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RESEARCH ARTICLE

Pseudo-Wind Perception Induced by Cross-Modal Reproduction of Thermal, Vibrotactile, Visual, and Auditory Stimuli

JURO HOSOI, YUKI BAN, (Member, IEEE), KENICHI ITO, AND SHIN'ICHI WARISAWA, (Member, IEEE)
Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, Chiba 2778563, Japan
Corresponding author: Juro Hosoi (jhosoi@s.h.k.u-tokyo.ac.jp)

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ABSTRACT Numerous wind displays have been developed to provide wind sensation in virtual reality applications. However, in previous studies, wind displays required the production of physical wind using a wind source. To release cold or hot wind, previous wind displays required large equipment for making the air temperature changes. In this study, we propose to induce pseudo-wind perception, perceiving wind even in the absence of physical wind, using visuo-audio-haptic cross-modal effects. We provide audio-visual stimuli with a head-mounted display and headphones, and vibrotactile and thermal stimuli to the skin using belt-type devices, instead of physical wind. We found that vibrotactile and thermal stimuli based on the measurement of skin displacement and temperature exposed to the wind are suitable for the tactile sensation of wind. We also found that thermal and audio-visual stimuli can induce wind sensation of cold wind, and that vibro-thermal stimuli in addition to audio-visual stimuli are effective for the wind sensation and realness of the experience of hot wind. In future, inducing variable types of wind sensations will be pursued as a research direction regarding pseudo-wind perception.

INDEX TERMS Cross-modal effect, multisensory stimuli, tactile sensation, virtual reality, wind display, wind perception, wind sensations.

I. INTRODUCTION

Humans typically sense various types of winds in their daily lives, such as hot, cold, or gusty winds. Moreover, winds can provide environmental information, such as air temperature, weather, climatic conditions of a location, and movement information such as speed and direction.

To simulate wind sensation and provide the aforementioned information, numerous wind displays have been developed in the field of virtual reality (VR). These wind displays can improve the sense of presence [1], [2], [3], [4], [5], reduce VR sickness [6], [7], [8], and enhance the emotional experience of a user [5], [9].

The wind displays reported in the literature thus far utilized physical wind and required wind sources such as fans. For example, WindCube [1] used 20 dc fans to produce winds from various directions. VaiR [2] utilized ten air nozzles that were attached to common head-mounted displays (HMDs).

However, the abovementioned wind displays using physical wind have several limitations. First, numerous wind sources are required to induce winds from multiple directions. As a solution to this problem, several studies have been conducted on changing the perception of wind direction with a few wind sources by cross-modal effects of visual, audio, and wind stimuli [10], [11].

Another issue is that while thermal wind enriches the VR experience [12], the devices that provide hot and cool winds tend to be large. This is because constantly changing the air

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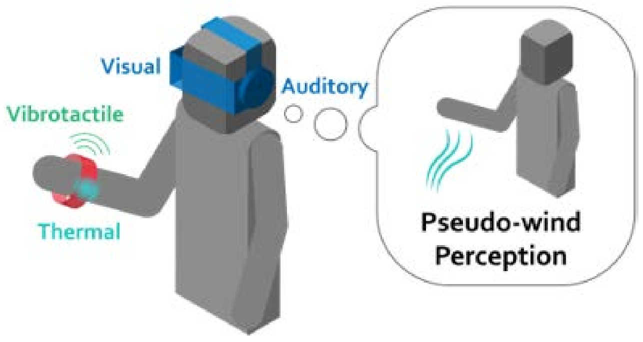


FIGURE 1. Concept of pseudo-wind perception.

temperature from room temperature to the target temperature while providing a hot or cold wind requires enormous heat exchange. A large heat sink and a large compressor are required for presenting hot and cold winds [13], [14], respectively.

In this paper, we propose inducing wind sensation without using physical wind as a solution to the problem of cold and hot winds. We define *pseudo-wind perception* as perceiving wind even in the absence of physical wind (Figure 1).

Wind perception is based on visual, auditory, and tactile perceptions. While experiencing winds, we observe flying leaves or swaying trees. As auditory perception examples, we hear wind sounds and fan noise. These stimuli can be provided using HMDs and headphones. Tactile perception includes pressure, vibration, shaking body hair, and skin temperature change. In previous studies, these stimuli were provided using physical winds. In this research, the applied approach is to present these stimuli without using actual wind.

The objective of this study is to investigate pseudo-wind perception inducement by cross-modal effects. The two main contributions of this study are as follows. First, we find that the tactile sensation of wind can be presented by wind-like tactile stimuli. Second, we show that cross-modal effects of the visual, auditory, vibrotactile, and thermal stimuli can enhance wind experiences in the VR space.

This study comprises two steps. In study 1, vibrotactile and thermal stimuli suitable for pseudo-wind perception are investigated. In study 2, visuo-audio-haptic cross-modal effects on wind sensation and the sense of presence are examined. For conducting the experiments, a belt-type device is developed to provide vibrotactile and thermal stimuli.

This paper is a revised version of the abstract we presented at SIGGRAPH Asia 2021, Emerging Technologies [15], with additional details on stimuli design suitable for pseudo-wind perception and experiments to clarify the effects of pseudo-wind perception by cross-modal effects.

II. RELATED WORK

This section describes the previously proposed approaches for providing wind sensation and presenting various tactile sensations. We then clarify the position of this study in relation to previous studies.

A. WIND DISPLAY

Wind displays are devices that provide wind sensation to their users. Sensorama [16], which is one of the earliest examples of multimodal displays, utilizes winds to induce the sense of presence. Several wind displays, such as WindCube [1] and VaiR [2], contain many wind sources to simulate different wind directions. Other types of wind displays include actuators for changing the wind direction by moving the wind sources [2], [3], [5].

