Upper Body Thermal Referral and Tactile Masking for Localized Feedback

Hyungki Son*, Haokun Wang*, Yatharth Singhal*, and Jin Ryong Kim

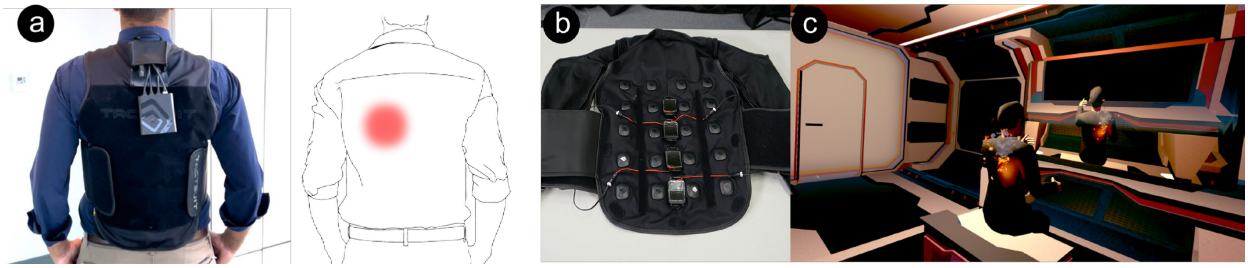

Fig. 1: a) A person wearing a thermal vest and perceiving localized thermal feedback, b) an inside view of the vest showing a 2D array of haptic actuators with thermal actuators in the middle column, and c) a VR scene showing the user looking at his back through the monitor screen.

Abstract—This paper investigates the effects of thermal referral and tactile masking illusions to achieve localized thermal feedback on the upper body. Two experiments are conducted. The first experiment uses a 2D array of sixteen vibrotactile actuators (4×4) with four thermal actuators to explore the thermal distribution on the user's back. A combination of thermal and tactile sensations is delivered to establish the distributions of thermal referral illusions with different numbers of vibrotactile cues. The result confirms that localized thermal feedback can be achieved through cross-modal thermo-tactile interaction on the user's back of the body. The second experiment is conducted to validate our approach by comparing it with thermal-only conditions with an equal and higher number of thermal actuators in VR. The results show that our thermal referral with a tactile masking approach with a lesser number of thermal actuators achieves higher response time and better location accuracy than thermal-only conditions. Our findings can contribute to thermal-based wearable design to achieve greater user performance and experiences.

Index Terms—Thermal referral, thermal vest, tactile masking, localized feedback, haptic vest

1 Introduction

Thermal interaction in virtual reality (VR) is emerging as providing thermal sensations can increase the sense of immersion and presence. A number of research works have been focused on delivering thermal sensations to users' hands [39], arms [29], face [34,36], and torso [9,11] using Peltiers, infrared lasers, thermal radiation, liquid, or mid-air haptic displays. These efforts significantly enhance the user experience, allowing users to perceive not only the shapes and tactile properties but also the temperature information through their skins, just like physical world experiences.

While a significant amount of research efforts have been dedicated to the development of thermal feedback systems, providing localized thermal sensations still remains challenging. Thermal devices and components are more expensive compared to typical vibrotactile actuators, such as LRA and ERM. They also require high-power consumption, making it difficult to extend them to a large-scale display, such as a VR suit or vest for full-body thermal interaction. Human thermal perception of slower response to temperature changes than vibrotactile stimulus [12, 30] can also add more complexity to designing a large-scale thermal display, along with other issues like thermal discomfort and thermal safety. The activation time in typical thermal actuators is also slower than that of vibrotactile actuators.

Our method of providing localized thermal sensations at a large scale is based on thermo-tactile interaction called a thermal referral [16, 17] and tactile masking [13, 14]. The thermal referral phenomenon is the illusion that the thermal sensations can be referred to a nearby body location through thermo-tactile interaction. An earlier study shows that all three fingers felt hot when warm stimuli were applied to the index and ring fingers, and the thermally neutral stimuli were applied only to the middle finger [17]. That is, the thermal sensation from those index and ring fingers is referred to the middle finger, yielding thermal sensations on all three fingers. Another important finding was that this thermal referral only happened when the middle finger was in contact with the neutral stimuli. Such tactile feedback of neutral stimuli is required to achieve thermal referral. A more recent study [29] showed that thermal referral could be extended to provide thermal moving illusions by shifting pressure stimulation on the human's forearm. We further hypothesize that thermal and tactile stimuli can be interplayed to achieve localized thermo-tactile sensations through thermal referral and tactile masking. Tactile masking is the reduced ability to detect the target signal in the presence of a background stimulus. That is, a weaker signal can be *masked* by a stronger signal, perceiving only the stronger feedback. In our approach, we assume that thermal sensations can be migrated to the presence of stronger tactile feedback, perceiving the thermal sensations from the stronger tactile site by masking the original thermal site. In this way, we can perceptually achieve localization of thermal sensations on a larger body area, such as a human's back.

In this paper, we propose an approach to achieving a perception-based localization of thermal sensations on a human's back (see Figure

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1). We show that thermal sensations can be migrated and perceived on different body sites where vibrotactile feedback is only activated, and thermal components are placed and activated in nearby locations using only four thermal actuators. We then compare our approach with thermal displays with different thermal resolutions to evaluate its validity. The main contributions of this paper are i) a perception-based localization of thermal sensations through thermal referral and tactile masking phenomena with a small number of thermal components on a large-scale thermal display and ii) a demonstration of benefits and validation of our approach by comparing it with thermal display with a higher thermal resolution.

2 Related Works

2.1 Thermal Perception

Humans perceive thermal sensations based on absolute and relative changes in skin temperature [43, 47, 50]. Thermal sensations are perceived through thermoreceptors when hot and cold stimuli are above or below the skin temperature [7, 27]. Unlike vibrotactile information that is detected by mechanoreceptors activating the somatosensory cortex in the human brain, thermoreceptors activate the insula cortex (a region of the brain deep in the cerebral cortex). Still, it is unknown how the simultaneous presentation of thermal and tactile stimuli are being processed to interplay; the cross-modal thermo-tactile interaction has shown a number of clear benefits, such as thermal sharpening [41, 42], thermal referral [1, 6, 16, 17, 22], and thermo-tactile identification [33, 38, 40]. The thermal thresholds for warm and heat-pain detection range from 30°C to 34°C, and 39°C to 50°C, respectively [2, 3, 10, 31, 48]. The response time of thermoreceptors is between 0.5 and 2s [8, 25], and it is generally slower than the response time of mechanoreceptors (a few milliseconds) [21, 30, 37].

