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Fundamental Investigation of Warmth Motion Illusion Induced by Pulling Illusion

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***Abstract*—The presentation of thermal sensation is expected to improve immersive experience. However, thermal perception is slower than visual and tactile perception, and there is insufficient discussion regarding the presentation of the sensation of warmth motion. Conventional methods have explored tactile-dependent illusions; however, these methods are limited in their ability to represent rapid directional changes and fine motions. This study focuses on a pulling illusion, a type of tactile-dependent illusion, and examines whether it can produce the sensation of warmth motion. The experimental results indicate that the pulling illusion creates the sensation of warmth motion. Furthermore, we speculate that the principle underlying this illusion might be the warmth motion in response to changes in the body scheme. Subsequently, we investigated the extent of the warmth motion produced. The results revealed that the subjective motion distance of the illusory warmth motion is considered to be equivalent to the movement of approximately 9.25 mm of a heat source. The findings of this study can serve as a basis for future research into the sensation of warmth motion induced by the pulling illusion and provide design guidelines for warmth motion displays.**

***Index Terms*—virtual reality, non-contact thermal display, pulling illusion, body scheme.**

I. Introduction

In virtual reality, a technique that provides thermal sensation as sensory feedback has been studied. Presenting thermal stimuli simultaneously with music and images can change the mental image [1], and presenting temperature information simultaneously with visual information can improve the sense of immersion [2]. Furthermore, noncontact thermal presentation is particularly useful because it does not cause a reduction in immersion owing to the sense of contact or discomfort of the thermal element [3]. To date, many haptic devices that use thermal sensation have been developed, such as those that provide thermal feedback alongside head-mounted displays [4] or glove-type wearable devices [5]. However, temperature is perceived more slowly than other senses, such as vision and touch, and there is little discussion on how to represent the sensation of warmth motion. In real-world environments, thermal sensations dynamically change due to natural phenomena such as wind or thermal convection. By representing such dynamic changes in thermal sensation, it becomes possible to present heat perception that more closely resembles real-world environments, thereby enhancing immersion and realism. The first possible method is to move heat physically. However, this approach is challenging owing to the mechanical limitations of the equipment. Therefore, the fact that touch-dependent illusions are likely to produce similar illusions of warmth [6] has led to active research on methods that exploit illusions. However, quick direction changes and fine movements are difficult to represent using conventional methods that employ illusions. In contrast, the pulling illusion [7], which is a tactile-dependent illusion, can express a sense of motion with rapid direction changes. Ito *et al.* proposed a device called HeatFlicker, which reproduces the sensation of flickering fire through asymmetric vibration to create a pulling illusion and LED light to present a noncontact temperature sensation [8]. It has been suggested that the presentation of warmth simultaneously with the pulling illusion may generate the warmth motion illusion; however, it remains unclear whether the pulling illusion actually generates the warmth motion illusion. In addition, the principles underlying its generation and sensory characteristics remain unclear. This study clarifies whether the pulling illusion generates an illusory sensation of warmth motion. This will be useful for future designs when discussing their fundamental characteristics. Furthermore, a specific contribution of this study lies in its applicability to the VR/AR domain. The sensation of warmth motion generated by our proposed method can reproduce the dynamic thermal changes found in real environments, such as the flickering of a campfire or candle. These have traditionally been used for mental relaxation and well-being through visual and auditory effects, but our method may add emotionally evocative thermal

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sensations, enhancing their affective impact. And also, the sensation of warmth motion evoked by our method is suggested to rely on a different perceptual mechanism from that of physical thermal stimuli. Therefore, this method may be applicable in cases of impaired thermal sensation, such as peripheral neuropathy or limb loss, enabling thermal feedback even in areas without functional thermoreception, such as artificial hands.

II. Related Works and Research Question

A. Body Schema and Thermal Illusion

Body schema refers to the unconscious, brain-integrated senses of one's body, postural status, and other somatic sensations. The body schema can be changed using tools, visual and tactile information, and illusions [9]. For example, the illusion of joint extension can be created by applying vibratory stimulation to the tendons of the extensor muscles of the joint [10]. During the presentation of this illusion, touching the nose can provide the sensation that the nose is elongated. This is called the Pinocchio illusion, and it is known that touching not only the nose but also the waist can change its body schema [11]. In contrast, illusions that are dependent on tactile sensations are prone to similar illusions related to warmth [6]. For instance, phenomena such as phantom sensations [12], [13] and apparent motion [14], [15], which are commonly discussed in the context of touch, can also occur in thermal sensations and allow for the representation of warmth motion without changing the position of the thermal stimuli. Thus, warmth may also be influenced by body schema. In our study, we hypothesize that this dependence of warmth on body schema might give rise to the warmth motion illusion.

B. Pulling Illusion

Steeper accelerations are perceived more strongly than gentler accelerations. Amemiya *et al.* proposed a method for presenting a virtual unidirectional force vector or a pulling illusion by generating asymmetric accelerations in a periodic translational motion [16]. Tanabe *et al.* proposed a method to generate a pulling illusion using asymmetric vibrations synthesized from two fundamental waves and identified the types of asymmetries in the input vibration waveform that contribute to the generation of the pulling illusion through psychophysical experiments [17]. Tanabe *et al.* suggested that a similar change in body schema occurs with a pulling illusion [18]. In our study, asymmetric vibrations with phase differences were used to present the pulling illusion in the front-back direction and change the body schema.

