Non-Contact Thermo-Visual Augmentation by IR-RGB Projection

Daisuke Iwai, *Member, IEEE,* Mei Aoki, and Kosuke Sato, *Member, IEEE*

Abstract—This paper presents an approach for non-contact haptic augmentation with spatial augmented reality (SAR). We construct a thermo-visual projection system by combining a standard RGB projector and a fabricated infrared (IR) projector. The primary contribution of this paper is that we conduct thorough psychophysical experiments to investigate a design guideline for spatiotemporal projection patterns for both RGB and IR projectors to render a warm object with high presence. We develop application systems to evaluate the validity of the proposed system and design guideline. The evaluation results demonstrate that the proposed system can render warm objects with significantly higher presence than a standard SAR system.

Index Terms—Spatial augmented reality, projection mapping, IR projector, cross modal, non-contact haptic feedback.

1 Introduction

Spatial augmented reality (SAR), also known as projection mapping, merges real and virtual worlds by projecting synthesized computer graphics onto the surfaces of real objects [1]. SAR does not require users to wear/hold any devices because the projectors can be installed in the application environments, while other approaches (e.g., video and optical see-through) generally require such devices. Since first introduced [2], SAR researchers have attempted to develop methods to change the textures of real surfaces and provide immersive experiences by displaying virtual creatures or distant humans in game or telepresence applications [3], [4], [5]. To this end, various image quality enhancement technologies have been proposed [6], some of which overcome the technical limitations of standard projectors such as limited dynamic range [7], [8], narrow depth-of-field [9], [10], subsurface scattering [11], and shadows [12].

In addition to visual augmentation, AR experiences can also be enriched by providing cues through other modalities, e.g., haptic feedback. Thermal information would be a suitable haptic dimension for plausibly displaying warm objects, such as distant people and virtual creatures. Typically, SAR systems are not attached to users; therefore, haptic systems should not require them to wear/hold any equipment. Although thermal displays have been widely researched, previous techniques assume user contact with a display that provides warmth stimuli using a heat pump or a Peltier device [13], and some studies have focused on non-contact thermo-visual augmentation [14], [15]. Furthermore, to the best of our knowledge, design guidelines for such spatial thermo-visual augmentations have not been proposed.

In this paper, we propose non-contact thermo-visual augmentation using a fabricated infrared (IR) projector and a commercially available RGB projector. The RGB projector projects the visual information of a virtual warm object (e.g., a distant person or virtual pet) onto part of the user's body. The IR projector controls the direction of a single IR spotlight using a pan-tilt mirror to illuminate the same position on the body (e.g., arm and forearm) to overlay the thermal information onto the projected RGB image based on thermal radiation and radiant heating (Figure 1). Currently, constructing an IR projection system with spatial resolution that is as high as that of an RGB projector is difficult; thus, we cannot control thermal information with the same spatial accuracy as the corresponding visual information. Therefore, investigating the extent to which such spatial inconsistency affects user perception of the displayed virtual warm object is necessary. The primary contribution of this paper is that we derive a design guideline from psychophysical experiments. Thermo-visual AR application developers can use the proposed guideline to design IR and RGB projected information to render a target virtual warm object with high presence. In addition, we describe several applications implemented using our proposed system and guideline.

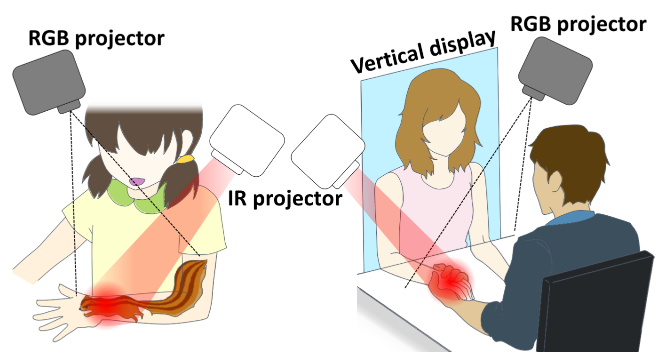

Fig. 1. Concept of the proposed system: (left) a virtual creature is moving on a forearm, (right) a teleconference system.

The primary contributions of this paper are as follows.

- We propose a non-contact thermo-visual augmentation method that uses an IR-RGB projection system.
- We introduce a design guideline for projected IR and RGB information to render a virtual warm object

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with high presence onto a human body that considers the significantly different spatial resolutions of the IR and RGB projectors.

2 Related Work

A major principle of non-contact haptic feedback is spatiotemporal modulation of air pressure to exert pressure on a user's body that can be perceived by the skin. There are two approaches to achieve the non-contact haptic feedback. The first approach employs air cannons to generate force [16], [17], [18]. An air cannon, consisting of an enclosed box with an aperture and speaker, generates a vortex by using the speaker to force air out of the box through the aperture to exert a perceivable force onto the user's body. To provide force feedback at different positions, the air cannon is mounted on a pan-tilt gantry that controls the direction of the vortex. The second approach applies a 2D array of ultrasound transducers to provide airborne ultrasound radiation pressure [19]. The phased array focusing technique generates an ultrasound focal point by controlling the phase delays of multiple transducers, and the generated air pressure can be perceived by human skin. Some studies have proposed a mid-air visual-haptic interface by combining an ultrasound haptic feedback system with floating imaging technology based on the transmissive mirror principle [20], [21].