2.2 Thermal Referral

Green [16, 17] discovered a phenomenon of thermal referral. In his experiment, all three fingers felt warm when warm stimulators were applied to the index and ring fingers, and the neutral-temperature stimulator was applied to the middle finger. This cross-modal interaction of referring thermal sensation to a nearby location was also discovered in cold stimuli. Interestingly, this only happens when all three fingers are in contact with the stimulators; the thermal referral illusion was not discovered when the middle finger was lifted from the neutral-temperature stimulator. However, Cataldo et al. [6] showed that thermal referral also occurred in purely thermal conditions without any tactile information. Ho et al. [22] discovered that all three fingers felt the same temperature with reduced intensity, suggesting that the temperatures on the index and ring fingers are spatially summated and redistributed over three fingers. Watanabe et al. [49] showed the mutual interaction of thermal referral between two thermo-tactile stimuli on the forearm. They found that there is a strong asymmetry between the stimuli locations and between the thermal conditions. Liu et al. [29] reported that the thermal referral can be extended to provide an illusion of moving thermal sensations with pressure stimulation and thermal sensations from a water system. Most thermal referral studies showed its phenomenon and applications in different aspects. However, the exact mechanism of how it works in the human sensory system is still unknown.

2.3 Tactile Masking

Tactile masking occurs when a stronger signal dominates a weaker tactile signal, perceiving only the stronger one [12–14, 19, 46]. The underlying mechanisms of tactile masking are not known, but usually, tactile masking is caused by changing the signal-to-noise ratio [15]. The most commonly used masking techniques are forward masking (signal follows the masker), backward masking (signal precedes the masker), simultaneous (signal and the masker starts and ends at the same time), and sandwich masking (signal is sandwiched between two masking stimuli). Tan et al. [44] investigated the temporal masking properties of stimuli with sinusoidal mixtures using the Actuator. Participants were asked to identify the target signals perceived from their finger pads under three different masking paradigms: forward masking, backward masking, and sandwiched masking. Participants showed good performance in forward and backward masking but poor performance in sandwich masking. Tactile masking technique can be used to achieve perceptual localized tactile feedback. For example, Kim et al. [28] investigated the masking effects of key-click feedback signals on a flat surface. In their study, the users perceived localized key-click feedback on their active fingers with a sufficiently weaker signal applied to passive fingers.

2.4 Thermal Devices and Interfaces

The thermal device can be categorized into contacted-based and non-contacted-based, with one of the thermal transfer methods: conduction, convection, and radiation. The contact-based thermal device delivers heat through conduction or convection, directly placed on the human body to ensure enough contact area for a better thermal transfer rate. The commonly used approach is the Peltier device, which could generate heat quickly through the thermoelectric effect and deliver various thermal cue sizes through a different number of Peltier pack [9, 11, 34]. Another widely used contact-based approach is a water pipe [18, 20, 52]. With the high thermal conductivity of water, it can deliver heat sensation quickly, and its formability ensures various thermal cue sizes and shapes. The non-contact-based thermal device delivers heat through convection or radiation, which doesn't need to be worn on the body, enabling a more natural experience. One commonly used approach is airflow, which delivers ambient thermal sensation through hot air flow in close range [36, 40]. Another approach is radiation-based infrared [23, 26] or laser device [32, 35].

In VR, many thermal interfaces have been explored to provide more realistic multi-sensory experiences, including VR headsets, gloves, sleeves, and vests. The thermal components can be attached to VR headsets, saving space for peripheral placement using Peltiers and fan-propelled airflow in HMD with different levels of temperature [36] or using a Peltier pack attached to the inner side of HMD [34]. The gloves can deliver a heat sensation on the hand using a water pipe attached to the finger to provide thermal sensation with different temperatures [20] or using an airbag below the finger to provide a thermal sensation [4]. The sleeve is placed on the forearm and has a larger area for implementation, and doesn't hinder hand movement [29]. The vest could provide a large thermal cue on the body using Peltier [9] or a water pipe on the vest [18].

3 Design

3.1 Approach

Our approach to providing localized thermal sensations is based on cross-modal thermo-tactile interaction by utilizing thermal referral and tactile masking. We hypothesize that a thermal sensation can be moved to a nearby particular tactile site with stronger intensity, and its thermal source can be masked, perceiving strong thermo-tactile sensation only at the tactile site. Figure 2 shows the concept of our approach. There are 4×4 vibrotactile actuators and four thermal actuators in the back of the vest. Thermal actuators are placed between the 2^{nd} and 3^{rd} columns of vibrotactile actuators, having four vibrotactile actuators and one thermal actuator in the middle of each row. In Figure 2(a), when the 2^{nd} actuator in the first row and the thermal actuator in the same row are activated, the thermal sensation is generated from the thermal actuator and migrated to the 2^{nd} actuator, creating thermo-tactile illusions on the area that the 2^{nd} actuator is activated. Similarly, when the 4^{th} actuator in the third row and the thermal actuator in the same row are activated, the thermal sensation is created from the thermal actuator and migrated to the 4^{th} actuator in the same row, creating thermo-tactile sensations on the area that the 4^{th} actuator is activated (see Figure 2). In this way, we could achieve perception-based localized thermo-tactile feedback by utilizing thermo-tactile interaction. The thermal referral is achieved by activating thermal and tactile actuators at the same time, and localization is achieved by providing a strong intensity only on tactile cues for tactile masking. With combinations of thermal and vibrotactile actuators, we can achieve localization of thermal sensations at larger body areas.