C. Noncontact Thermal Presentation

The most common device for thermal presentation is the Peltier device because of its ease of control. However, in the presentation of warmth using Peltier elements, a sense of contact with the element may prevent the induction of the illusion. Noncontact temperature sensation is provided by visible light-emitting diodes (LED), infrared light lamps, and laser light. In the case of warmth presentation with infrared light lamps, it is difficult to switch presentations quickly [19], whereas in the case of laser light warmth presentation, it is easier to perceive it as a tactile stimulus than a warmth stimulus [20]. In contrast, noncontact thermal presentation using visible-light LEDs allows for easy and quick adjustments to the output through pulse-width modulation (PWM) control, as heating is achieved via light energy [3]. In our study, noncontact thermal presentation with LEDs was used to prevent the generation of the warmth motion illusion from being disturbed by the contact sensation and to control it in accordance with the pulling illusion.

D. Research Question

It is unclear whether the pulling illusion produces an illusory sense of motion in the warmth sensation. In addition to the basic characteristics of the warmth-motion illusion, such as the intensity and direction produced, the principle of how the illusion is created remains unclear. Therefore, this study aimed to confirm whether warmth sensations generated a sense of motion. Simultaneously, we compared the sensation of warmth motion and the actual movement of the heat source, as well as the effect of the pulling illusion on the sensation of warmth motion of the heat source. In addition, the principle of generating the warmth motion illusion through the pulling illusion was discussed.

III. Device Development

In our study, to avoid influencing changes in the body schema due to the pulling illusion, it was necessary to present thermal stimuli without contact. In addition, a device that can arbitrarily change the thermal presentation position is required for a comparison with the sensation of warmth motion caused by the movement of the heat source. In this section, we describe the experimental system that can present a noncontact thermal sensation at any location using visible-light LEDs and a linear actuator, as well as the setup procedure for the experiment.

A. Noncontact Thermal Presentation Device

In the experiment, it was necessary to present a working heat source for comparison with the warmth motion illusion due to the pulling illusion. As shown in Fig. 1, we created a device that can present a noncontact thermal stimulus with an LED light at any desired location. The thermal presentation device consisted of a linear actuator (Oriental Motor EZSM4RD015AZAC) and a box-shaped LED light presentation device. The box-shaped LED light presentation device has two flat LEDs (HighPower Chip LED 50 W, Coairrwy) on the top surface and DC fans (YDM2507C05F, Shenzhen YCC-FAN) on both sides of the box for internal heat dissipation. In addition, a slit cover was fitted to limit the range of LED light presentation and prevent participants' hands from coming into direct contact with the LEDs. The parts of the noncontact thermal presentation device were fabricated using a 3D printer (Raise3D Pro2 Plus, Raise 3D). The intensities of the LED light and linear actuator were controlled using a microcomputer (Arduino Uno, Arduino) mounted on a box-shaped LED light presentation device. The pulling illusion was presented by applying asymmetric vibration signals to a voice coil vibrator (639897, Foster Electric) grasped by the user's fingertips. The input signals were output from an audio interface (PAA-U4P, MIYOSHI) and amplified using a D-class amplifier (PAM8403DR, Diodes, Inc.). The waveforms proposed by Tanabe *et al.* [17] with a fundamental wave of 75 Hz were used for the asymmetric vibration waveform.

B. Experimental Setup

In a preliminary experiment, the generation of the motion illusion of warmth was significantly reduced when the hand was fixed to the table. Thus, the stimulus presentation was performed with the elbow fixed and the hand off the table, as shown in Fig. 2(a). In addition, as shown in Fig. 2(b), a thermal sensation presentation using an LED light was applied to the lower part of the palm, distant from the fingertip where vibration stimuli are presented. The thermal presentation was conducted with LED light exposure for 5 s per trial. The skin temperature change during the stimulus presentation averaged from 35.5 °C to around 38.9 °C. The amplitude measured for the intensity of the vibration stimulus was 60.82 m / s^2 with the vibrator grasped. To avoid bias in the responses due to linear actuator motion, the device was covered during stimulus presentation. White noise was played through the headphones worn by the participants. Prior to the experiment, the perception of the pulling illusion was confirmed. Asymmetric vibrations, which induce the pulling illusion, and sinusoidal vibrations, which do not, were presented in random order. The participants were asked to report whether the pulling illusion was perceived until they were able to answer in the same direction, as presented three times in a row. The experiment was terminated if the participant did not provide a correct answer at the end of 30 trials. To mitigate the effects of arm movement, the position of the strap attached to the wrist was measured using a laser displacement meter during the stimulus presentation. The data analysis excluded data corresponding to arm movements. In the experiment, both noncontact thermal stimuli using visible-light LEDs and vibration stimuli were presented simultaneously.