The wind displays developed thus far have been adopted to present self-movements [2], [4], [17], climates of VR environments [2], [3], [5], and movements of virtual objects [18], [19]. Studies have confirmed that such devices enhance the sense of presence in virtual environments [1], [2], [3], [4], [5] and improve the emotional responses [5] of users.

Some wind displays can also generate hot and cold winds. WindTherm [13] provides hot winds using a Peltier element and a heat sink. Hapmosphere [20] contains a heat blower to enable hot wind feedback. Xu et al. [14] proposed employing a vortex tube and a compressor to generate a cold airflow. In comparison with previous approaches, which require large equipment to produce a hot or cool wind, we propose pseudo-wind perception without physical wind.

Ito et al. showed that perceived wind directions can be manipulated by visuo-audio-haptic cross-modal effects [11]. Their approach is similar to the concept of this study, wherein multiple sensory modalities are stimulated to induce cross-modal effects in wind perception. However, manipulation of the perceived wind directions still requires physical wind, in contrast to pseudo-wind perception.

B. MATERIAL DISPLAY WITH VIBROTACTILE AND THERMAL PRESENTATION

To our best knowledge, there is no study on reproducing haptic stimuli for inducing the tactile sensation of wind. However, various methods of presenting other tactile sensations with vibrotactile and thermal stimuli have been developed in previous studies. Tactile sensations of objects or materials are based on various factors, such as softness, roughness, and coldness [21], [22], [23], [24]. Some previous studies present tactile sensations using actual materials [25], such as previous wind displays, while others present these tactile factors alternatively with low complexity and cost.

Vibrotactile elements of touch sensations can be distinguished by the presence of different frequencies in the vibration [26]. Thus, researchers have measured the position and acceleration of the object or the skin as a user touched them, and generated a vibration waveform based on the measured data [27], [28], [29]. Regarding thermal stimuli for tactile sensation, the cooling rate and end-temperature are both important cues for material recognition [30], [31]. Ino et al. measured the temperature change of the skin surface when the skin touched the materials, and presented tactile sensation of objects such as aluminum and glass by reproducing the temperature change from the normal skin temperature [32].

Other research simulated rapid change of skin temperature on touch and presented thermal stimuli [33]. Oh et al. developed a multimodal sensing and feedback glove using heat sheets, vibrators, and sensors for experiencing a contact status and discriminating materials [34]. For presenting various materials, a device with a pin-array was also developed to provide vibrotactile and thermal feedback [35].

III. METHOD

This section describes the stimulation method and the device utilized for the study of pseudo-wind perception. First, we discuss the approach for providing stimuli for pseudo-wind perception. Second, we detail the device components used to provide vibrotactile and thermal stimuli. Finally, we measure the haptic stimuli induced by winds.

A. APPROACH FOR PSEUDO-WIND PERCEPTION

As mentioned in Section I, wind is perceived through multiple modalities: visual, auditory, and tactile. Therefore, this research took the approach of presenting wind sensation through cross-modal effects with small-scale devices without fully reproducing the physical stimuli caused by wind.

Tactile stimuli by wind consist of pressure stimuli, shaking of body hairs, vibrotactile stimuli, and thermal stimuli. The pressure stimuli and the shaking of body hairs can be presented using pin arrays and static electricity [36], [37], [38], [39], respectively; however, to present the delicate tactile sensation of wind with them, the size and complexity of the device need to be large. In this research, from the viewpoint of compactness and complexity, vibrotactile and thermal stimuli were used as tactile stimuli with reference to previous studies [40], [41], [42] reviewed in II-B.

Tactile presentations of materials by vibrotactile and thermal stimuli have been studied mainly for solids [28], [32]; however, wind is fluid and softer than skin. Therefore, the skin stimuli of wind are generally subtle. When the amplitude of the applied vibration is extremely high, it is experienced only as vibrations, and is inappropriate for providing vibrotactile stimuli for pseudo-wind perception. This research used subtle vibrotactile and thermal stimuli based on measurements of tactile stimuli to the skin, and presented the pseudo-wind sensation induced by these tactile stimuli in addition to visual and auditory stimuli.

B. DEVICE FOR VIBROTACTILE AND THERMAL STIMULI

As described in III-A, in this study, we utilize thermal and vibrotactile stimuli rather than a physical wind display. Wind is mainly felt on the exposed part; hence, as the first step of the study on pseudo-wind perception, this research is limited to stimuli to the forearm, which has a large area and has been used as the target of vibrotactile, thermal, and wind stimuli in previous studies [42], [43], [44], [45], [46], [47]. To apply thermal and vibrotactile stimuli simultaneously and at the same location, we developed a belt-type device to fix a Peltier element and a vibrator to the arm of the user (Figure 2). In addition, for comfort, the part of the belt device that contacts the skin, excluding the thermal and vibrotactile components, was covered with cotton. The length and weight of the belt were 50 cm and approximately 65 g, respectively.