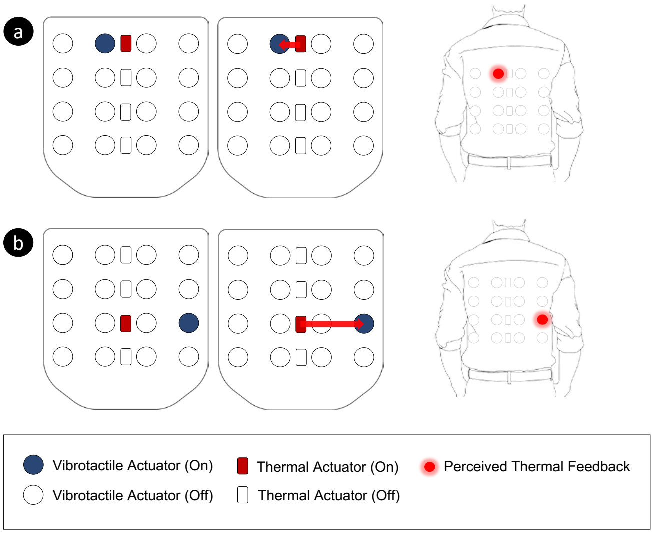

Fig. 2: Concept diagram highlighting the approach behind the proposed thermal illusion. When the vibrotactile actuator is activated, the thermal feedback is referred to that location.

3.2 Setup

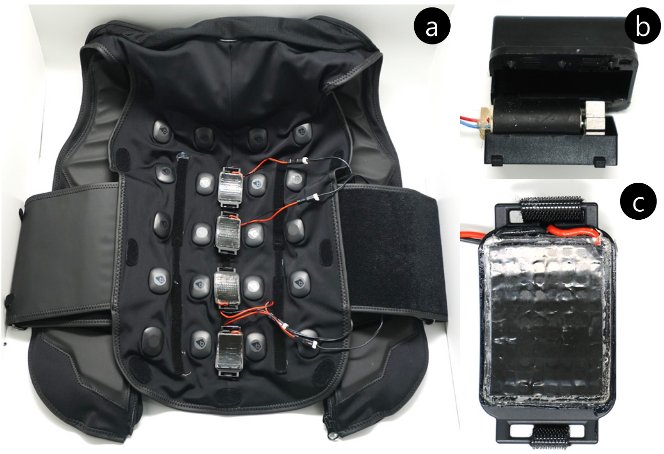

Fig. 3: Experiment setup. (a) A vest with vibrotactile actuators and thermal actuators, (b) vibrotactile actuator, and (c) thermal actuator

Figure 3 shows our setup. We used a commercialized haptic vest (Tactot DK3, bHaptics), having 40 individually controlled ERM vibrotactile actuators (20 for front and 20 for back). The vest has a length of 22.5 to 24 inches and a body circumference of 25-50 inches, with a total weight of 1.7 kg. We additionally installed four thermal actuators (ThermoReal, Tegway) at each row, between the second and the third columns of the vibrotactile array (see Figure 3(a)).

The thermal actuator is a flexible thermoelectric device with a size of 5.99 cm (length) $\times$ 3.35 cm (width) $\times$ 1.11cm (height) and a weight of 34.5 g, having a structure with a curved surface on the top and the bottom (see Figure 3(c)). A heat sink is attached to the opposite side of the release sheet in contact with the skin. A fixed current of 1.34A is applied, and the duty cycle ratio controls the output intensity. The thermal actuator can be activated using either a power supply or a Lithium-ion battery.

In our setup, we used the Lithium-ion battery (MP103 450P) with a rated voltage of 3.7V, a capacity of 2000mAh, and a discharge rate of 1C. A current of 1.34A can be provided continuously for about 86 minutes with a single charge. We compared the performance of the thermal actuator by powering it with a Lithium-ion battery and digital power supply (Navitech NP6005), and the result showed no difference in the current supply and actuator performance. All participants started the experiment with fully charged batteries.

Figure 4 shows the characteristics of the thermal component. The thermal component can provide hot sensations, ranging from room temperature (23.5°C) to 50°C. The thermal component can reach a certain temperature level in a short time (less than 3 seconds), and it takes 15 seconds to return to room temperature. Each temperature level can be reached based on operating power (see Figure 5). In our approach, the thermal intensity was set to 90 %, which generates an average of 50°C on the surface of the thermal actuator and 40°C with cloth, ensuring perceivable and comfortable thermal sensation to the participant.

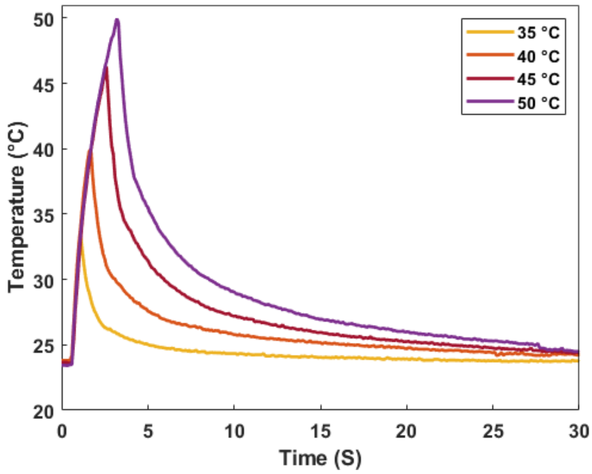

Fig. 4: Thermal actuator temperature change over time from room temperature (23.5°C) to 35, 40, 45, 50°C, respectively, and their thermal recovery time

The vibrotactile actuators (B07PXZSP7J, Tatoko) in the haptic vest are equally distributed, with an interval distance of 8 cm vertically and horizontally, forming a 5 $\times$ 4 array in the front and the back of the vest to provide tactile feedback to the front and the back of the upper body. Each vibrotactile actuator (see Figure 3(b)) has 3 cm (length) $\times$ 1.8 cm (width) $\times$ 1.2 cm (height). The vibrotactile actuators are fixed in the same positions for all users, as the vest comes in one size. The vest is designed to fit different shapes and sizes by adjusting shoulder snap buttons and side straps for a tight fit for all participants.

We conducted a preliminary study with different intensity levels of the vibrotactile actuators to evaluate the thermal referral effect and find appropriate intensity levels. We found that stronger intensity of the vibration also could achieve thermal referral, but participants felt uncomfortable if the intensity was too strong. We set 10% of the intensity level that yields 0.1 N with 125 Hz vibration frequency (see Figure 6).

We chose to use a 4 $\times$ 4 array in the back for this study for more controlled experiments. The first row in the back was not used, as the actuators in the first row could not be tightly in contact with the human body, compared to the other four rows of the array. The thermal actuators are placed at the center of each row, from the first to the fourth row of the vest. The interval distance between the thermal actuator and the vibrotactile actuator is 2 cm. We chose to place one thermal component per row instead of per column through a preliminary study with 4 participants. We confirmed that participants perceived clearer thermo-tactile sensations when we placed the thermal modules per row instead of per column. Both thermal and vibrotactile actuators can be controlled via Bluetooth.