IV. Experiment 1: Basic Verification of Illusion

A. Experimental Conditions

The first experiment aimed to verify whether the pulling illusion induced the warmth motion illusion. A comparison was also made with the presentation of the heat source in motion. Simultaneously, the effect of combining the pulling illusion with the heat source movement on the sensation of warmth motion was investigated. In Experiment 1, as presented in Table I, five stimulus patterns combining the vibration presentation patterns, asymmetry or symmetry, and the movement patterns of the heat source are presented randomly. Responses are obtained using a five-point one-way Likert scale (1: not felt at all, 2: felt a little, 3: felt, 4: felt strongly, 5: felt very strongly). Additionally, the participants were not given any prior information about the movement of the heat source, the presence of the pulling illusion, the maximum or minimum stimuli in their responses, or any other details. Participants were instructed that both vibratory and thermal stimuli would be presented simultaneously, and they were asked to answer questions regarding their perception of the sensation of warmth motion. There are two types of vibration patterns: sinusoidal vibration, which does not produce the pulling illusion, and asymmetric vibration, which produces the pulling illusion [21]. The pulling illusion is presented by periodically changing the direction (forward or backward) and switching every second. In addition, the movement patterns of the heat source using the linear actuator were of three types: a fixed pattern (fixed), a reciprocating motion with forward and backward movements (same loop), and a reciprocating motion in the opposite direction of the same loop (opposite loop). In the same-loop pattern, the heat source moved in the same direction as the pulling illusion, whereas in the opposite loop pattern, the heat source moved in the opposite direction to the pulling illusion. The direction of motion of the heat source was changed simultaneously with the switching of the

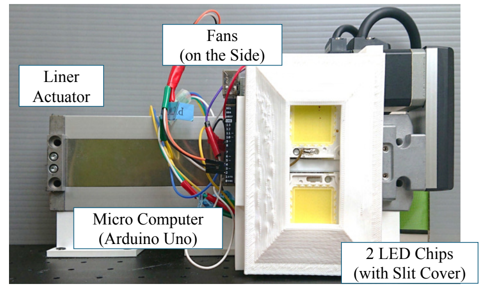
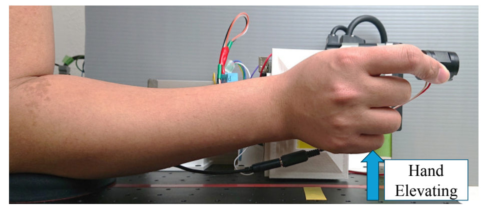
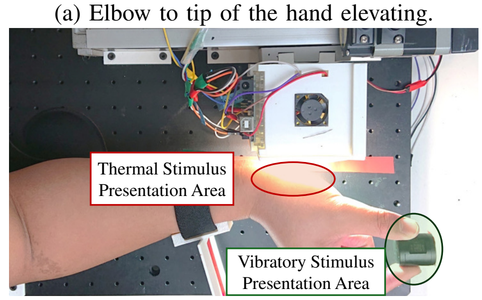


Fig. 1: Non-contact thermal presentation device: It is composed of the box-shaped LED light presentation device and the linear actuator.



(a) Elbow to tip of the hand elevating.



(b) Location of stimulus presentation.

Fig. 2: The images of the device in use.

TABLE I: STIMULUS PATTERNS IN EXPERIMENT 1

Pattern	Heat Source Movement	Vibration
FS	fixed	sinusoidal
FA	fixed	asymmetrical
SS	same loop	sinusoidal
SA	same loop	asymmetrical
OA	opposite loop	asymmetrical

direction of the pulling illusion every second. The forward and backward reciprocations in the case of sinusoidal vibrations were identical. The distribution density of warmth-sensitive spots in the human palm is given as $\rho = 0.004\,\mathrm{mm}^{-2}$ [22]. This implies that the average area per warmth-sensitive spot is:

$$A_{\text{spot}} = \frac{1}{\rho} = \frac{1}{0.004} = 250\,\mathrm{mm}^2 \tag{1}$$

Thus, a single warmth-sensitive spot exists within every $250\,\mathrm{mm}^2$ of the palm.

To evoke the sensation of warmth motion, the heat source must be moved by a distance sufficient to stimulate spatially distinct warmth-sensitive spots. Given the derived threshold of 15.8 mm for perceiving warmth motion, a preliminary experiment was conducted in which the heat source was moved in increments of 1 mm within the range of 10 mm to 20 mm during warmth stimulation. The goal was to verify the detectability of warmth motion. The results indicated that perceptual differences between displacements of 20 mm and 15 mm were minimal. Therefore, 15 mm was chosen as the minimum physical amplitude capable of reliably evoking the sensation of warmth motion. Accordingly, the amplitude A of the reciprocating motion was set as:

$$A = 15\,\mathrm{mm} \tag{2}$$

In Experiment 1, 25 trials were conducted for each stimulus pattern. Experiment 1 was conducted with nine males and two females between the ages of 22 and 24 years. The participants were not involved in the system development. They were paid approximately 12 USD through Amazon gift cards to participate in the experiment. The recruitment of participants and the content of the experiments were approved by the Institutional Ethics Committee of the Faculty of Engineering, Information, and Systems, University of Tsukuba, Japan (approval number 2023R829) The participants provided written informed consent to participate in the experiments.