Recently, spatiotemporal modulation of IR illumination has been proposed to provide non-contact haptic feedback [14], [15], [22], i.e., radiant heat generated by IR light can warm a user's body. Although, these previous studies demonstrated that their proposed systems can deliver warmth information, the spatial resolution of the IR light is very low. Normal RGB projectors achieve high spatial resolution by applying spatial light modulators (SLM), such as LCD, DMD, and LCoS. However, SLMs are typically not robust against heat; thus, an IR cut filter is typically inserted between the light source and SLMs to avoid unnecessary increases in temperature. Therefore, such SLMs are not suitable for IR projectors. Another approach to achieve high spatial resolution thermal projection is applying a laser beam. A 2D thermal pattern can be displayed by modulating the direction of the beam using galvanometer scanners. However, a high powered, invisible laser is required for a user to perceive heat; thus, this option is also not suitable due to potential eye damage. Consequently, given current technical limitations, we must apply a low-resolution IR projection system comprising an IR light source and pan-tilt mirror gantry to control the direction of the IR light.

When a visible image is projected onto the same area of a user's body an IR light is illuminated, it is possible that the visual information will affect thermal sensation through cross modal effects [23], [24] and improve the perceived spatial resolution of the thermal sensation. It has been revealed by previous studies that visual information significantly affects thermal sensation [25], [26], [27]. However, these studies investigated the interaction between visual and thermal information in the human brain using contact-based thermal displays. Therefore, it remains unclear how one should design non-contact visual and thermal information to effectively and plausibly render virtual warm objects.

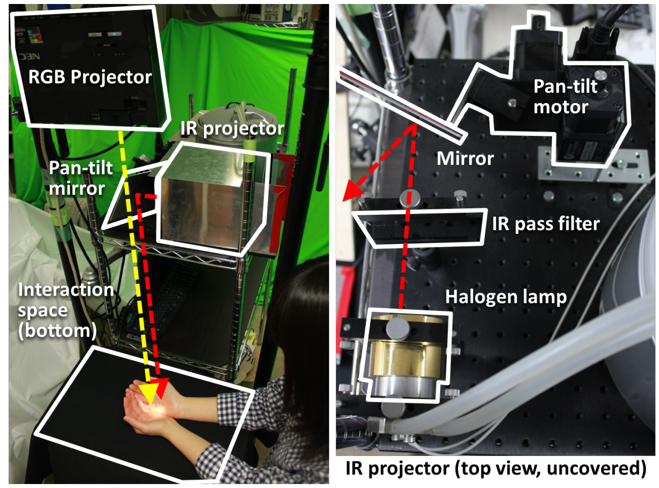


Fig. 2. Prototype (dashed yellow line: projected visible light; dashed red line: projected IR light).

In this study, we investigated a design guideline for non-contact thermo-visual augmentation through psychophysical experiments, and we applied the deign guideline to several application systems.

3 Prototype System

Our IR-RGB projection system consists of an RGB projector (NEC, NP-L50WJD) and a fabricated IR projector (Figure 2). The light source of the IR projector is a halogen lamp (FINTECH, HSH-60f ∞/36v-450w) that is supplied power by a large-current direct current power source. The emitted light forms a parallel beam using a parabolic mirror and the direction of the beam is controlled by a pan-tilt mirror (SUSTAINable Robotics, PTU-D46). Before hitting the mirror, the parallel beam passes through an IR pass filter (HOYA, IR-80) to cut off the visible light spectrum. We assume that the interaction space of this prototype is a cuboid (bottom: 0.45×0.30 m, height: 0.25 m), as shown in Figure 2. Therefore, the user's hand and arm can be illuminated by the IR-RGB projection system when they are located within this space. This space is sufficiently large to investigate the thermo-visual cross modal effects and demonstrate working applications. Note that the room temperature was 25.5 to 27.5 °C in our experiments and applications.

To ensure that users do not suffer burn injuries, including low temperature burns, we employed a very conservative policy regarding the maximum temperature. We determined the maximum temperature as 37.0 °C, which corresponds to the temperature of a human with a low-grade fever; therefore, we believe that this temperature is sufficient to display a virtual or distant creature. In a preliminary test, we confirmed that the skin temperature of the palm is consistently less than the maximum temperature when 360 W is supplied to the IR light source and the palm is placed on the bottom surface of the interaction space of the projection system, which is 60 cm from the pan-tilt mirror of the IR projector. Therefore, we use 360 W as the maximum input power. We also determined the minimum input power at which a user can feel a warm sensation as 120 W.

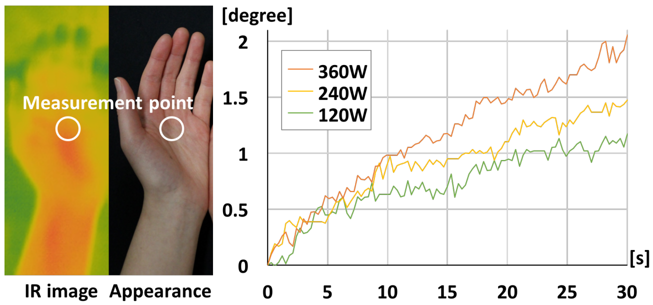
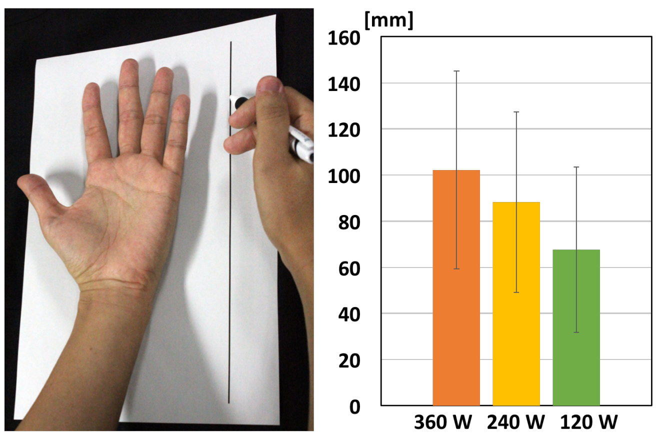


Fig. 3. Temperature transition (difference from original temperature) of the central point on a palm under continuous IR projection.