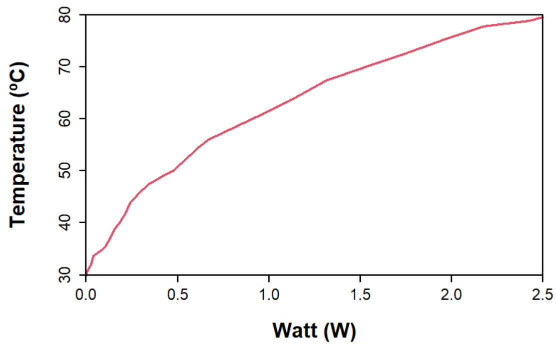

Fig. 5: Operating temperature of the thermal actuator with different power consumption

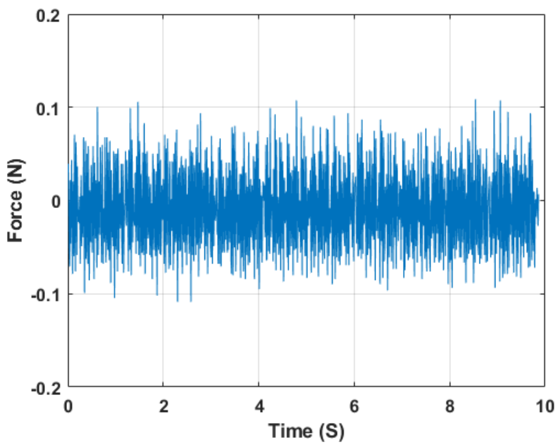

Fig. 6: Force profile of vibrotactile acturator

4 Experiment 1: Thermal Referral Illusions on Upper Body

This experiment investigates the perceived illusions of thermal referral and tactile masking on the upper body. A user study is conducted to validate this illusion and prove that users perceive thermal feedback at the referred location.

4.1 Participants

Sixteen participants, ranging from 18 to 31 years old (2 females; mean age: 24.5 years old; SD = 3.8), took part in this experiment. They were asked to wear light tops for the experiment. None of them reported any disorder affecting the sensations on their backs. Each participant was paid a $10 gift card for their participation. All the participants gave written informed consent to participate in the study. The experiment was approved by the author's institution's Institutional Review Board.

4.2 Apparatus

Figure 8 shows a participant wearing the vest we designed. A custom Android application was developed to allow participants to draw the region they felt thermal sensations. The application interface showed the image of the vest with 16 vibrotactile actuators (circle) and four thermal actuators (rounded rectangle). We used a tablet (Galaxy S8+ Tab, Samsung) with a digital pen to run the application.

4.3 Experimental Design

We designed a within-subject study with a combination of four *single* (actuating only one actuator at a time), three *double* (actuating two actuators at a time), two *triple* (actuating three actuators at a time), and one *quadruple* (actuating four at a time) actuators, yielding ten trials in a row. The thermal actuator at the corresponding row is also activated simultaneously. The total number of trials was 40 (10×4 rows). The order of trials was randomized, and the order of the row was also randomized per participant using Latin Squares. The task was to draw a region where they felt thermal sensations after experiencing each trial on a tablet with a digital pen.

Visual feedback of a red arrow indicating the current row was provided as a minimum guidance to instruct which row they are currently working on. This minimum information is to prevent mislocalization in adjacent rows, if any, as the thermal sensitivity in the back is relatively low [5]. Also, layers of clothing and the large size of the thermal display make it even less sensitive.

An exit questionnaire sheet was prepared to measure the participants' responses on *Thermal Comfort* – I felt comfortable while taking the trials on *Thermal Clarity* – I perceived the thermal sensation clearly. Participants were asked to respond to each question by marking a check on a standard 10 cm length of visual analog scale with a label on each end: 'Strongly Disagree' and 'Strongly Agree' per feedback.

4.4 Procedure

Participants were briefed about the experiment and asked to read and sign a consent form. They were asked to wear the vest and sit comfortably on a chair. A practice session was provided to confirm the operations of individual vibrotactile and thermal actuators and familiarize the participant with the actuators' spatial location. Each trial consisted of providing the stimulus for 10 seconds, a break of 20 seconds, and then the same stimulus for another 10 seconds. A stimulus duration of 10 seconds was chosen because it was found to be the adequate duration to perceive thermal referral and masking effects during the preliminary test. The stimulus was repeated to confirm the delivery of sensations. We noticed that some participants wore multiple layers of clothing, making them less confident about their responses. In order to make consistency across all participants, we decided to repeat the stimulus for confirmation. After each trial, we asked them to draw the area where they felt thermal sensations using a tablet and a digital pen. They were free to modify and redraw their drawing. A two-minute break was given after each row was completed. The entire experiment lasted for one hour, including the time taken to fill out the exit questionnaire.

4.5 Results & Discussion

Figure 9 shows the distributions of thermal sensations for all participants based on their perceived thermal region on their back. The higher intensity of the red color indicates a higher number of participants' responses, while the lower intensity indicates fewer participants' responses to demonstrate the distribution of thermal sensations and localization over the human back. It was clearly observed that most of the concentrated areas were well matched with the locations where vibrotactile actuators are placed, suggesting thermal referral illusions occurred on an upper body. We also confirmed that no thermal sensation was perceived where actual thermal actuators are located in left-most and right-most activations (*Single* 1 and *Single* 4). This is interesting to see because there were thermal sensations directly applied to the human's upper body. This may suggest that a stronger intensity of tactile feedback can mask thermal sensations. Other combinations (i.e., double, triple, and quadruple) of the distributions were clearly observed, confirming that perceived localization of thermal sensations could be achieved with different cue sizes.

Figure 10 shows the performance measures for thermal clarity and comfort. The result shows participants perceived thermal sensations clearly (*Thermal Clarity* = 8.1, SD = 1.357), and the thermal sensations provided were not uncomfortable or painful (*Thermal Comfort* = 8.6, SD = 1.371). Participants mentioned that the perceived heat was comfortable and it was not "burning hot". They also mentioned that they could clearly feel the thermal feedback for *single*, *double*, and *quadruple* cases while they were a little unsure about the two *triple* conditions.