B. Result and Discussion

Data obtained with arm displacements exceeding 10 mm were not used because the arms were assumed to have moved. Data that could not be measured by the laser displacement meter because the arm was tilted were also excluded because it could not be guaranteed that the arm had not moved. After excluding 172 data points from 1125 data points, the main effect of stimulus patterns was analyzed using the Friedman test. The results of the test revealed a main effect ($\chi^2(4) = 104.63, p < 0.05$); therefore, pairwise comparisons were conducted using the Wilcoxon signed-rank test with Bonferroni correction. The results are presented as box-and-whisker plots in Fig. 4. Asterisks indicate statistical significance. First, we investigated whether the pulling illusion generated a warmth motion illusion. A statistically significant difference between Patterns FS and FA was confirmed based on Fig. 4. This suggests that the sensation of warmth motion can be induced even when the heat source is fixed, through the presentation of the pulling illusion.

Subsequently, the intensity of the sensation of warmth motion generated by the pulling illusion was compared with that of a moving heat source. Statistically significant differences were observed for Patterns FA and SS, with Pattern SS exhibiting a stronger response. Thus, the warmth motion illusion generated by the pulling illusion generated a smaller motion sensation than the reciprocating motion of the heat source, with an amplitude of 15 mm. Finally, the effect of the combination of presenting the pulling illusion and moving the heat source on the sensation of warmth motion is discussed. Statistically significant differences were confirmed for Patterns SA and OA, whereas no significant differences were found for Patterns SS and SA and Patterns SS and OA. While the sensation of warmth motion appears to be induced by the presentation of the pulling illusion during heat source movement, the effect may be too small to produce a statistically significant difference depending on the presence or absence of the illusion. Additionally, it is possible that the direction of the perceived warmth motion varies depending on the direction in which the pulling illusion is presented. This may depend on the direction of the warmth motion illusion caused by the pulling illusion. As shown in Fig. 3(a), if the sensation of warmth motion generated by the pulling illusion tends to be perceived in the same direction as that of the pulling illusion, then Pattern OA, in which the heat source is moved in the opposite direction, may generate a stronger sensation of warmth motion relative to Pattern SA, in which the heat source is moved in the same direction. This could imply that the direction of the sensation of warmth motion produced by the pulling illusion is possibly aligned with that of the pulling illusion. Therefore, although the pulling illusion appears to change the body schematic, the position of the warmth sensation might also change concomitantly, as shown in Fig. 3(b). Even though no relative positional warmth motion should occur in the local coordinate system of the body schematic, the results of Experiment 1 suggest that such a sensation of warmth motion is generated. This may point to the possibility that a world coordinate reference point could be involved in the perception of warmth motion and that the perception of warmth motion might be based on absolute position. We tentatively hypothesize that the principle of the warmth motion illusion caused by the pulling illusion lies in the relationship between the change in body schema and the reference point for the perception of warmth motion. However, although the body schema is constructed by vision, touch, and somatosensory perception, it remains uncertain whether the warmth perception is altered by the change in the body schema; this consideration of the cause of the warmth motion illusion caused by the pulling illusion is only a hypothesis. As shown in Fig. 4, even in Pattern FS, where the sensation of warmth motion is not expected to be elicited by the illusion, some participants reported high ratings such as 4: felt strongly and 5: felt very strongly. Additionally, the overall distribution of the ratings appears to be widely dispersed. One possible explanation for this result is the influence of bias introduced by the Likert scale used in Experiment 1. In this experiment, we employed a five-point one-way Likert scale consisting of the following options: 1: not felt at all, 2: felt a little, 3: felt, 4: felt strongly, and 5: felt very strongly. However, the nature of these ratings is potentially unbalanced: while rating 1 clearly indicates the absence of any motion sensation, ratings 2 through 5, despite differing in intensity, all imply the presence of some degree of motion sensation. This asymmetry may have introduced a response bias, whereby participants felt compelled to report some level of warmth motion even when it was not actually perceived.

V. Experiment 2: Discrimination of Motion Direction

A. Experimental Conditions

Experiment 2 investigated the relationship between the direction of the pulling illusion and the perceived sense of warmth motion. The pulling illusion was presented while changing direction with a fixed heat source. To prevent adaptation to the stimulus, the initial direction of the presented pulling illusion was randomized into forward (Pattern 1) and backward (Pattern 2) directions. After five seconds of stimulus presentation, participants were asked to report the perceived direction of the sensation of warmth motion, comparing it with the direction of the pulling illusion. Responses were collected using two alternative forced choices indicating whether the direction was the same or the opposite. A total of 100 trials were conducted. Experiment 2 was conducted on 11 males between the ages of 22 and 28 years. Compensation and ethical approval for participation were the same as in Experiment 1.