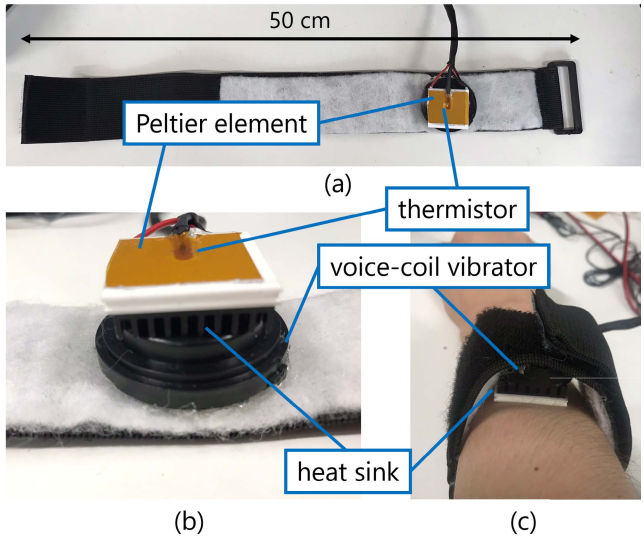


FIGURE 2. Belt-type device. (a) Top view. (b) Side view. (c) Belt-type device attached to right arm.

A Peltier element can generate both warm and cold stimuli. It was used for providing thermal stimuli because of its high thermal response and small size. We integrated a Peltier element (CUI Devices CP603315H), thermistor (SEMITEC 103JT), and small heat sink, which were controlled by proportional–integral–derivative (PID) control of the Peltier controller (PLC-24V10A, Kurag Electronics). By directly heating or cooling the skin using a Peltier element, the corresponding thermal equipment was smaller than that of previous studies in which the methods necessitated constantly changing the room air temperature to the target wind temperature over a short time.

For providing vibrotactile stimuli, a voice-coil vibrator (Vp2, Acouve Laboratory) was used owing to its compactness and ability to present wide ranges of frequencies (16 Hz–15 000 Hz) and subtle stimuli. The vibrations were controlled using an amplifier connected to a PC.

C. MEASUREMENT OF HAPTIC STIMULI BY PHYSICAL WIND

As described in Section II, in previous research, measurements and simulations of actual haptic stimuli were conducted to reproduce tactile sensations. However, the appropriate stimuli for wind tactile sensation were not clear, and skin stimuli induced by wind itself have not been studied in detail. To design tactile stimuli based on wind information, measurements of wind-induced skin stimulation were made in this study. We measured skin displacement for vibrotactile stimuli and skin temperature change for thermal stimuli.

Figure 3 shows the sensing environment for wind stimuli. The sensing environment consisted of two stands on which the arm was placed, a laser displacement sensor (LK-

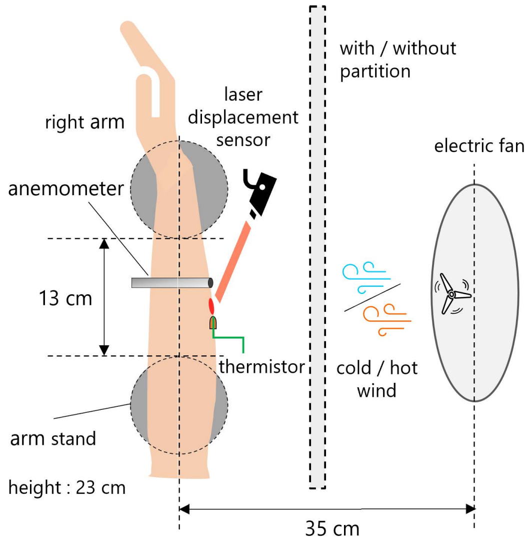


FIGURE 3. Environment for measuring skin displacement and temperature changes induced by cold and hot wind viewed from above.

G5000V, LK-H055, Keyence Corp.), a thermistor (103JT, Semitec), an electric fan (HFX85W14C, De'Longhi) that can produce cold and hot wind, and a partition. The wind temperatures and speeds at a room temperature of 25 °C were measured by anemometers (405-V1, Testo SE) located at the arm position. The results were 25.4 °C and 1.4 m/s for the cold wind and 34.1 °C and 1.1 m/s for the hot wind, respectively. Haptic stimuli were measured by applying cold and hot winds to the right arm for 7 s using a partition.

The skin displacements of eight people were measured using a laser displacement sensor in a non-contact manner. Figure 4 shows the mean value of the frequency analysis of measured skin displacement induced by cold and hot winds. For skin displacements in both cold and hot winds, the low-frequency components are large, and the displacements decrease exponentially with frequency. When used as vibrotactile stimuli, the cutoff frequencies of the high-pass and low-pass filters were set to 20 Hz and 500 Hz, respectively, to suppress body motion components and prevent sounds emanating from the vibrator.

The skin temperature changes of nine people were measured using a thermistor, which is thin and sufficiently small for the area exposed to the wind. Figure 5 shows the mean value of skin temperature changes induced by cold and hot winds. Skin temperature began to change approximately 1 s after the wind started, and slowly returned to the initial temperature when the wind ended. The maximum skin temperature changes during cold and hot winds were approximately −1.5 °C and +1.1 °C, respectively.

IV. STUDY 1: EFFECTS OF VIBROTACTILE AND THERMAL STIMULI ON TACTILE SENSATION OF WIND

The objective of this research was to study pseudo-wind perception induced by the cross-modal effects of vibrotactile, thermal, and audio-visual stimuli. As mentioned in Section II, the haptic stimuli used to present tactile sensations were simple stimuli [44], [48], [49] or stimuli based on simulation or measurements [27], [28], [32]. Thus, either of these haptic stimuli could be expected to induce the tactile sensation of wind, as in these previous research studies. In study 1, considering only haptic stimuli, we explored vibrotactile and thermal stimuli suitable for pseudo-wind perception. The objective of study 1 was to investigate the details of the suitable haptic stimuli, and to determine the haptic stimuli used in study 2, in which visuo-audio-haptic stimuli were provided. We applied the haptic stimuli to the arms of the participants to mimic the natural scenario of arm exposure to winds. In study 2, we explored the effects of all haptic stimuli, in addition to the audio-visual stimuli and the cross-modal effects for pseudo-wind perception.

