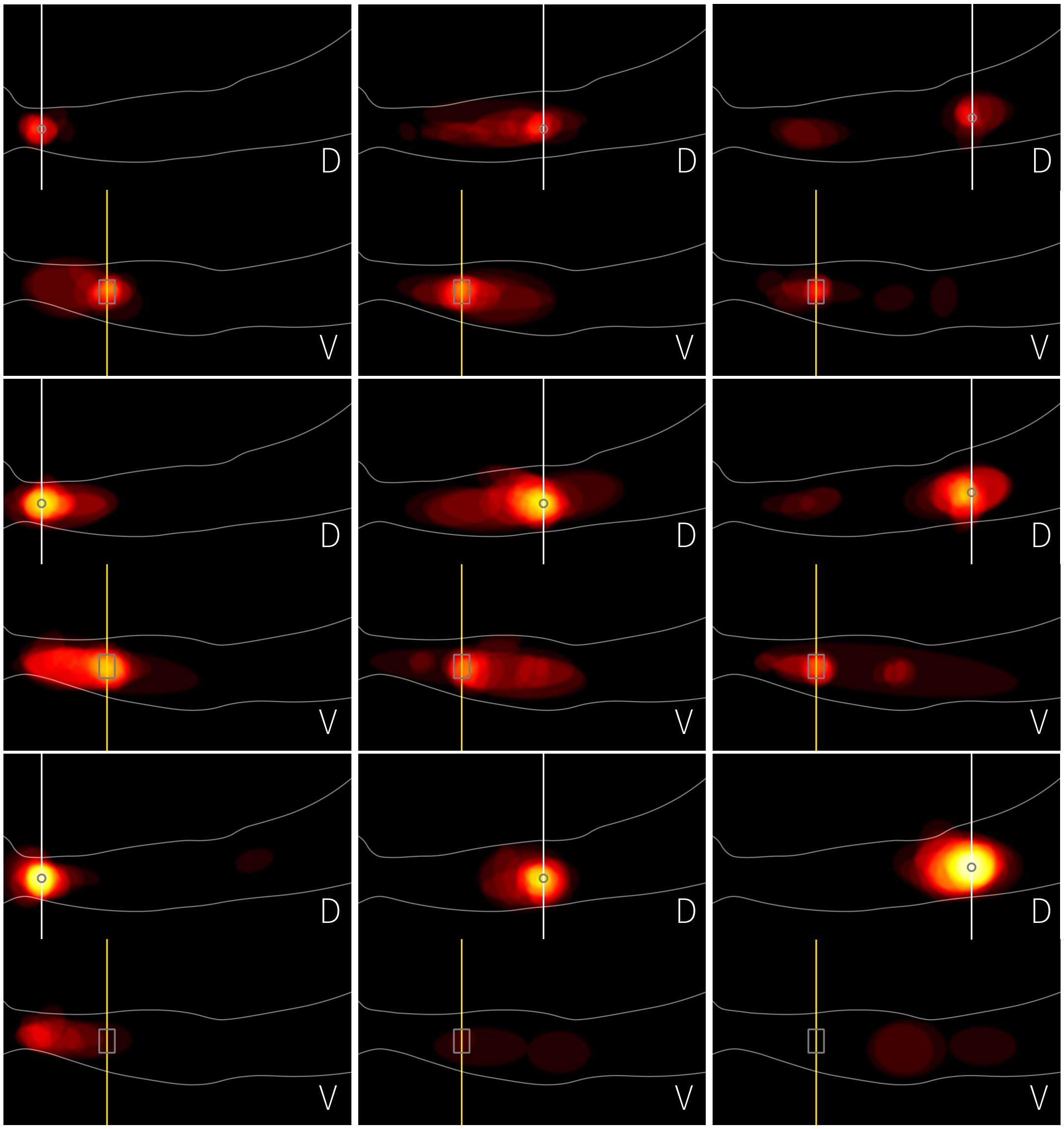

Figure 18: Perceived thermal distribution by weak referral, strong referral, and masking with the warm temperature. From top to bottom row: *Weak Referral, Strong Referral, Masking*. From left column to right column: -8cm, 8cm, 16cm. Rectangle contour = Thermal actuator, Circle contour = Tactile actuator, Yellow line = Center of the thermal actuator, White line= Center of the tactile actuator. D: Dorsal side of the arm, V: Ventral side of the arm.

contradicts the existing theory, and this could potentially impact various thermal user interfaces and displays. With non-uniform thermal redistribution properties in thermal referral, we can design effective thermal interfaces using a combination of thermal and vibrotactile actuators. This can be advantageous when developing a large-scale thermal display, as it allows large coverage areas with relatively few thermal actuators, such as gloves, vests, suits, sleeves, and shoes. Additionally, this approach can be cost-effective as thermal actuators are relatively more expensive and require more power. Eventually, adopting thermal masking could simplify the engineering complexity and enhance the efficiency of designing various thermal interfaces. Furthermore, a complete migration of thermal sensation can lead to creating immersive interaction experiences by designing thermal motion illusions that move from one point to another, delivering various thermal motion effects on the human body. It can be applied to various engineering hardware and human-computer interfaces like gloves, vests, and even handheld controllers that can be integrated with VR and AR to deliver dynamic thermal patterns and animation for immersive user experiences. We believe that our findings can help overcome current hardware limitations of providing thermal feedback, benefitting designers and engineers in the HCI community.