B. Result and Discussion

The summed values for Patterns 1 and 2 in the same and opposite directions were calculated. Fig. 5 shows box-and-whisker plots of the proportions in the same and opposite directions. A paired t-test was conducted, and the normality assumption was confirmed using the Shapiro-Wilk test. No significant differences were observed $(t(10) = 0.736, p < 0.05)$. The effect size (Cohen's d) was 0.22, which was considered small, suggesting a minor trend. In addition, the same and opposite direction responses are approximately 50 percent of the chance level, suggesting that the direction of the warmth motion illusion cannot be determined. The results of Experiment 1 revealed a difference in the sensation of warmth motion between Patterns SA and OA; however, the direction of this illusion could not be determined in Experiment 2. This could be due to masking of the warmth by the vibratory stimulus. Vibratory stimuli are stronger and more perceptible than thermal stimuli, as is the masking of warmth by vibratory stimuli [23], [24]. In Experiment 2, participants compared the direction of the sensation of the warmth motion with that of the pulling illusion. Thus, it is assumed that they concentrated on the fingertips where the pulling illusion occurred and where the vibratory stimulus was presented. This suggests that the location of warmth and the perception of warmth motion may have become ambiguous, and the direction of the sensation of warmth motion may have become unrecognizable.

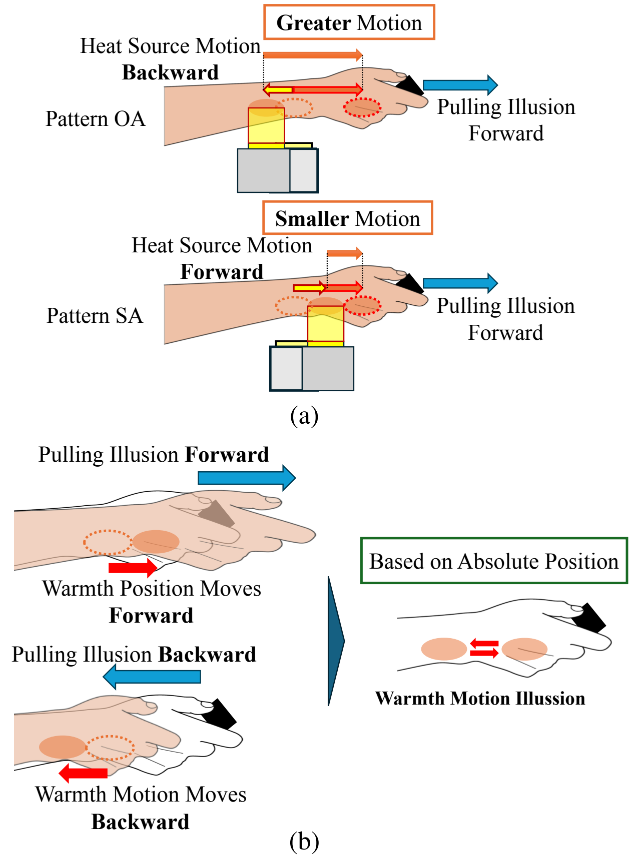
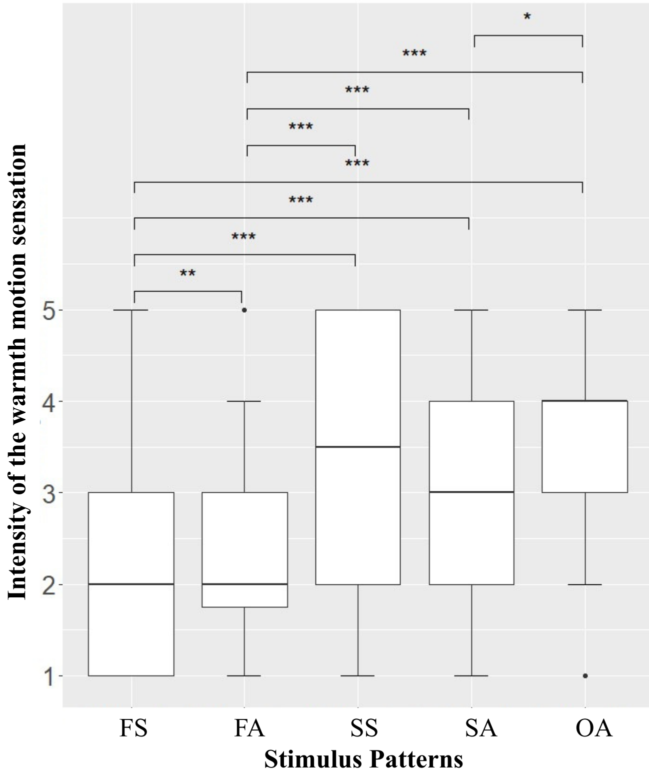


Fig. 3: Motion of warmth sensation by the pulling illusion: (a) Discussion of why Pattern OA induced a stronger sensation of warmth motion compared to Pattern SA in the result of Experiment 1. (b) Hypothesis on the principle of the warmth motion illusion induced by the pulling illusion: The position of warmth perception might change in association with changes in body schema, while the sensation of warmth motion might be perceived with reference to absolute position.

VI. Experiment 3: Subjective Motion Distance

A. Experimental Conditions

In Experiment 3, the warmth motion illusion caused by the pulling illusion was compared with the sensation of warmth motion when the heat source moved reciprocally. Specifically, the experiment investigated which amplitude of the reciprocating movement of the heat source was equivalent to the



* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Fig. 4: Experiment 1: Relationship between stimulus patterns and the sensation of warmth in motion.