The University of Tokyo Ethics Committee approved the experiments presented in this section and the next section (No. 20-204), and written informed consent was obtained from each participant.

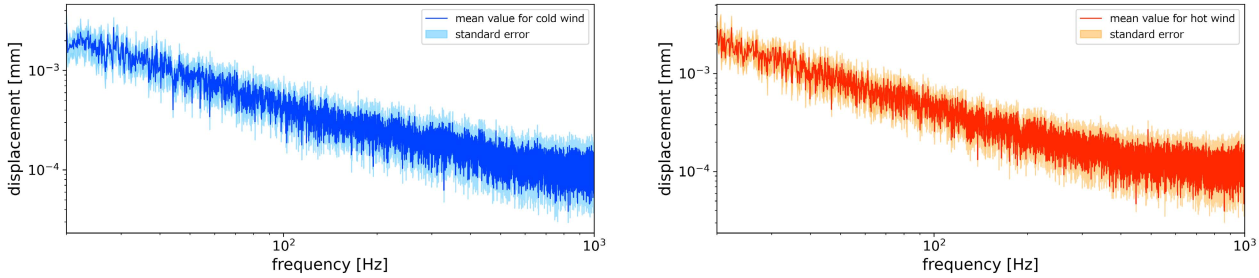
A. EXPERIMENTAL DESIGN

In study 1, 16 people (11 male and 5 female) participated, with an average age of 24.1 years. All were right-handed. The vibrotactile and thermal stimuli were provided to the participants using the belt device.

After the presentation for 7 s, the participants answered the questions from a list of 13 options of materials about which tactile sensation the haptic stimuli felt most like. This is based on the experimental procedure of Ho et al. [25]. Since studies on tactile sensation usually focus on objects colder than the skin, we limit the subject of study 1 to cold wind, by excluding hot wind. The participants were not informed that the research target of study 1 was wind perception.

To investigate the suitable haptic stimuli for pseudo-wind perception, we compared vibrotactile and thermal stimuli under three conditions; *none*, *simple*, and *wind-like* based on the measurement in III-C. The number of experimental conditions for vibrotactile and thermal stimuli was three, for a total of nine (3 × 3) combinations in total. Each condition was performed three times and the subject of study 1 was limited to cold wind, for a total of 27 (9 conditions × 3 repetitions × 1: only cold wind) trial sessions. The order of trials was randomized for each participant.

For vibrotactile stimuli, vibration waveforms suitable for pseudo-wind perception have not been investigated. There is a method of presenting audio signals as vibration, such as the TECHTILE toolkit [50]; however, it was difficult to extract only the sound of wind from recorded wind sound because it included the sound of a fan. In this study, as an initial attempt at pseudo-wind perception, we tested using single-frequency (175 Hz) sine waves and wind-like waves based on frequency analysis of the measured displacement. The simple sine wave of 175 Hz was used in the previous study on wetness sensation for comfort [48]. The vibrotactile stimuli based on wind-like waves were presented through the input,



(a) Cold wind (b) Hot wind

FIGURE 4. Frequency analysis of measured skin displacements induced by wind.

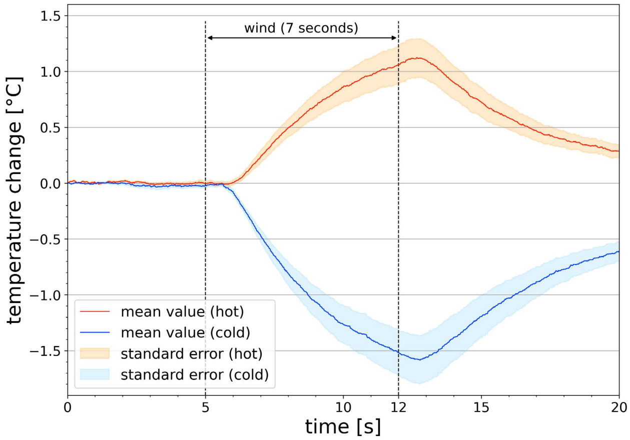


FIGURE 5. Measured temperature change from initial temperature of skin induced by wind.

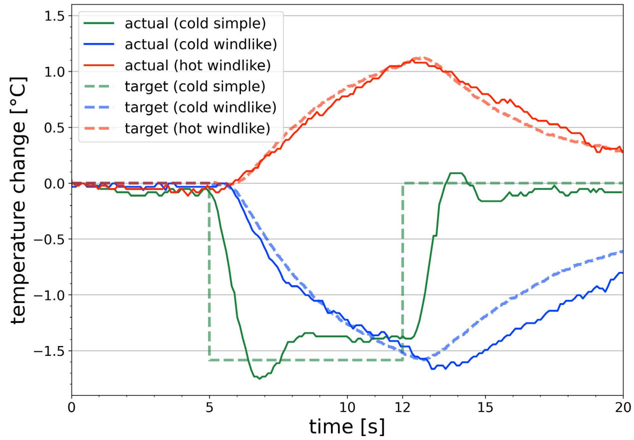


FIGURE 6. Target temperature and actual temperature measured by thermistor attached to Peltier element.