Input power	360 W	240 W	120 W
Average	102 mm	88 mm	68 mm
Standard deviation	43 mm	39 mm	36 mm

Fig. 4. Perceived area.

We measured the transition of the skin temperature on the human palm where the IR light is projected. First, an experimenter placed their hand on the bottom surface of the interaction space. After turning on the projector with three input powers (360, 240, and 120 W), we measured the temperature of the approximate central point on the hand using a thermal IR camera (Optris PI-450, 382×288 pixels) every 0.3 s. Before projection, the skin temperatures of this point were 31.4, 31.9, and 31.3 °C when input powers of 360, 240, and 120 W were applied, respectively. Figure 3 shows the temperature measurement results. A previous literature [28] describes that a human detects skin warming with increase in temperature of approximately 0.5 °C when the original skin temperature is 31.0 to 32.0 °C and heat stimulus is 15 cm^2. The literature also describes that the spatial summation of heat stimulus lowers this threshold. Therefore, from the experimental result, we confirmed that a user can perceive radiant heat shorter than 5 s after the IR light is illuminated regardless of the input power level.

We investigated the perceived spatial resolution of the projected IR light. We asked participants to identify the size of the area on their skins, which became warm under IR projection. We prepared a sheet of paper with a printed straight line on the bottom surface (Figure 4). Each participant placed their hand on the paper. While the IR light was projected onto the palm, the participant marked two points on the line, which represent the area orthogonally projected onto the line, where they felt warmth. Figure 4 shows the result. Note that the perceived warm area increases as the input power to the IR projector increases. The area is approximately the same or slightly larger than the size of an adult human's palm. This spatial resolution is nearly equivalent to that of previous systems [14], [15], [22].

In terms of human perception, the spatial acuity of thermal sense in a non-contact condition is approximately 50 mm on the forearm [29]. On the other hand, the RGB projector can display approximately 350×410 pixels on the same palm. This resolution is significantly higher than that of the IR projector. Considering a cross model effect whereby the visual sensation overrides the thermal sensation to some extent [25], [26], [27], we can provide suitable thermal sensation by carefully designing IR projection patterns in combination with the high resolution RGB projection. To this end, we conducted psychophysical experiments to investigate appropriate combinations of IR projection patterns and visual information.

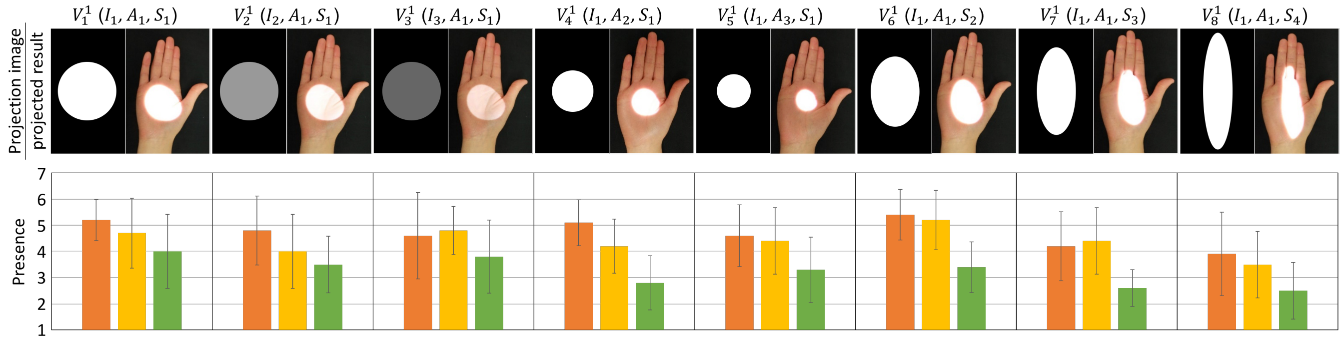
4 Psychophysical Experiments

We conducted psychophysical experiments to investigate what kinds of thermal perceptions are caused by different types of thermo-visual projections on human skin. The investigation results are useful for designing both thermal radiation conditions and visual images to render a warm object with high presence as if the thermal perception is caused by the displayed object. To avoid semantics affecting participant perception, a simple graphical primitive was applied as the visual stimulus in our experiments. The experiments were conducted using the prototype described in Section 3 under environment light (610 lx) to evaluate several potential application scenarios. Ten participants (eight males, two females; 21-24 years) from the local university volunteered for the experiments. Each participant placed their hand or arm on a table 60 cm from the pan-tilt mirror of the IR projector.

4.1 Static properties

The first experiment was conducted to investigate a basic design question regarding thermo-visual projection, i.e., how static properties of visual and thermal stimuli affect the presence of a displayed object. Here, we investigated the effects of the brightness, area, and shape of the visual stimuli, as well as the input powers applied to the IR projector.