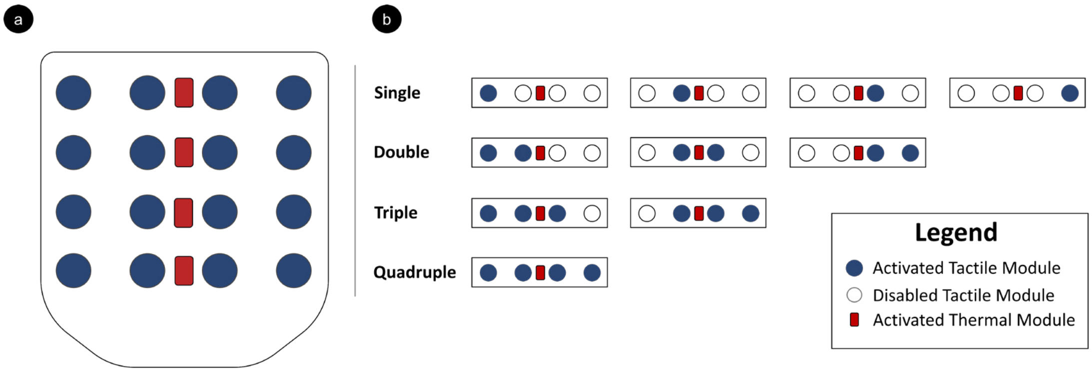

Fig. 7: a) Location of 16 vibrotactile and 4 thermal actuators on the vest and b) all 10 conditions per row provided to the participants.

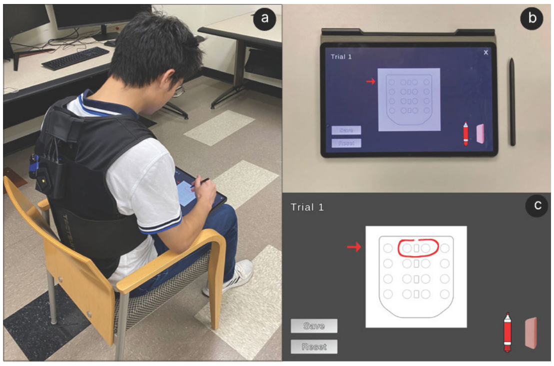

Fig. 8: a) A participant making a selection during the trials, b) tablet for collecting the responses during the experiment, and c) a snapshot of the screen during the process of marking the affected area.

5 Experiment 2: Human Performance Evaluation in VR

The goal of experiment 2 is to evaluate our approach by comparing it with thermal-only conditions with a different number of thermal actuators in a VR environment. Our hypothesis is that our perception-based approach can be competitive in terms of human performance and user experience compared to conditions with more number of thermal-only actuators.

5.1 Participants

Sixteen participants, ranging from 22 and 34 years old (7 females, mean age = 29.5 years old; SD=2.83), who did not participate in the first experiment took part in this experiment. They were asked to wear light tops. All participants had no problems perceiving tactile or thermal sensations on their backs. Participants were paid with coffee coupons (approximately $6 USD) for their participation.

5.2 Experimental Design and Setup

Figure 11 shows the actuator-placement conditions for this experiment. We prepared three actuator-placement conditions. The first condition is a thermal-only condition with four thermal actuators, placing four thermal actuators in each row (*ThermalOnly(4)*). In this condition, the placement of thermal actuators is the same as one in Experiment 1, but none of the vibrotactile actuators are activated. The second condition is a thermal-only condition with eight thermal actuators, placing four thermal actuators in the second column, and another four thermal actuators in the position of the third column of the vibrotactile actuator array (*ThermalOnly(8)*). This condition has twice the number of thermal actuators as *ThermalOnly(4)*. Similar to *ThermalOnly(4)*, none of the vibrotactile actuators would be are activated in this condition. The third condition is a thermo-tactile condition with four thermal actuators and 16 vibrotactile actuators (*ThermalTactile(4)*). This condition is the same as the one we used in Experiment 1 (our approach). These experimental conditions are selected to check where our approach (i.e., *ThermalTactile(4)*) will be laid between two thermal-only conditions (i.e., *ThermalOnly(4)* and *ThermalOnly(8)*), which are typical conventional approaches for thermal displays.

	Thermal Only(4)	Thermal Only(8)	Thermal Tactile(4)
Thermal Actuators	10.72 W	21.44 W	10.72 W
Vibrotactile Actuators	N/A	N/A	0.96 W
Total	10.72 W	21.44 W	11.68 W

Table 1: Total power consumption in three actuator-placement conditions (assuming all actuators are all activated simultaneously).

The total power consumption of *ThermalOnly(4)*, *ThermalOnly(8)*, and *ThermalTactile(4)* are 10.72 W, 21.44 W and 11.68 W, respectively, as shown in Table 1. The placement of the thermal actuators can be switched using velcro strips attached to the actuators and the vest. Similar to Experiment 1, the thermal actuators are powered by Lithium-ion batteries (MP103 450P), and all participants started the experiment with fully charged batteries.

We used a Windows laptop (CPU: Intel i7-10875H 2.30GHz / GPU: NVIDIA Geforce GTX 2080 Super / RAM: 64GB) with the Oculus Quest 2 headset to run the experiment. The headset was connected to the laptop with an Oculus Link, and the vest and thermal actuators were connected through Bluetooth. A VR application was implemented using Unity. We implemented one female and one male avatar for the participant's virtual representation. The participant's head and hand movements were tracked and mapped with the avatar's movement to achieve a sense of embodiment. A spaceship VR scene was created with a size of 2m $\times$ 2m. In the scene, an avatar was initially placed in front of a large screen while monitoring the back of his body through the screen. The live streaming of his virtual body was displayed via a security camera installed at the top of the ceiling, providing a visual information of avatar's back.