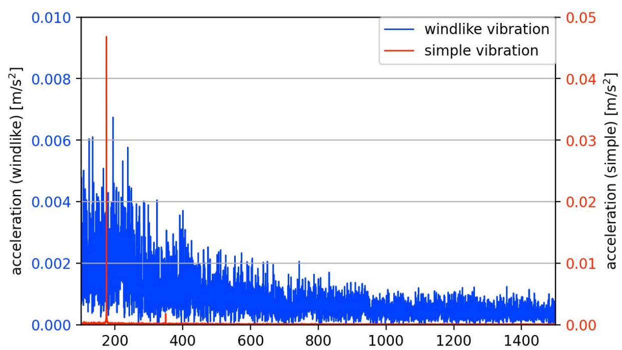


FIGURE 7. Frequency analysis of measured accelerations by vibrator.

where the displacements measured in III-C were converted to audio data.

Vibrotactile stimuli were applied under the following three conditions: no vibrations (*Vibro-none*), simple sine wave of 175 Hz (*Vibro-simple*), and following measured vibrations by a cold wind (*Vibro-windlike*).

Thermal stimuli were applied under the following three conditions: no temperature change (*Thermal-none*), −1.5 °C steady temperature change (*Thermal-simple*), and following measured temperature change by a cold wind (*Thermal-windlike*); −1.5 °C was the maximum temperature change for *Thermal-windlike* condition. The standard temperature was the surface temperature of the arm of each participant measured using a thermistor.

Prior to the experiment, the room temperature was controlled to be approximately 25.0±0.5°C and the room humidity was controlled to be approximately 50 ± 5%. During the experiment, the air conditioner was switched off to prevent unwanted airflow.

B. PRELIMINARY STUDY TO CONFIRM STIMULI CAPABILITY OF DEVICE

Prior to conducting experiments using the developed device, we confirmed that the intended stimuli could be presented by the device and that the experiments could be conducted properly. For the verification, the temperature and acceleration of the device were measured. Acceleration is one of the indicators commonly used to evaluate vibration in previous research [29], [51], [52].

Figure 6 shows the temperature change when the Peltier element is controlled. The dotted and solid lines correspond to the target temperature and the actual temperature measured by the thermistor, indicating the device's adequate capability for thermal presentation.

As mentioned in III-A, a strong vibration is inappropriate for wind sensation; it was also difficult to adjust the vibration outputs of variable wind sounds that were not explicitly felt

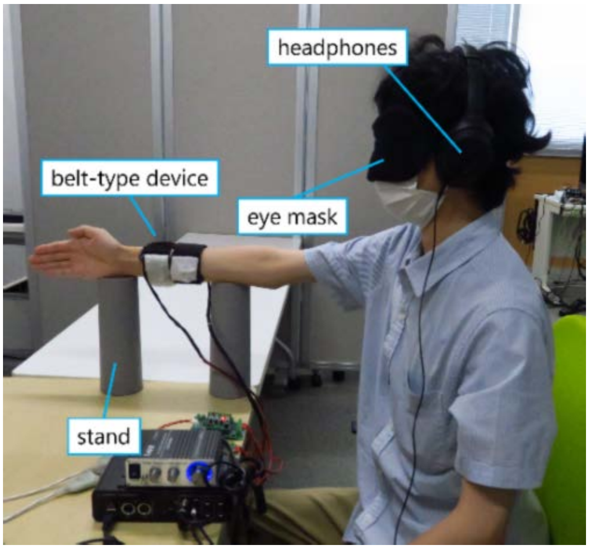


FIGURE 8. Apparatus for study 1. Participant with eye mask, headphones, and belt-type devices placing right arm on stands.

as only vibration. In a preliminary experiment, we asked the participants the amplitude of the vibration that was not explicitly experienced as only vibrations and could be interpreted as wind. As a result, in this study, we set the amplitude to 0.61 m/s^2 for vibro-simple and 0.29 m/s^2 for vibro-windlike. At these amplitudes, the vibration was investigated in detail because the vibration was transmitted through the Peltier element and heat sink and it was not obvious whether the intended vibration of the input source could be presented. The abovementioned vibrations were measured using an acceleration sensor (AS-3ACC3, Asakusa Giken) at the part where the skin touched the belt; the frequency analysis results are shown in Figure 7.

The (approximately) 175 Hz component was at the maximum for the input of the vibro-simple 175 Hz vibration, and the acceleration decreased with frequency for the wind-like vibration, similar to the case in Figure 4.

C. EXPERIMENTAL PROCEDURE

After receiving an explanation of the experimental procedure, the participants sat on a chair and wore an eye mask and wireless noise-canceling headphones (WH-1000XM3, Sony). They placed their right arms on stands on a desk, with their palms oriented to the left (Figure 8). The positioning of the stands and arm was the same as that during the skin measurements in Section III.

For each trial, the procedure outlined below was adopted. The participants remained still, and two belt devices were attached to the right arm 3 cm and 10 cm away from the wrist. Their tightening conditions were unified for each participant. To stabilize the temperatures of the Peltier elements, a tuning time of 10 s was provided. Following this, temperatures and vibrations based on the experimental conditions were presented for 7 s. The participants were made aware of the start and end of the presentation by beep sounds. They were instructed to stretch and hold their arms straight during the presentation.

After the presentation, the participants answered a question on the haptic sensations. The question was "Which tactile sensation did the presentation feel most like?" and answer options are "wind," "water," "stainless steel," "glass," "rubber," "stone," "ABS," "sponge," "foam," "wood," "hair," "none," and "others." The answer options for materials were based on the options of previous studies with vibrotactile and thermal stimuli [25], [27], [32], [53], in addition to "wind," "water," "hair," "sponge," "none," and "others" (free answer). The order of the answer choices was randomized for each participant, respectively.