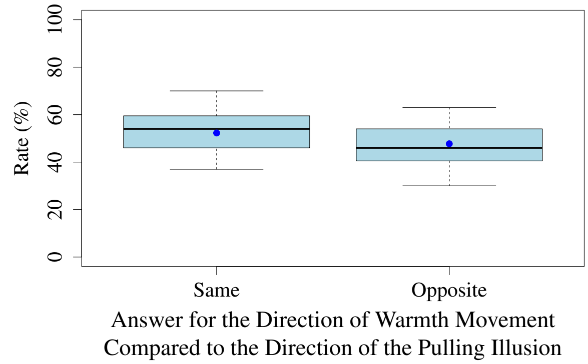


Fig. 5: Experiment 2: The relationship between "same" and "opposite" in the experiment 2.

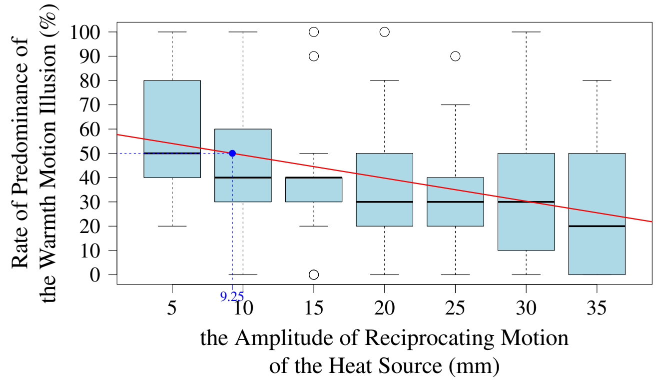
sensation of warmth motion induced by the pulling illusion. The experiment included two patterns: one in which the heat source was fixed and the pulling illusion was presented while switching its direction (Pattern FA in Experiment 1), and the other in which no pulling illusion was presented. Instead, a sinusoidal dummy vibration was applied, and the heat source reciprocated at random amplitudes of 5, 10, 15, 20, 25, 30, and 35 mm (Pattern SS in Experiment 1 but with a changing amplitude, referred to as SS-CA). The two patterns were presented in random sequences. After the stimulus presentation, participants were asked to respond using a two-alternative forced choice method to indicate whether they subjectively perceived greater motion in the sensation of warmth when the stimulus was presented the second time compared to the first presentation. They were asked to choose between "Yes" or "No." The responses were used to determine the degree of motion. 70 trials were conducted. When the amplitude of the reciprocating motion of the heat source was small, a stronger sensation of warmth motion was generated by the FA pattern. As the amplitude of the reciprocating motion of the heat source increases, the probability that the sensation of warmth motion generated by the pulling illusion will result in a greater sense of motion is expected to decrease monotonically. Therefore, we first calculated the probability of a greater sense of motion in the warmth sensation induced by the pulling illusion for each reciprocal amplitude of the heat source. Then, we determined the reciprocation amplitude of the heat source with a 50 percent probability of occurrence using the regression line obtained from the scatter diagram. Finally, the degree to which the sensation of warmth motion was induced by the pulling illusion was evaluated quantitatively. Experiment 3 was conducted with 11 males and two females between the ages of 22 and 28 years, as in Experiment 2. Compensation and ethical approval for participation in the experiment were the same as in Experiments 1 and 2.

B. *Result and Discussion*

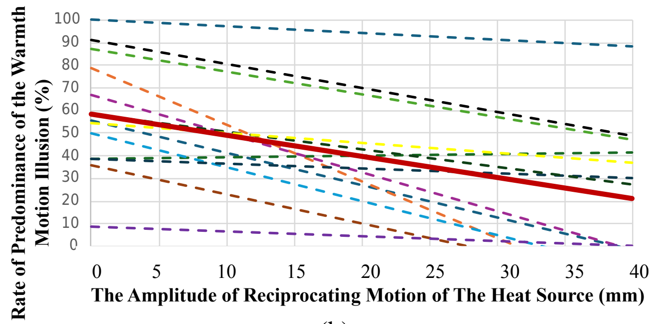
Fig. 6(a) shows box-and-whisker plots of the probability of perceiving a greater sensation of warmth motion based on the data obtained, where pattern FA was compared to pattern SS-CA for each reciprocation width. An regression line was drawn from the scatter plots. From the regression line, we determined the amplitude of the reciprocating motion at which there was a 50 percent likelihood of experiencing a stronger sensation of warmth motion induced by the pulling illusion. The amplitudes were 9.25 mm. In Experiment 1, the sensation of warmth motion was perceived more strongly in Pattern SS compared with Pattern FA. In Pattern FA, the heat source was fixed while the pulling illusion was presented. In Pattern SS, the heat source reciprocated with an amplitude of 15 mm, and the pulling illusion was not presented. The intensity of the warmth motion illusion at an amplitude of 9.25 mm (as determined in this experiment) aligned with the results of Experiment 1. In Section IV-A, we derived the physically perceivable threshold for thermal motion based on the density of warm spots on the skin, which was 15.8 mm. However, the equivalent amplitude of motion sensation induced by the pulling illusion in the Experiment 3 was 9.25 mm, indicating that a sensation of warmth motion was evoked even at a smaller amplitude, approximately 6.5 mm less. This suggests that, in the method proposed in this study, where the sensation of warmth motion is induced by the pulling illusion, it does not arise from changes in the responses of warm receptors at warm spots. Rather, it is likely generated by the responses of sensory receptors associated with other modalities, such as vibration. Therefore, the warmth motion illusion by the pulling illusions may be based on a different perceptual mechanism than that of physically induced thermal motion. Owing to this difference in perceptual mechanism, it may become possible to functionally guide and shift warmth sensations to areas where warm spots are not actually present by leveraging unaffected regions, an outcome with promising potential applications.