We examined the following hypotheses in this experiment. First, relative to the provided energy, there may be a positive correlation between the brightness of a visual stimulus and the input power of a thermal stimulus. Thus, H1 is "*to render a warm object with high presence, a brighter visual stimulus should be displayed with a thermal stimulus with a larger input power.*" Second, the same kind of correlation is found between the area of a visual stimulus and the input power of a thermal stimulus. Thus, H2 is "*to render a warm object with a high presence, a larger visual stimulus should be displayed with a thermal stimulus with a larger input power.*" Third, it is natural to think that high presence of a displayed



Visual stimuli	V_1^1			V_2^1			V_3^1			V_4^1		
Thermal stimuli	T_1^1	T_2^1	T_3^1	T_1^1	T_2^1	T_3^1	T_1^1	T_2^1	T_3^1	T_1^1	T_2^1	T_3^1
Average	5.2	4.7	4.0	4.8	4.0	3.5	4.6	4.8	3.8	5.1	4.2	2.8
Standard deviation	0.8	1.3	1.4	1.3	1.4	1.1	1.7	0.9	1.4	0.9	1.0	1.0

Visual stimuli	V_5^1			V_6^1			V_7^1			V_8^1		
Thermal stimuli	T_1^1	T_2^1	T_3^1	T_1^1	T_2^1	T_3^1	T_1^1	T_2^1	T_3^1	T_1^1	T_2^1	T_3^1
Average	4.6	4.4	3.3	5.4	5.2	3.4	4.2	4.4	2.6	3.9	3.5	2.5
Standard deviation	1.2	1.3	1.3	1.0	1.1	1.0	1.3	1.3	0.7	1.6	1.3	1.1

Fig. 5. Visual stimuli in psychophysical experiment for static properties (top), and the average and standard deviation of perceived presence scores (middle and bottom). : T_1^1 (360 W), : T_2^1 (240 W), : T_3^1 (120 W).

object is achieved when the shape of a visual stimulus is identical to that of a thermal stimulus. Thus, H3-1 is "*to achieve high presence of a displayed object, the shape of a visual stimulus should be close to that of a thermal stimulus (a circular spotlight) from the IR projector.*" On the other hand, due to a cross modal effect whereby visual sensation overrides thermal sensation, it is possible that a small shape difference will not cause a serious lack of presence. Thus, H3-2, which is related to H3-1, is "*a small shape difference is acceptable.*"

4.1.1 Procedure

For visual stimuli projected from the RGB projector, we prepared three illuminance values ($I_1 = 4.10 \times 10^3$ lx, $I_2 = 3.95 \times 10^3$ lx, $I_3 = 2.32 \times 10^3$ lx), three areas (A_1 : 9π cm^2, A_2: $\frac{9\pi}{2}$ cm^2, A_3: $\frac{9\pi}{3}$ cm^2), and four shapes. The shapes consist of a true circle (S_1) and three ellipses (S_2, S_3, S_4). The areas of the ellipses were the same as A_1, while the length of the short axis varied by 5 cm for S_2, 4 cm for S_3, and 3 cm for S_4. Combining these properties, we prepared eight visual stimuli ($V_1^1, \dots, V_8^1$), as shown in Figure 5. Note that V_1^1 was designed such that it covers the entire palm area. For the IR projector, we prepared three thermal stimuli (T_1^1, T_2^1, T_3^1) generated by different input powers (T_1^1: 360 W, T_2^1: 240 W, T_3^1: 120 W). Consequently, there were 24 (=8×3) conditions in this experiment.

For each condition, we projected both visual and thermal stimuli on each participant's right palm for 5 s. Both the center of the visual circle and the direction of the IR projector were fixed at the center of the palm. Then, the participant answered the following subjective question on a seven-point Likert scale regarding the presence of the displayed object, "*How strongly do you feel the presence of the stimuli? (1: not at all, . . ., 4: undecided, . . ., 7: strongly feel)*," Then, we asked the participant to place their palm on a Peltier device (Misumi PELT No. 70) to cool it down to 30.0 °C. Each participant tested all conditions, which were counterbalanced to control for order effects. Figure 5 shows the results.

4.1.2 Validation of H1 (brightness-temperature consistency)

To validate H1, we compared the results of V_1^1, V_2^1, and V_3^1. The illuminances of the visual stimuli differed among these conditions.

The mean values were greater than 4 (undecided) for all visual stimuli when the input power of the IR projector was T_1^1 and T_2^1. We analyzed the results regarding the illuminance of visual stimulus and the input power to the IR projector. A Friedman test showed the main effect due to the input power ($\chi_2 = 16.46, p < 0.01$). Then, a post-hoc analysis was performed using Dunn-Bonferroni test for pairwise comparison. The results showed statistically significant differences among the thermal stimuli as represented by the inequality $T_1^1, T_2^1 > T_3^1$ ($p < 0.05$). Note that "$C_1 > C_2, C_3$" represents that the mean scores of condition C_1 were significantly greater than those of C_2 and C_3.

To render a warm object with high presence, input power of 240 W or greater should always be applied to the IR projector for any illuminance of the visual stimuli in this prototype. Note that the illuminance of a visual stimulus does not affect presence significantly. From these results, we consider that H1 is rejected. In other words, we do not have to adaptively determine input powers according to the visual illuminance, i.e., fixed input power is sufficient.

4.1.3 Validation of H2 (size-temperature consistency)

To validate H2, we compared the results of V_1^1, V_4^1, and V_5^1. The areas of the visual stimuli differed among these conditions.

The mean values were greater than 4 for all visual stimuli when the input power of the IR projector was T_1^1 and T_2^1. We analyzed the results regarding the area of visual stimulus and the input power to the IR projector. A Friedman test showed the main effect due to both the area ($\chi_2 = 7.01, p < 0.05$) and the input power ($\chi_2 = 29.57, p < 0.01$). A post-hoc analysis was performed using Dunn-Bonferroni test for pairwise comparison. The results show statistically significant differences among the thermal stimuli as represented in the inequality $T_1^1, T_2^1 > T_3^1$ ($p < 0.05$), while showing no significant difference among the visual stimuli.