D. RESULTS

The results for all thirteen options are presented in Supplementary Materials. Figure 9a shows the rate of respondents who answered "wind" under each condition, respectively. The error bars are the standard errors. The results were statistically analyzed to confirm whether the thermal and vibrotactile conditions affect the pseudo-wind perception. In the following, the results of the statistical analysis are discussed. In this study, the critical p-value was set as 0.05 ($* : p < 0.05, ** : p < 0.01$).

We confirmed that the answer rate did not break the sphericity assumption by conducting Mauchly's sphericity test ($\chi^2(35) = 34.2130, p = 0.5463$). The two-way repeated analysis of variance (ANOVA) showed that the thermal factor ($F(2, 30) = 10.2826, p = 0.0004$) had significant effects; however, vibrotactile factor ($F(2, 30) = 2.4322, p = 0.1050$) conditions and their interactions ($F(4, 60) = 0.4884, p = 0.7442$) were not significant. Figure 9b shows the average of the response rate summarized by vibration condition. We conducted a post-hoc Tukey test for each thermal condition. Figure 9c shows the results. Under the thermal conditions, the answer rates under thermal-simple ($q(3, 45) = 3.4274, p = 0.022$) and thermal-windlike ($q(3, 45) = 4.5364, p = 0.007$) conditions were significantly higher than that under thermal-none conditions.

E. DISCUSSION

Based on Figure 9, the wind response rates under the thermal-simple and thermal-windlike conditions were significantly higher than those under the thermal-none condition. This means that cold thermal stimuli are effective for reproducing the tactile sensation of cold wind.

The highest mean value for the "wind" answer rates among all conditions was 0.292 under (vibro-windlike, thermal-windlike) condition. This means that nearly 30% of the respondents without prior knowledge and audio-visual cues felt that the stimuli for the proposed method were wind, indicating that wind-like tactile stimuli can induce the virtual tactile sensation of wind. This also suggests that even under the highest mean value condition in the proposed method, an accurate reproduction of the tactile sensation of wind was

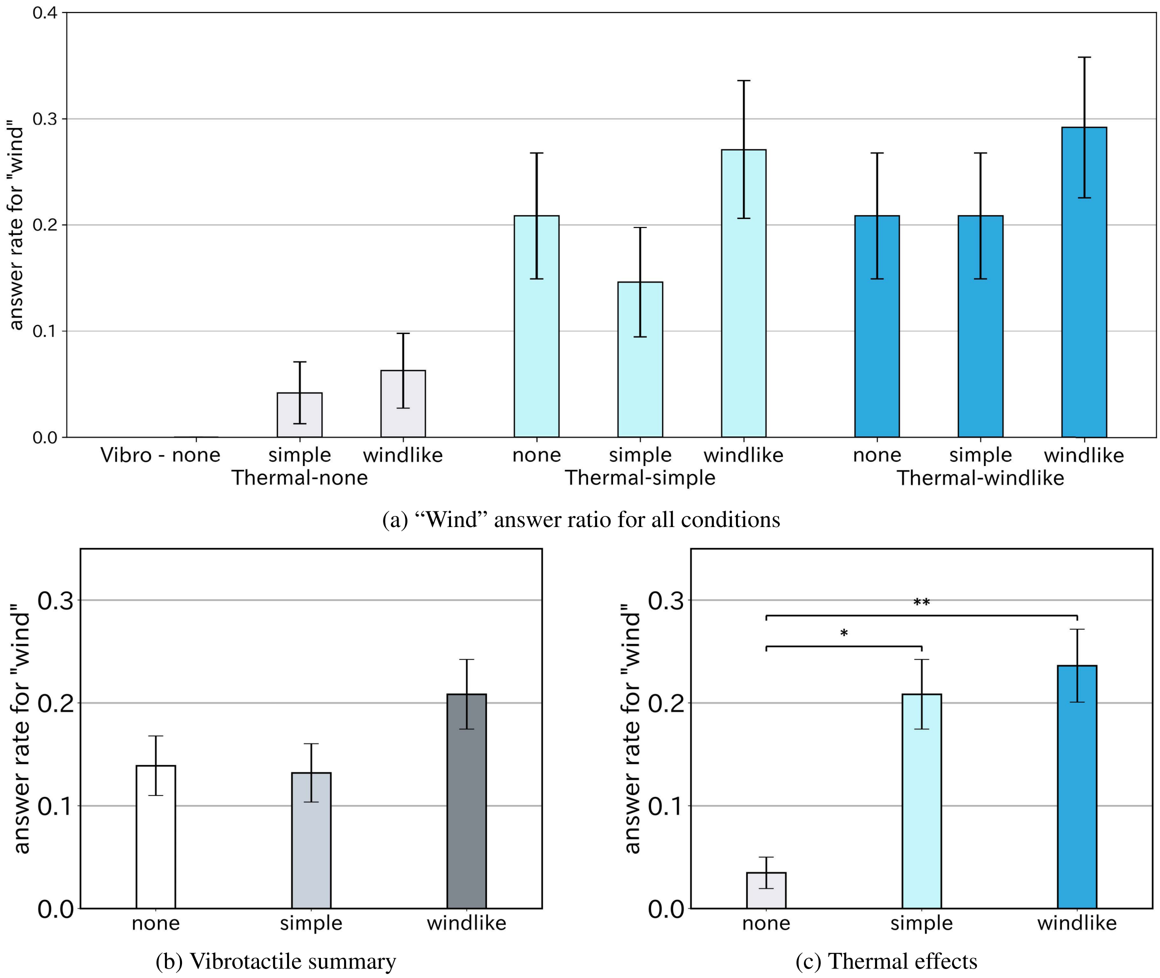


FIGURE 9. Rate of respondents who answered "wind" under each condition.

not achieved. This may be because of the inability to fully reproduce haptic stimuli, such as shaking of body hair or the spatial extent to which the wind hits the skin.