VII. Limitation and Future Works

However, this study has several limitations, including the relationship between warmth perception and body schema, as well as the parameters that determine the strength of the illusion. The current results suggest that further research is essential for a better understanding of these factors. Specifically, considering the mechanisms behind the warmth motion illusion could shed light on the body schema changes induced by the pulling illusion. In addition, there were individual differences in the responses for Experiment 3. The value of 9.25 mm obtained is not an exact measurement but rather a rough estimate because the number of participants was relatively small, and there were individual differences in the participants' responses, as shown in Fig. 6(b). For example, some participants in Pattern FA had a higher probability of perceiving a stronger sensation of warmth motion. This was observed even in Pattern SS-CA, with the largest reciprocal amplitude of the heat source exceeding 50 percent. In contrast, some participants had a probability of occurrence of less than 50 percent in Pattern SS-CA, with the smallest amplitude. This may be attributed to an insufficient sample size for the two-alternative forced choice method employed in Experiment 3. Regarding the influence of participant age and gender on the results, previous studies on age-related changes in the perception of the pulling illusion and in thermal perception suggest that in younger individuals, there are no significant gender differences in thermal perception or in the occurrence of the pulling illusion [25]. Therefore, the sensation of warmth motion should be elicited reliably in this population. However, in older individuals, it has been reported that thermal sensitivity in the upper arm tends to be lower in women, and that the pulling illusion may not occur as readily in some elderly female participants [26]. Consequently, the warmth motion illusion induced by pulling illusion may not be elicited in certain elderly women. In addition, in all the experiments, parameters such as the amplitude and presentation time of the asymmetric vibration generating the pulling illusion were unified. However, individual differences due to insufficient calibration of the thermal stimuli also represent a limitation of this study. The stimulus intensity was not calibrated for temperature change for each participant, so there could be individual differences in thermal presentation. To eliminate the influence of individual differences, it is necessary to measure skin temperature using a thermal camera and flexibly adjust the intensity of thermal stimulation for each participant. And to generalize the conclusions presented in this study, it will be necessary to recruit participants from a wider age range, conduct experiments with a larger sample size, and calibrate thermal stimulation individually for each participant. These aspects are intended to be addressed in future work. In addition, the effects of varying the intensity and presentation time of the pulling illusion on the intensity of the warmth motion produced have not been investigated. It is essential to clarify the factors related to the generation and intensity of the warmth motion illusion. Clarifying these factors is important for developing warmth motion displays in the future.



(a)



(b)

Fig. 6: Experiment 3: Rate of the sensation of warmth motion in case FA is greater than that in case SS-CA. (a) Box plots showing the rate for each amplitude, along with the regression line of all samples. (b) Dotted lines showing the regression lines for each participant and a solid red line showing the regression line of all samples, as in (a).

VIII. Conclusion

Our study demonstrated that the sensation of warmth motion tended to be generated and enhanced by the pulling illusion. The principles underlying the warmth motion illusion caused by the pulling illusion were considered. The perceived position of warmth varies in association with changes in body schema. It was also inferred that the sensation of warmth motion experienced was approximately 9 mm. This study provides a basic investigation into the warmth motion illusion caused by the pulling illusion. The findings from this study can serve as a foundation for future research on the warmth motion illusion caused by the pulling illusion and provide design guidelines for warmth motion displays.

REFERENCES

[1] M. Akazue, M. Halvey, L. Baillie, S. Brewster: The Effect of Thermal Stimuli on the Emotional Perception of Images, Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, 4401–4412, 2016.

[2] R. L. Peiris, W. Peng, Z. Chen, L. Chan, K. Minamizawa: ThermoVR: Exploring Integrated Thermal Haptic Feedback with Head Mounted Displays, Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, Association for Computing Machinery, pp. 5452-5456, 2017.

[3] A. Sakai, T. Yamaguchi, H. Mitake, S. Hasegawa: Contactless Warmth Display Using Visible Light LED for HMDVR, TVRSJ, Volume 24, Issue 1, pp. 83-92, 2019.

[4] N. Ranasinghe, P. Jain, S. Karwita, D. Tolley, E. Y. L. Do: Ambiotherm: Enhancing Sense of Presence in Virtual Reality by Simulating Real-World Environmental Conditions, CHI 2017, May 6-11, 2017.