To render a warm object with high presence, input power of 240 W or greater should always be applied to the IR projector for any visual stimuli areas in this prototype. On the other hand, although the Friedman test showed that the area of a visual stimulus also affects presence, the pairwise comparison showed that the area difference even between the largest and smallest visual stimuli in our experiment was not sufficient to provide significantly different presences. It is natural to assume that the area of a visual stimulus is within this range in our potential user scenarios where an object is presented on a palm or forearm (cf. Figure 1). Therefore, we consider that H2 is rejected, i.e., the area of a visual stimulus does not affect presence, particularly in our applications. In other words, we do not have to adaptively determine input powers according to the area of the visual information, i.e., fixed input power is sufficient.

4.1.4 Validation of H3 (shape consistency)

To validate H3-1 and H3-2, we compared the results of V_1^1, V_6^1, V_7^1, and V_8^1. The shapes of the visual stimuli differed among these conditions.

The mean values were greater than 4 in the following combinations of visual and thermal stimuli: $V_1^1, V_6^1, V_7^1 \leftrightarrow T_1^1, T_2^1$. Note that "$V_a, V_b \leftrightarrow T_a, T_b$" represents any combination of visual stimuli V_a and V_b and thermal stimuli T_a and T_b. We analyzed the results regarding the shape of visual stimulus and the input power to the IR projector. A Friedman test showed the main effects in both the shape ($\chi_2 = 38.29, p < 0.01$) and the input power ($\chi_2 = 37.36, p < 0.01$). A post-hoc analysis using Dunn-Bonferroni test showed statistically significant differences in the visual stimuli as represented in the inequality $V_1^1 > V_8^1$ and $V_6^1 > V_7^1, V_8^1$ ($p < 0.01$), and the thermal stimuli as $T_1^1, T_2^1 > T_3^1$ ($p < 0.01$).

From the mean values, a warm object can be rendered with high presence when the shape does not differ extremely from a true circle and when the input power is greater than or equal to 240 W. From the statistical analyses, we confirmed that slight anisotropy in the shape (up to V_6^1) of the visual information is acceptable. From these results, we consider that H3-1 and H3-2 are supported.

4.2 Dynamic property

The second experiment was conducted to investigate how to design spatiotemporal patterns of visual and thermal stimuli to render a warm object with high presence that is moving dynamically on a palm or forearm. Note that the current IR projector cannot project a complex spatiotemporal pattern, such as the dynamic deformation of an object. The spatial resolution is very low because the IR projector is a single pixel spot light. On the other hand, we can modulate the IR light temporally in synchronization with the motion of the corresponding visual stimulus.

We validated the following hypotheses in this experiment. First, the response time of human perception of a thermal stimulus is relatively slow compared to other haptic sensations [30], and heat remains on a surface once it is warmed [31], [32]. Therefore, if we move a rendered object quickly on human skin, the visual and thermal perceptions may be separated spatially. Thus, H4 is "*to render a dynamic warm object with a high presence, the speed of the object should be slow.*" Second, when the movement of a visual stimulus is small, the IR projector cannot distinguishably display the same movement of a thermal stimulus due to the low spatial resolution. However, in such a case, we can temporally synchronize the thermal stimulus with the corresponding visual motion. For example, we can decrease the input power to the IR projector when the visual stimulus becomes small (and vice versa). Higher presence may be provided when a thermal stimulus is modulated temporally in synchronization with the dynamic change of a visual stimulus than when the thermal stimulus is static with constant input power. Thus, H5 is "*to render a dynamic warm object with a high presence, the thermal pattern should be synchronized with the corresponding visual stimulus.*"

4.2.1 Procedure

We prepared three types of motion for a warm object: (1) deformation, (2) movement on the palm, and (3) translation on the forearm.

As stimuli of the deformation on the palm, we prepared three patterns with different deformation speeds. Here, we gradually changed the shape of the visual stimulus from a true circle to an ellipse by modulating the length of the short axis from 6.0 to 1.5 cm, while that of the long axis was constant at 6.0 cm (Figure 6(a)). The length of the short axis $S_\omega(t)$ is expressed as

$$S_\omega(t) = 3.75 - 2.25\cos(\omega t), \tag{1}$$

where ω is the angular speed of the modulation. The visual stimuli of the three deformation patterns are represented as $V_{1,\omega}^2$, where $\omega = \frac{\pi}{2}$ rad/s, π rad/s, and 2π red/s. We prepared two types of thermal stimuli T_s^2 and T_d^2. T_s^2 applied static input power of 240 W, and T_d^2 applied dynamic, temporally varying input power of 0 to 360 W, which was synchronized with the visual stimulus. The input powers $P_s(t)$ and $P_d(t)$ for thermal stimuli T_s^2 and T_d^2 are as follows:

$$\begin{aligned} P_s(t) &= 240, & (2) \\ P_d(t) &= 180 - 180\cos(\omega t). & (3) \end{aligned}$$

The center of the visual information and thermal spotlight were fixed at the center of the right palm of each participant. The visual and thermal stimuli were projected until the visual stimulus was deformed five cycles.

For stimuli with movement on the palm, we prepared three revolving motions with different angular speeds for visual stimuli and two temporal patterns for thermal stimuli. The visual stimuli, represented as $V_{2,\omega}^2$, were a true circle (radius: 1.8 cm) moving in a circle with a radius of 1.8 cm (Figure 6(b)). Here, the center of the circle corresponded to the center of the right palm of each participant. The angular speeds ω were $\frac{\pi}{2}$ rad/s, π rad/s, and 2π rad/s, which correspond to 2.8 cm/s, 5.7 cm/s, and 11.3 cm/s, respectively. In addition, we prepared static and dynamic thermal stimuli, T_s^2 and T_d^2. Note that, using the pan-tilt mirror, the center of the thermal spotlight always followed that of the visual stimulus. The visual and thermal stimuli were projected until the visual stimulus rotated five cycles.