In each actuator-placement condition, visual feedback of flame occurs in one of the 16 locations in the back. These 16 locations are the same location as the positions of vibrotactile actuators, and eight of them are also the same location as the positions of thermal locations in *ThermalTactile(4)*. Visual effects are added for a realistic visual rendering of the flame. When the visual feedback appears in one of 16 locations in the avatar's back, a corresponding thermal sensation is provided at the same time. In *ThermalOnly(4)* condition, the thermal actuator in the same row where visual feedback appeared is activated. For example, if the visual feedback appears in the first row in the fourth column, then the thermal actuator in the first row is activated. In *ThermalOnly(8)* condition, the closest thermal actuator in the same row where visual feedback appeared is activated. For example, if the visual feedback appears in the first row in the fourth column, then the second thermal actuator in the first row is activated. In *ThermoTac-*

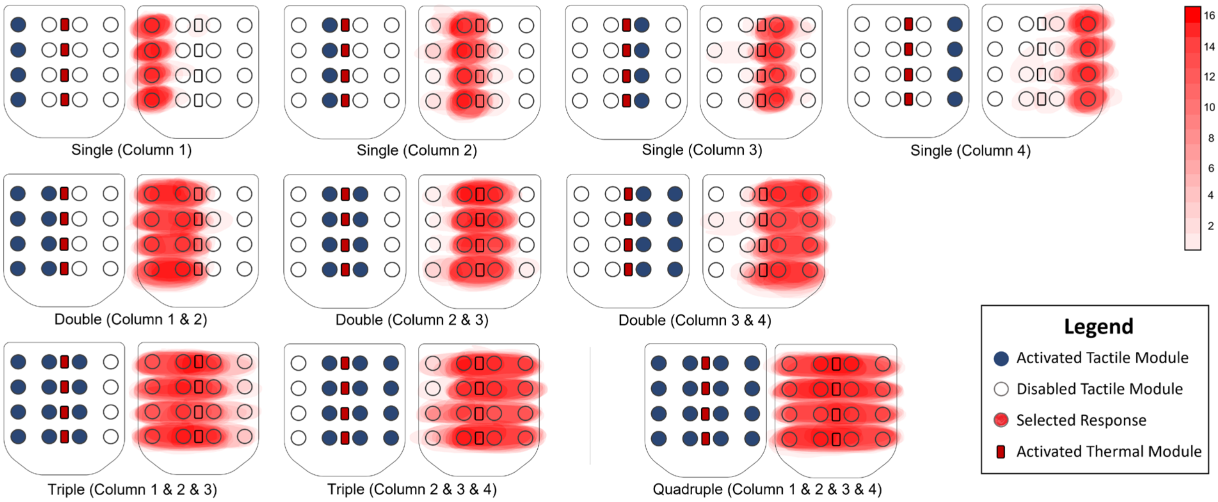

Fig. 9: Combined result per the condition of the traces drawn by all the participants. The color shows the amount of overlap in the responses, ranging from 0 (no overlap) to 16 (overlap by all participants).

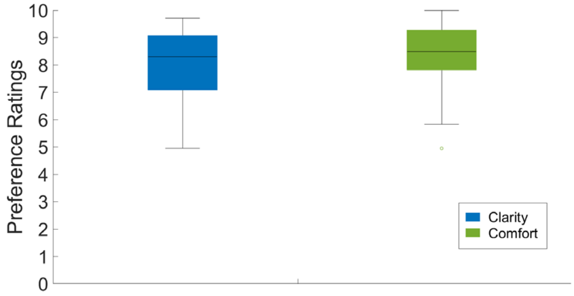

Fig. 10: Performance measures for thermal clarity and comfort

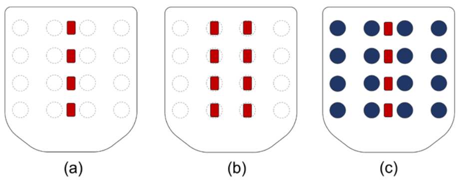

Fig. 11: Experimental conditions: (a) *ThermalOnly(4)*, (b) *ThermalOnly(8)*, and (c) *ThermoTactile(4)*.

tile(8) condition, the thermal actuator in the same row where visual feedback appeared is activated together with corresponding vibrotactile actuators. Again, if the visual feedback appears in the first row in the fourth column, then the thermal actuator and the fourth vibrotactile actuator in the first row are activated.

The user's task is to detect and identify the thermal sensation on their back as soon as s/he sees the flame appear in one of the sixteen locations. Then, the participant was asked if the location of the visual feedback matched the location of the perceived thermal sensations by answering 'yes' or 'no'. We instructed participants to answer 'yes' only if the location of the fire on their back matched the location of their sensation. There were a total of 96 trials (16 locations $\times$ 2 repetitions $\times$ 3 conditions), and this question was asked in all trials. After each condition, a questionnaire was provided: Appropriateness – Thermal sensation was appropriate and suitable for visual feedback of flame; Realism – thermal sensation was realistic; Clarity – Thermal sensation was clearly perceived. The participant was asked to respond to each question by marking a check on a horizontal line (visual analog scale) with a label on each end: 'Strongly Disagree' and 'Strongly Agree'. The order of the 16 locations was randomized with two repetitions. The order of the placement condition was also randomized. The entire experiment took about an hour.

5.3 Procedure

Participants were briefed about the experiment and asked to read and sign a consent form. They were asked to wear the VR headset and the vest and sit on a chair. Two VR controllers were also provided for the user task. A practice session was provided to confirm the operations of the vest and familiarize the participant with the VR environment and equipment. In each trial, the flame randomly appeared in one of the sixteen locations on the back, and the thermal sensation is presented based on the current condition. Both visual and thermal stimuli were presented for 20 seconds, followed by 20 seconds of break. Participants were asked to press the trigger on one of the VR controllers when they detected thermal stimuli. Once the trigger is pressed, a question is displayed on a screen, asking if the position of the perceived thermal sensation matches the position of the visual feedback. After each condition, participants were asked to take off the vest and the VR headset and fill out the questionnaire for that condition with a five-minute break. The entire experiment took about an hour per participant.

5.4 Results & Discussion

Figure 13 shows the performance of all conditions in terms of mean task time and mean accuracy. The mean task completion time T was calculated by averaging the time between visual feedback provided and when participants noticed thermal sensation for all 32 trials in each condition. In Figure 13 (a), T was 8.4, 6.5, and 5.4 seconds for *ThermalOnly(4)*, *ThermalOnly(8)*, and *ThermoTactile(4)*, respectively. Kolmogorov-Smirnov (K-S) test was performed, and we confirmed the normality of the data. Levene test was conducted on T, and we confirmed the homogeneity of variances ($p = 0.6245$). A one-way ANOVA with repeated measures and a post-hoc Tukey test revealed that *ThermoTactile(4)* had a significant difference from both *ThermalOnly(4)* ($p = 0.0009$) and *ThermalOnly(8)* ($p = 0.00008$). These results indicate that thermal sensations can be identified faster with our approach.