One of the aims of study 1 was to explore vibrotactile and thermal presentations suitable for pseudo-wind perception, which were subsequently used in study 2. As Figure 9b and Figure 9c show, vibrotactile and thermal stimuli were the most effective under the wind-like condition, respectively. For these reasons, in study 2, vibro-windlike was used for vibrotactile stimuli and thermal-windlike for thermal stimuli.

V. STUDY 2: CROSS-MODAL EFFECTS OF AUDIO-VISUAL, VIBROTACTILE, AND THERMAL STIMULI ON PSEUDO-WIND PERCEPTION

In study 1, we found that wind-like vibrotactile and thermal stimuli can induce the tactile sensation of winds. Some previous studies have conveyed rich information in VR experiences by presenting audio-visual stimuli in addition to tactile stimuli. These studies have applied cross-modal effects of audio-visual and tactile stimuli to induce a variety of sensations, such as wetness sensations, that require large-scale hardware and are difficult to present [48], [49]. Similarly, in this research, the combination of tactile and audio-visual stimuli was also expected to enhance wind sensation and wind experience through cross-modal effects. The objective of study 2 was to evaluate the pseudo-wind perception and wind experience achieved by cross-modal effects using vibrotactile and thermal stimuli in addition to audio-visual stimuli with an HMD (Meta Quest 2) and headphones (WH-1000XM3, Sony).

A. EXPERIMENTAL DESIGN

Sixteen people (11 male and 5 female) participated, with an average age of 24.1 years; all were right-handed. The vibrotactile and thermal stimuli or the physical wind were presented to the participants in the VR space where the cold or hot wind hit their right arm. After the presentation, they answered a questionnaire about wind sensation and the sense of presence.

The participants underwent a cold wind task (*Cold task*) and a hot wind task (*Hot task*) in sequence in a randomized order. There were five conditions for each task: *None*, *Vibro*, *Thermal*, *Vibro-Thermal*, and *Physical wind*. Under the *None* condition, no haptic stimuli were presented, and only VR images and audio were presented. Under *Vibro*, *Thermal*, and *Vibro-Thermal* conditions, all presentations by the belt device

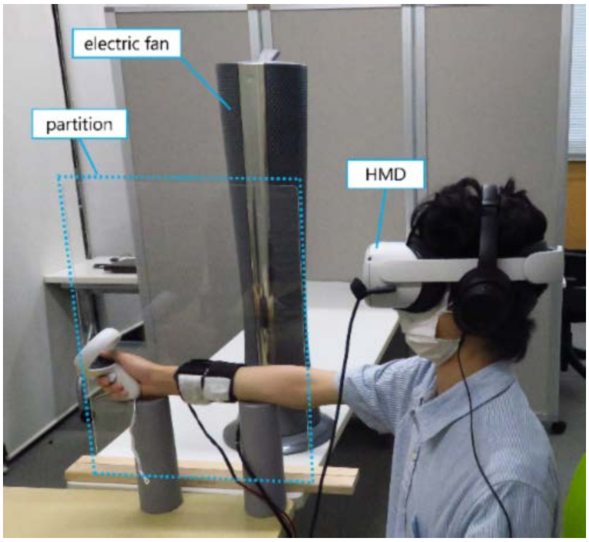


FIGURE 10. Apparatus for study 2. Participant with HMD, headphones, and belt-type devices placing right arm on stands near fan and partition.

were *windlike* stimuli with the highest mean values obtained from study 1. Under *Physical wind* condition, the physical wind was presented. For providing wind stimuli, as a physical wind source for comparison in experiments, we utilized an electric fan (HFX85W14C, De'Longhi) that can produce hot and cold winds, as shown in Figure 10. The timing of wind stimuli and VR scene was synchronized by switching the use of partitions. There were separate desks for the fan and the right arm to prevent fan vibration from transmitting to the arms via the desk and stands. The presentation order of the five conditions was randomized.

The participants experienced a VR space where they received wind on their right arms from a wind source. Figure 11 shows the VR space. As visual stimuli of wind, the particles were presented, as in the previous study [11]. The wind particles were in cold colors (#3fe8ff) in the Cold task, and hot colors (#ff5d3f) in the Hot task. As audio stimuli, the sounds of cold and hot winds were measured by a shotgun condenser microphone (ATM57a, Audio-Technica). The sound source of the wind was placed at the wind source in the VR space, and the sound was presented to be heard from the direction of the wind source. The participants received stimuli according to the conditions along with the wind in the VR space. In each task, we presented the same VR space and sounds under all conditions.

Prior to the experiment, the room temperature was controlled to be approximately 25.0±0.5°C and the room humidity was controlled to be approximately 50 ± 5%. The air conditioner was switched off during the experiment to prevent unwanted airflow.

B. EXPERIMENTAL PROCEDURE

The study was explained to the participants, who signed informed consent forms. They sat on a chair and wore an HMD (Meta Quest 2) and wireless noise-canceling headphones (WH-1000XM3, Sony). They placed their right arms on stands on a desk with palms oriented to the left (Figure 10).