For translation on the forearm, we prepared four rectilinear movements with different speeds v for visual stimuli $V^2_{3,v}$ (Figure 6(c)) and a thermal stimulus with constant input power of 240 W (i.e., T^2_s). The speeds of the visual stimuli were 2 cm/s, 6 cm/s, 10 cm/s, and 14 cm/s. The center of the thermal spotlight always followed that of the visual stimulus using the pan-tilt mirror. These stimuli were applied to the palmar side of the right forearm of each participant and moved 20 cm from the wrist toward the elbow. Here, we prepared only one thermal stimulus because the rectilinear movement was sufficiently large to be reproduced by the IR projector. Note that we did not compensate the input power for the speed to provide the same total amount of radiated heat power.

Consequently, there were 16 ($= 3 \times 2 + 3 \times 2 + 4$) conditions in total. Note that we used the maximum brightness for the visual stimuli. Here, the experimental procedure was the same as the first experiment (Section 4.1). After each trial, the participant answered the same subjective questions regarding the presence of the displayed object. Then, we asked the participant to place their palm or forearm on the Peltier device to cool it down to 30.0 °C. Each participant tested all conditions, which were counterbalanced to control for order effects.

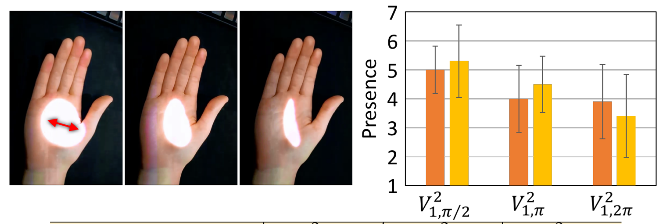
4.2.2 Validation of H4 (speed) and H5 (temporal consistency)

We validated H4 and H5 by comparing the experimental results. Note that the results of the three motions were analyzed separately.

Figure 6(a) shows the result for the deformation motion. The mean values were greater than 4 in the following combinations of visual and thermal stimuli: $V^2_{1,\frac{\pi}{2}}, V^2_{1,\pi} \leftrightarrow T^2_s, T^2_t$. We analyzed the results regarding the deformation speed of visual stimulus and the temporal modulation of thermal stimulus. A Friedman test showed the main effect due to the deformation speed ($\chi_2 = 19.04, p < 0.01$), and a post-hoc analysis using Dunn-Bonferroni test showed statistically significant differences in deformation speed as represented in the inequality $V^2_{1,\frac{\pi}{2}} > V^2_{1,2\pi}$ ($p < 0.01$).

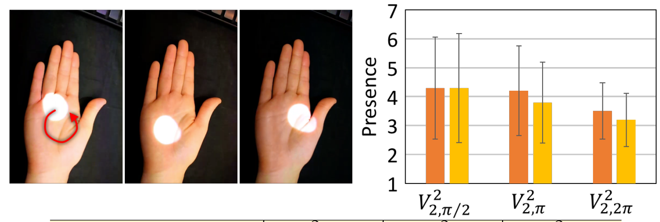
Figure 6(b) shows the results for the second motion (i.e., movement on the palm). The mean values were slightly greater than 4 in the following combinations: $V^2_{2,\frac{\pi}{2}} \leftrightarrow T^2_s, T^2_t$ and $V^2_{2,\pi} \leftrightarrow T^2_s$. We analyzed the results regarding the angular speed of visual stimulus and the temporal modulation of thermal stimulus. A Friedman test showed the main effect due to the angular speed ($\chi_2 = 9.54, p < 0.01$), and a post-hoc analysis using Dunn-Bonferroni test showed statistically significant differences in angular speed as represented in the inequality $V^2_{2,\frac{\pi}{2}} > V^2_{2,2\pi}$ ($p < 0.05$).

Figure 6(c) shows the results for the third motion (i.e., translation on the forearm). The mean values were greater than 4 in the visual stimuli of $V^2_{3,2}$ and $V^2_{3,6}$. A Friedman test showed the main effect due to the speed of the visual information ($\chi_2 = 18.35, p < 0.01$), and a post-hoc analysis using Dunn-Bonferroni test showed statistically significant differences in speed as represented in the inequalities $V^2_{3,2} > V^2_{3,10}, V^2_{3,14}$ ($p < 0.05$).



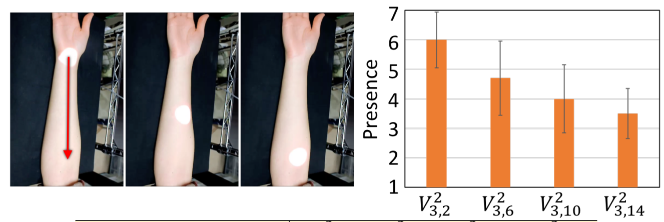
Visual stimuli	$V^2_{1,\pi/2}$		$V^2_{1,\pi}$		$V^2_{1,2\pi}$	
Thermal stimuli	T^2_s	T^2_d	T^2_s	T^2_d	T^2_s	T^2_d
Average	5.0	5.3	4.0	4.5	3.9	3.4
Standard deviation	0.8	1.3	1.2	1.0	1.3	1.4

(a) Deformation



Visual stimuli	$V^2_{2,\pi/2}$		$V^2_{2,\pi}$		$V^2_{2,2\pi}$	
Thermal stimuli	T^2_s	T^2_d	T^2_s	T^2_d	T^2_s	T^2_d
Average	4.3	4.3	4.2	3.8	3.5	3.2
Standard deviation	1.8	1.9	1.5	1.4	1.0	0.9

(b) Movement on a palm



Visual stimuli	$V^2_{3,2}$	$V^2_{3,6}$	$V^2_{3,10}$	$V^2_{3,14}$
Average	6.0	4.7	4.0	3.5
Standard deviation	0.9	1.3	1.2	0.8

(c) Translation on a forearm

Fig. 6. Visual stimuli in psychophysical experiment for dynamic properties (left), and the average and standard deviation of perceived presence scores (right and bottom). Each red arrow indicates the deformation or movement of each stimulus. ■ : T^2_s, ■ : T^2_d.