The mean accuracy A was calculated as the percentage of "yes" out of all trials in the follow-up question, asking whether the position of visual feedback matched the position of thermal sensation they perceived. In Figure 13(b), A was 64.1%, 91.0%, and 91.7% for *ThermalOnly(4)*, *ThermalOnly(8)*, and *ThermoTactile(4)*, respectively. The normality

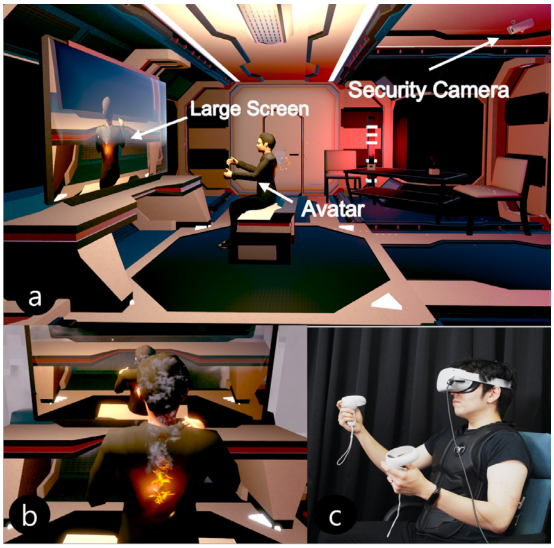

Fig. 12: Experiment 2 setup. (a) A virtual scene, (b) an avatar with visual feedback, (c) a participant performing the task.

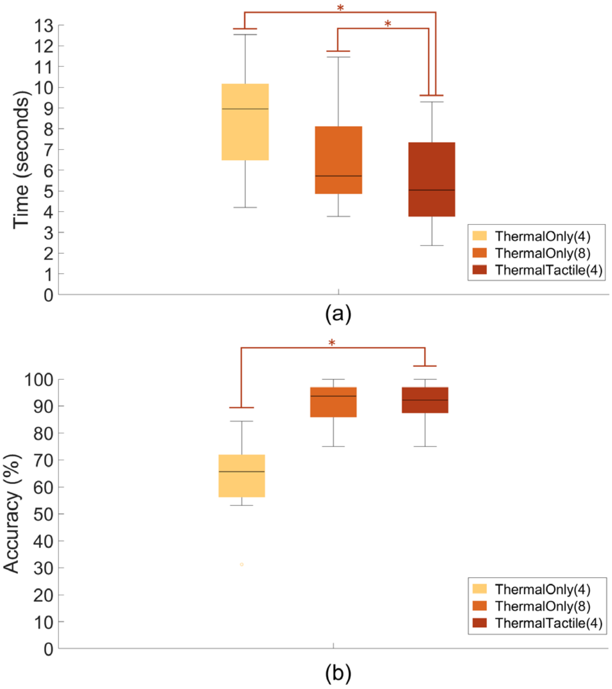

Fig. 13: Performance measures for ThermalOnly(4), ThermalOnly(8), and ThermoTactile(4) conditions. a) Time and b) Accuracy. The symbol * indicates p < 0.05.

of the data for *A* was confirmed using the K-S test. The homogeneity of variances among the input data was confirmed by the Levene test ($p = 0.09267$). A one-way ANOVA showed that *ThermoTactile(4)* had a significant difference on *ThermalOnly(4)* ($p = 0.0003$) for *A*, but no significant effect was found between *ThermoTactile(4)* and *ThermalOnly(8)*.

Subjective measures show that participants rated *ThermalOnly(8)* (8.5, SD = 0.9) and *ThermoTactile(4)* (8.5, SD = 0.9) to be equally appropriate for the visual feedback, but lower in *ThermalOnly(4)* (7.2, SD = 1.2) (see Figure 14). They perceived *ThermoTactile(4)* (8.6, SD = 0.9) to be more realistic than *ThermalOnly(8)* (8.3, SD = 1.3) and *ThermalOnly(4)* (7.4, SD = 1.8). Similarly, they perceived *ThermoTactile(4)* (8.8, SD = 1.0) to be more clear than *ThermalOnly(8)* (8.3, SD = 1.3) and *ThermalOnly(4)* (7.1, SD = 1.7). Kolmogorov-Smirnov (K-S) test was performed to confirm the normality of the data. A Levene test on the collected data showed the homogeneity of variances among them for all three measures ($p = 0.7666$ for Appropriateness; $p = 0.3168$ for Realism; and $p = 0.2252$ for Clarity). A one-way ANOVA with repeated measures revealed a significant effect with a large effect size of conditions on all three subjective measures, Appropriateness ($p = 0.0013$, $\eta^2 = 0.24$), Realism ($p = 0.0028$, $\eta^2 = 0.17$), and Clarity ($p = 0.0032$, $\eta^2 = 0.21$). Further analysis using Tukey test revealed significant differences between *ThermalOnly(4)* and the other two conditions ($p < 0.001$) while *ThermoTactile(4)* and *ThermalOnly(8)* were not found to be significantly different ($p = 0.9$ for Appropriateness; $p = 0.8$ for Realism; and $p = 0.5$ for Clarity), showing higher preferences in both *ThermoTactile(4)* and *ThermalOnly(8)* conditions over *ThermalOnly(4)*.

We also noticed the high accuracy for *ThermalOnly(8)* condition. This is probably because the thermal spatial resolution is relatively poor than tactile spatial resolution, and participants were dominated by visual feedback so that if perceived thermal sensations were close enough, they felt that the sensation matched with its location.

6 Discussions

This paper presents a cross-modal thermo-tactile approach to achieve localized feedback on the upper body. Thermal referral and tactile masking phenomena were clearly observed when we simultaneously applied thermal and vibrotactile cues on the human's back. We showed that our approach to providing localized thermal sensations could be perceived in specific body locations with different thermal cue sizes. We further demonstrated that we could achieve higher response time and better location accuracy with our system than those with thermal-only actuators.