We show several important takeaways from this study. We clearly observed that thermal masking can impact a wide effective range and space. This phenomenon could reach long distances (i.e., 24 cm) and the other side of the arm, demonstrating the feasibility of 3D thermal cues that could cover the entire arm. The wrist area (-8 cm) showed a high masking occurrence rate, implying optimal actuator placement location for wearable applications. Another interesting finding was the perceived thermal dispersion. We observed that the perceived thermal sensation in thermal masking (and other referral states) was considerably larger than the actual size of vibrotactile actuators. We also observed that in many cases, this perceived thermal illusion was even larger than the original sensations in other referral states. This is interesting as the size of vibrotactile actuators (diameter of 10 mm) is much smaller than that of thermal actuators (30 mm (width) × 40 mm (height)). Leveraging this property can expand the thermal interaction space around the location of actuators to cover a relatively larger area than the physical size of actuators.

Another interesting finding is that warm stimuli showed a relatively higher probability of thermal masking than cool stimuli. It could be due to the sparse distribution of warm receptors that resulted in a lower magnitude of thermal stimuli, which raises the masking occurrence rate. It exhibited a comparable observation in the previous thermal referral studies [20, 28]. While the warm conditions outperformed the cool and cold conditions in thermal masking, the occurrence rate of other referral states is in the acceptable range for implementing large-scale displays with cool and cold sensations. In addition, we also noticed that the temperature should not be too far from the skin temperature to increase the masking probability. Earlier studies indicated that higher intensity of thermal feedback might reduce referral effects [28]. We also observed similar properties in thermal masking in that a higher rate of masking was observed under warm conditions compared to hot conditions.

The underlying mechanism of thermal masking is still unknown. One hypothesis is the diversion of attention while experiencing simultaneous cross-modal stimuli. Masking is observed when both signals are presented simultaneously or in quick succession. The dominant signal interferes with the processing of the target signal, diverting processing resources away from it [16, 18]. It is known that tactile and thermal stimuli are processed in different regions of the cerebral cortex. Thermal signals activate the insular cortex, while tactile signals activate the somatosensory cortex. Shubert et al. [46] found that in a masking scenario, the weaker stimulus signal activated the primary somatosensory cortex even if it was masked. This is interesting as it could mean that both the strong and weak signals are processed in the brain, but only one of them is perceived. They conclude that masking results from a shift in attentional focus and conscious perception induced by activity in the reticular formation [6]. We hypothesize that the change in attentional focus and conscious perception is caused by the sudden appearance of the new and unexpected phantom stimulus, which functions as an *interrupter* for the ongoing processing of the initial stimulus. This interruption may lead to the masking of the original thermal cue.

An alternative hypothesis can be that the masking could potentially take place in the latter phases of signal transmission to the brain, perhaps as signals travel from the thalamus to the cerebral cortex. Meador et al. [40] demonstrated asymmetric thresholds exist between the left and right hand for somatosensory stimuli. They hypothesized that masking occurs during the interaction within the thalamocortical pathway. This finding can provide another hypothesis for the thermal masking process. Previous studies have shown that masking is more probable when the target and the masked signals share a channel while getting transmitted to the cortical region [40, 46, 51]. Thermal and tactile signals are received and processed differently by our neural system. Tactile stimuli are received by various mechanoreceptors present in the skin. Typically, the detection of tactile cues relies on one of four distinct mechanoreceptors (i.e., Pacinian corpuscle, Mesissner's corpuscle, Merkel's disk, and Ruffini ending). Thermal stimuli are detected by thermoreceptors located in the skin, with warm stimuli activating warm receptors and innocuous cold stimuli activating cold receptors. These receptors convert physical stimuli into electrical signals that are then transmitted along peripheral nerves to the spinal cord [13, 38]. The signals are then transferred to the thalamus, which serves as a gateway to the cerebral cortex and redirects the signal to the specialized regions of the cortex. Since the thalamus is the common gateway for both signals, it is possible that masking occurs during the thalamus-to-cortex transition.

We plan to expand our work to investigate factors including the vibrotactile cue size, intensity, frequency, and moving cue. The exploration of vibrotactile cue size helps reveal the thermal redistribution between two stimuli. It's known that tactile masking requires the masker signal with a specific signal-to-noise rate [18, 51]. In previous studies, the vibrotactile frequency impacts tactile masking [15, 51]. The study on intensity and frequency could show the strength range of thermal masking and unveil the relationship between those two masking mechanisms. We also plan to explore the moving cue to examine the thermal masking occurrence on moving body parts. Finally, the time duration that it takes to perceive the thermal illusion was not captured clearly. We believe exploring this factor could help reveal the occurrence process of thermal masking and its lasting time.

8 CONCLUSION

This study investigated the thermal masking phenomenon induced by thermal referral. We conducted three experiments to explore *no referral*, *weak referral*, *strong referral*, and *masking* using thermal and vibrotactile actuators on the user's arm. We confirmed that the thermal referral shows apparent masking effects under certain conditions, showing non-uniform redistribution of thermal sensation across different parts of the user's arm.

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