Here, we discuss two issues relative to these results. First, the result of the second motion indicates that the presence of the displayed warm object was not sufficiently high when it moved in the palm area. Therefore, we consider that a small movement (i.e., within the spot of the projected IR light) is not suitable for plausibly rendering a warm object. Second, the results of the other motions indicate that the presence scores were significantly worse when the rendered objects moved quickly. Therefore, the system can plausibly provide a dynamic warm object only when slow movement is applied to the visual information, e.g., $\omega = \frac{\pi}{2}, \pi$ rad/s (deformation and circular movement on the palm) and $v = 2, 6$ cm/s (translation). On the other hand, the statistical analyses showed that the presence of the presented object was not affected significantly by the temporal modulation of the thermal stimulus. Therefore, we confirm that H4 is supported and H5 is rejected for the deformation and large translation motions.

4.3 Design guideline

From our experiments, we obtained the following design guideline for thermo-visual projection to render a warm object on human skin with high presence. First, the thermal radiation the intensity should be high. In particular, the input power of the IR projector should be greater than or equal to 240 W. In addition, the input power does not have to be adjusted according to the illuminance, area, and shape of the visual information. Second, the shapes between the visual and thermal stimuli do not have to be perfectly identical, and a slight difference, possibly due to a cross modal effect, is acceptable.

The following three guidelines should be applied when the rendered object moves on the skin. First, when the object translates on the skin, the movement should be sufficiently large, at least greater than the size of the IR spot. Second, the speed of the movement should be slow. Specifically, the angular speed of a periodical deformation and circular movement on the palm should be π rad/s or less, and the transition speed should be less than or equal to 6 cm/s. Third, the thermal radiation does not have to be modulated temporally because temporal modulation does not significantly improve the presence of a rendered warm object.

We summarize the design guidelines as follows.

- The thermal radiation the intensity should be high regardless of the illuminance, area, and shape of the visual information.
- The shapes between the visual and thermal stimuli do not have to be perfectly identical.
- When the object moves on the skin, the movement should be sufficiently large and slow.
- The thermal radiation does not have to be temporally modulated.

5 APPLICATIONS

We considered three types of application scenarios and conducted user tests to validate our system and the design guideline (Section 4.3).

5.1 Virtual creature walking on hand and forearm

In the first application scenario, a virtual bunny [33] walked on a user's hand and forearm (Figure 7(a)). We rendered this character such that the shape of the projected visual appearance was roughly rounded to follow the design guideline. The size of the bunny was 8×9 cm^2 on the bottom surface of the interaction space of the projection system (i.e., 60 cm from the pan-tilt mirror of the IR projector). The projected bunny walked freely on the table at a speed of 2 cm/s. The center of the IR spotlight followed the center of the visual bunny. The input power to the IR projector was constant at 360 W.

We conducted a user study with seven participants (six males, one female; 22-24 years) to investigate the effectiveness of the proposed thermo-visual projection system and the design guideline. We prepared two experimental conditions, i.e., with and without IR projection. The projected bunny walked back and forth along a straight line path between two predefined positions 20 cm apart. Each participant was asked to place their hand and forearm on the table as shown in Figure 7(a). In each trial, the bunny walked on the hand and forearm for 30 s. The participant performed one trial for each condition. After the participant experienced both conditions, they were asked to identify under which condition they felt higher presence, or if presence was the same between the conditions. The participant was also asked to provide feedback regarding any thoughts about the experience.

(a) Virtual creature walking on hand and forearm

(b) Remote collaboration

(c) Virtual flame moving on hand and forearm

Fig. 7. Applications: (left) projection image from each video sequence, (right) projected result. Each red arrow indicates movement.

Three participants felt higher presence under the IR projection condition, and four participants felt the same level of presence under both conditions. No participant reported that they felt higher presence under the condition without IR projection. Therefore, we confirm that our system provides better or equal presence of a virtual creature, compared to a normal SAR system. Most participants (four out of seven) felt the same presence between the two conditions. They reported that the presented thermal and visual stimuli were not so congruent. Note that all participants were aware whether the IR projection was applied in each condition, while we did not explicitly disclose the condition to the participants. A Wilcoxon signed-rank test does not show significant difference between the conditions ($Z = -1.73, p = 0.08$).

5.2 Remote collaboration

The second application scenario was remote collaboration between two distant users. Two types of live video images were transferred to a distant site. One video showed the face and torso of a remote user captured using a front camera, and the other video showed the hand and forearm captured using a top camera. We combined a vertical LCD monitor with the proposed system such that it could display the received face and torso images. The top view images were projected onto the bottom surface (Figure 7(b)). In this scenario, we attempted to increase the presence of the remote collaborator by providing body heat to the projected dominant hand. Here, the participants could feel the sensation of each other's body heat when performing a shake hand gesture. The system also allowed the remote users to virtually touch each other's hands and forearms. To follow the guideline, the speed of the hand movement should be less than 6 cm/s, and the angular speed of the hand image deformation by the hand shaking gesture should be less than π rad/s. We believe that these speeds are not too slow for typical face-to-face communication. Here, the center of the IR spotlight followed the center of the projected dominant hand, and the input power to the IR projector was constant at 360 W.