We show our unique approach of using thermal referral and tactile masking and validate it through two experiments. Experiment 1 is to validate whether users can perceive localized thermal sensations on different parts of their back. The stimulus was repeated to confirm the delivery of sensations, maintaining high accuracy and ensuring thermal localization could be achieved through combinatory illusions of thermal referral and tactile masking. The thermal referral phenomenon was observed clearly in Experiment 1, showing that most of the concentrated thermal areas were well-matched with the locations of vibrotactile actuators. The goal of Experiment 2 is slightly different, as we evaluated our approach by comparing it with thermal-only conditions in a VR environment. The emphasis was more on the feasibility of our approach as compared to thermal-only displays, and thus, the requirement was different. However, thermal-only conditions could be considered in Experiment 1 to show the superiority of our approach with thermal referral and masking, which could yield better performance than just thermal feedback alone. The results from both experiments showed that our approach of localized thermal feedback could be achieved through thermal referral and tactile masking, and such an approach could be beneficial to design a cost-effective thermal vest and suit.

We observed that some participants slightly felt thermal sensations outside the tactile feedback (e.g., thermal sensations at the fourth point in the conditions with three vibration points). Although the underlying neural pathway still needs further investigation, we believe there are two possibilities related to this phenomenon. The low spatial discriminability of thermal sensations could lead to this phenomenon. Unlike a tactile spatial resolution, thermal spatial resolution is known to be poor on the body [27, 45, 51], especially on the back [5]. This is likely due to the fact that the skin summates intensity over space (i.e., spatial summation [27]) as people feel either warm or cold in their skin in terms of intensity and duration. We also think that layers of clothing also contribute to lower spatial discriminability. Another possible explanation is that the thermal referral might get involved in two consecutive processes of spatial summation and thermal redistribution [22]. The thermal illusion could have occurred during these processes in a larger thermal redistribution area.

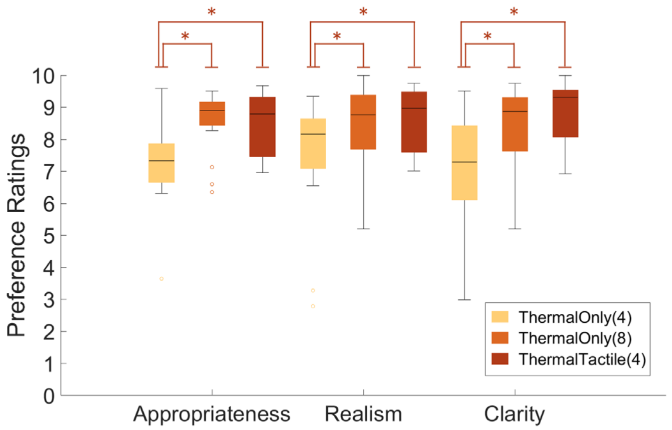

Fig. 14: Preference ratings of Appropriateness, Realism, and Clarity for ThermalOnly(4), ThermalOnly(8), and ThermoTactile(4) conditions. The symbol * indicates $p < 0.05$.

The placement of thermal actuators in our approach is simple but powerful to distribute thermal sensations over a large-scale human body. Our approach of simple placement is different from ThermoCaress [29] although both approaches are based on thermal referral. Their approach achieves thermal localization through moving pressure actuators and fixed thermal actuators, which require a mechanical setup to move the actuators, which may not be suitable for thermal suits or vests. Our approach adopts the fixed placement of thermal and vibrotactile actuators, which does not require any moving mechanism to localize thermal feedback. Furthermore, thermal cues could be localized at an arbitrary location between two vibrotactile actuators by applying tactile motion [24] or alternative activation of the actuators, which we confirmed through our preliminary test. Furthermore, our approach can provide different tactile sensations and patterns for presenting various thermal effects. In fact, this is one of our future directions to investigate further on this topic. We believe that our approach is more suitable for thermal suits or vests than ThermoCaress.

Another main benefit of our approach is low power consumption. Thermal actuators are generally expensive and require more power. Assuming that we use all the thermal actuators, the total power that *ThermalOnly(8)* uses would be 21.44 W (see Table 1). This is almost twice the power that our approach would use (11.68W). With only an 8.96% power consumption increase, *ThermoTactile(4)* could achieve better performance (i.e., time and accuracy) and user preference (i.e., appropriateness, realism, and clarity) than *ThermalOnly(4)*. Our approach could remarkably lower the power consumption when it is further optimized and applied in large-scale scenarios where multiple thermal stimuli must be presented on both sides of the back. Furthermore, our approach could achieve localized thermal sensations with significantly fewer thermal actuators, as generating thermal cues is typically slower than generating vibrotactile cues. This can lead to a more effective design for a cost-effective thermal vest.

We believe that our approach can be applied to many applications. A thermo-tactile vest can be designed and implemented to provide localized thermal cues for gaming applications for an immersive user experience. Users can enjoy FPS or sword fighting games while perceiving localized thermo-tactile sensations on their torso. Firefighting simulation can be another potential application. Users can experience firefighting simulation in a more realistic setting while feeling the localized thermal sensations on their bodies. Also, our approach can enhance the movie or theater experience, feeling dynamic thermo-tactile sensations while watching exciting movies.

We also identified some limitations. In Experiment 2, some participants felt that *ThermalOnly(8)* condition was more appropriate with visual feedback. They described that vibrotactile cues were not well-matched with their expectation of flame sensations, making them less preferred than *ThermalOnly(8)*. We plan to study the effect of various tactile feedback on thermo-tactile interaction for different types of visual feedback to achieve more pleasant and well-matched thermo-tactile sensations while providing localized feedback. This way, we may address some of the concerns raised in the current study.

We plan to study thermal referral and tactile masking with cold sensations. We believe that providing localized cold sensations on the upper body and other body parts will open up many potential applications and deliver a more immersive and richer VR experience. We will also investigate the effects of parameters for vibrotactile and thermal actuators, including intensity, frequency, and duration, and how they affect the thermal referral and masking effects. We also plan to investigate masking and temperature thresholds and the impact of the direction of the actuator placement.

7 Conclusion

Our paper showed perception-based thermal localization through thermal referral and tactile masking. We investigated the perceived thermal illusions on the upper body and proved that users could perceive localized thermal sensations at the referred location on the human's back. We further evaluated our approach by comparing it with thermal-only conditions with an equal or greater number of thermal actuators. We found that our approach of cross-modal thermo-tactile interaction shows competitive performance and user experience compared to that of thermal-only conditions. We believe that our finding is promising for achieving localized thermal sensations on a large area of the human body with a significantly lower number of thermal actuators.

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