[5] S. W. Kim, S. H. Kim, C. S. Kim, K. Yi, J. S. Kim, B. J. Cho, Y. Cha: Thermal Display Glove for Interacting with Virtual Reality, Scientific Reports, Volume 10, Issue 1, Article 11403, 2020.

[6] T. Ohyama, S. Imai, T. Wake: New Edition Handbook of Sensory and Perceptual Psychology Part 2, Seishin Shobo, pp. 421-422, 1994.

[7] T. Tanabe, H. Yano, H. Iwata: Evaluation of the Perceptual Characteristics of a Force Induced by Asymmetric Vibrations, IEEE Transactions on Haptics, Volume 11, Issue 2, pp. 220-231, 2018.

[8] T. Ito, T. Tanabe, S. Hasegawa, N. Ienaga, Y. Kuroda: HeatFlicker: A Virtual Campfire System Utilizing Flickering Thermal Illusions by Asymmetric Vibrations, arXiv preprint, arXiv:2411.05157, 2024.

[9] A. Maravita, A. Iriki: Tools for the Body (Schema), Trends in Cognitive Sciences, Volume 8, Issue 2, pp. 79-86, 2004.

[10] G. M. Goodwin, D. I. McCloskey, P. B. C. Matthews: The Contribution of Muscle Afferents to Kesthesesthesia Shown by Vibration Induced Illusions of Movement and by the Effects of Paralysing Joint Afferents, Brain, Volume 95, pp. 705-748, 1972.

[11] J. R. Lackner: Some Proprioceptive Influences on the Perceptual Representation of Body Shape and Orientation, Brain, Volume 111, pp. 281-297, 1988.

[12] J. Oohara, H. Kato, Y. Hashimoto, H. Kajimoto: Presentation of Positional Information by Heat Phantom Sensation, Haptics: Generating and Perceiving Tangible Sensations, EuroHaptics 2010, Volume 6192, pp. 839-847, 2010.

[13] S. Hashiguchi, F. Shibata, A. Kimura: Psychophysical Influence on Position and Amplitude of Temperature Perception by Mixed-Reality Visual Stimulation, TVRSJ, Volume 21, Issue 3, pp. 503-511, 2016.

[14] T. Nishimura, H. Karasawa, A. Seo, K. Doi: Influence of Temperature Stimulus Duration and Stimulus Onset Asynchrony on the Rate of Occurrence of Apparent Movement: A Study Based on the Temperature Sense of the Human Palm, Journal of the Japan Society of Kansei Engineering, Volume 11, Issue 3, pp. 475-481, 2012.

[15] T. Moesgen, H. N. Ho, Y. Xiao: Apparent Thermal Motion on the Forearm, Haptics: Understanding Touch; Technology and Systems; Applications and Interaction, Springer, pp. 56-68, 2024.

[16] T. Amemiya, H. Ando, T. Maeda: Non-Grounding Force Display Utilizing Nonlinearity of Human Perception, TVRSJ, Volume 11, Issue 1, pp. 47-58, 2006.

[17] T. Tanabe, H. Yano, H. Endo, S. Ino, H. Iwata: Pulling Illusion Based on the Phase Difference of the Frequency Components of Asymmetric Vibrations, IEEE/ASME Transactions on Mechatronics, Volume 26, Issue 1, pp. 143-152, 2021.

[18] T. Tanabe, H. Kaneko: Illusory Directional Sensation Induced by Asymmetric Vibrations Influences Sense of Agency and Velocity in Wrist Motions, IEEE Transactions on Neural Systems and Rehabilitation Engineering, Volume 32, pp. 1749, 2024.

[19] J. Dionisio: Virtual hell: a trip through the flames, IEEE Computer Graphics and Applications, Volume 17, Issue 3, pp. 11-14, 1997.

[20] J. H. Jun, J. R. Park, S. P. Kim, et al.: Laser-induced thermoelastic effects can evoke tactile sensations, Sci Rep, Volume 5, Article 11016, 2015.

[21] T. Tanabe, T. Amemiya, H. Endo, S. Ino: Research Trend of Pulling Illusion Induced by Asymmetric Vibrations, TVRSJ, Volume 25, Issue 4, pp. 291-301, 2020.

[22] T. Ohyama, S. Imai, T. Wake: New Edition Handbook of Sensory and Perceptual Psychology, Seishin Shobo, pp. 1249-1261, 1994.

[23] J. C. Craig, P. M. Evans: Vibrotactile masking and the persistence of tactual features, Perception & Psychophysics, Volume 42, Issue 4, pp. 311-317, 1987.

[24] H. Wang, Y. Singhal, H. Gil, J. R. Kim: Thermal Masking: When the Illusion Takes Over the Real, in: Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems, CHI '24, Association for Computing Machinery, pp. 419, 2024.

[25] T. Tanabe, S. Yamamoto, T. Yamada, D. Ishii, Y. Kohno: Age-Related Impact in Illusory Torque Cues Induced by Asymmetric Vibrations, IEEE Transactions on Haptics, pp. 1–9, 2025. doi:10.1109/TOH.2025.3557901.

[26] E. L. Harju: Cold and warmth perception mapped for age, gender, and body area, Somatosensory & Motor Research, Vol. 19, No. 1, pp. 61–75, 2002.