We conducted a user study with the same participants and prepared the same experimental conditions described in Section 5.1. Here, we recorded a shake hand sequence of a person (non-participant) using the front and top cameras in advance. Each participant was asked to shake hands with the recorded person whose face and torso were displayed on the vertical monitor and whose hands and forearms were projected onto the bottom surface. The duration of the shake hand was 3 s. After each participant experienced both conditions, they were asked to identify under which condition they felt higher presence of the displayed hand, or if presence was the same between the conditions. The participant was also asked to procide feedback about the experience.

Four participants felt higher presence under the IR projection condition, and three participants felt the same level of presence under both conditions. No participant reported that they felt higher presence under the condition without IR projection. Therefore, we confirm that our system provides equal or better presence of a remote hand, compared to a normal SAR system. For the most participants (four out of seven), our system improved presence. These participants reported they felt that the displayed hand actually touched their hands. Note that all participants were aware whether the IR projection was applied in each condition, while we did not explicitly disclose the condition to the participants. A Wilcoxon signed-rank test shows significant difference between the conditions ($Z = -2.00, p < 0.05$).

5.3 Virtual flame moving on hand and forearm

In the third application scenario, we investigated how the proposed system and design guideline work for a virtual object that is much warmer than natural creatures. Here, a flame was displayed on the user's hand and forearm. This application was same as the first application (Section 5.1), except for the displayed object (Figure 7(c)). The experimental procedure was also same as the first scenario, except for the question. This time, participants were asked to identify under which condition they felt higher presence, or if presence was the same between the conditions.

As a result, all participants felt higher presence of the virtual flame under the IR projection condition. Therefore, we can confirm that our system is more suitable to present a virtual flame than a normal SAR system. The participants reported that the presented thermal and visual stimuli were sufficiently consistent and the realism of the flame was very high. Note that all participants were aware whether the IR projection was applied in each condition, while we did not explicitly disclose the condition to the participants. A Wilcoxon signed-rank test shows significant difference between the conditions ($Z = -2.65, p < 0.01$).

6 Discussion

Through the application evaluations discussed in Section 5, we confirmed that the proposed system with the design guideline can display a warm creature or object, such as a virtual animal or human hand, with higher presence than a general SAR system. Although the proposed system did not provide better presence for some participants, it did not have negative effects. We believe the design guideline is also useful for a thermo-visual projection system that applies different thermal projection approaches [14], [15], [22], because current thermal projectors, including ours, have nearly the same properties (e.g., low spatial resolution). Surprisingly, a flame, which is much warmer than natural creatures, can also be plausibly displayed on a user's hand and arm using the proposed system. This indicates that we can safely display high-temperature objects without risk of harming human skin with projected heat.

A major limitation of the proposed system is the low spatial resolution of the thermal projection. From the psychophysical experiments, we confirmed that the shape of the projected IR light does not always have to be identical to that of the visual image (Section 4.1). However, a higher spatial resolution would allow us to display finer and more complex objects, which is preferable. By applying heat radiation as the principle of thermal projection, it is currently difficult to physically increase the spatial resolution because there is no SLM that can robustly work at high temperature due to IR illumination. To increase the perceived spatial resolution of a thermal stimulus, we could integrate a non-contact force feedback system into the thermo-visual projection system. Previous studies have revealed the difference in perceived thermal spatial resolution between contact and non-contact thermal stimulations [13]. Specifically, resolution is higher in the contact case. Therefore, interesting future work would be to integrate a non-contact force feedback system (e.g., one based on an ultrasound approach [19]) and investigate whether the perceived thermal spatial resolution is enhanced.

To keep the heat levels safe, we chose 360 W as the maximum input power to the IR projector. However, it also restricted the range of interactions. Therefore, it is important to consider how to balance the trade-off to realize more effective and plentiful heat representations while keeping the safety. To provide the base of this discussion, we will investigate the heat perception and the presence of a displayed object under more radiant heat powers through further experiments in our future work.

The experiments conducted in this paper have some limitations. Although clear user trends were obtained, the number of participants were relatively small. The question used in the experiments was also limited as it only asked about the presence of the presented stimuli. In addition, there was no interaction between participants and displayed objects. We tried to install gesture sensors such as Microsoft Kinect and Leap Motion, though they did not work well due to the interference of IR lights between the IR projector and the sensors. Therefore, the current system was not ready for testing in an interactive task. To increase the validity of the design guideline, we will conduct additional experiments by considering these issues in future.

The current system applies SAR for visual augmentation; however, there are other visual display technologies that can visually merge real and virtual spaces, including video and optical see-through head mounted displays and floating image displays, such as aerial imaging by retro-reflection [34]. When applying such technologies, we can display visual information in mid-air, which cannot be achieved by a projector. However, only few approaches have attempted to provide natural haptic feedback from a mid-air virtual object, one of which is heat radiation. Therefore, it would be interesting to integrate the proposed thermal projector with other visual display technologies and investigate whether such a system can increase the plausibility of a rendered mid-air object.

7 Conclusion

This paper has presented a novel method for non-contact haptic augmentation with SAR. We built a thermo-visual projection system by combining a typical RGB projector and a fabricated IR projector. In addition, in psychophysical experiments, we investigated a design guideline for spatiotemporal projection patterns to plausibly render a warm object. We developed application systems and evaluated the validity of the proposed system and design guideline. The results demonstrate that the proposed system can render warm objects with higher presence than a normal SAR system. One important future work is to downsize the IR projection system such that thermo-visual projection can be easily applied to other existing SAR systems.

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