For each trial, the procedure described below was conducted. Under the None, Vibro, Thermal, and Vibro-Thermal conditions, two belt devices were attached to the right arms at the same positions, as mentioned in Section IV. Under the physical wind condition, the belt devices were not attached because the purpose of study 2 was to compare the stimuli of the belt device with the conventional method of the wind display in the previous studies. After the participants were blindfolded, the VR space was shown. The VR space consisted of a room, a human hand, a wind source, and two stands. The participants were instructed to look at their right arms. The arms in the VR space were reflected in the movement of the participants, and the avatar's hands were stretched out and placed on the stands, as in the actual postures. To stabilize the temperatures of the Peltier elements, we ensured a tuning time of 10 s. Subsequently, stimuli according to the experimental condition and the wind in the VR space were presented for 7 s. They were instructed to hold their arms straight during the presentation.

The participants removed the devices and answered questionnaires after each presentation. The questionnaires were about wind sensation and the sense of presence in the VR space. The question about wind sensation was "To what extent did the wind experience in the virtual reality space feel like the wind experience in reality?" and could be answered from 1 to 10 (1: not real at all, 10: completely real). Igroup Presence Questionnaire (IPQ) [54] was used to evaluate the sense of presence, spatial presence, involvement, and realness. The minimum and maximum values of IPQ were set as 1 and 5 to match the previous studies. The participants knew that the stimuli presented under the Vibro, Thermal, and Vibro-Thermal conditions were not caused by the actual wind because they wore the belt devices on their arms.

At the end of the experiment, the participants provided open-ended answers about the entire study.

C. RESULTS

Figure 12a shows the average scores of the Cold task and Figure 12b shows the ones of the Hot task. The error bars show the standard errors. The scores of wind sensation are the values for the first question about the reality of the wind experience in VR. The scores of the general presence are the mean of the values in all scores in the IPQ, and each of the spatial presence, involvement, and realness is the mean of the scores labeled as each category in the IPQ.

We performed statistical tests to evaluate the pseudo-wind perception by the thermal and vibrotactile stimuli in addition to audio-visual stimuli. We adopted the Bonferroni procedure for each test to avoid type I errors because there were five independent variables (wind sensation, presence, spatial presence, involvement, and realness). We performed the Friedman test and found there was a significant difference for the wind

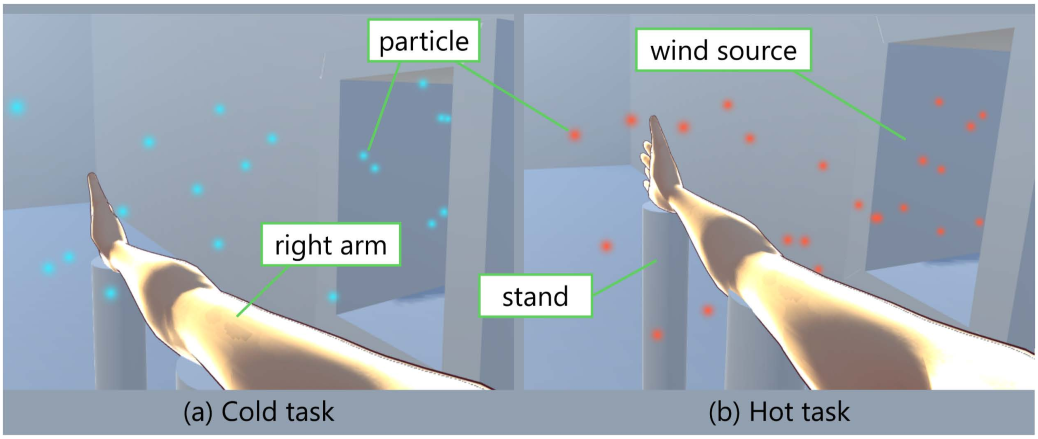


FIGURE 11. Virtual reality space for study 2 in which wind is blowing the arm avatar on the stands.

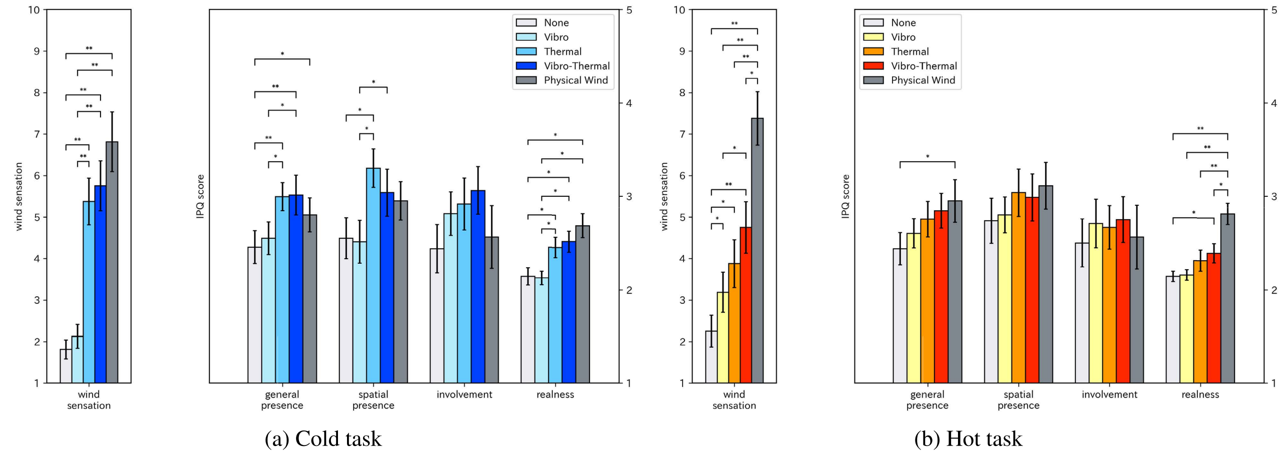


FIGURE 12. Means values of wind sensation, general presence, spatial presence, involvement, and realness from left to right. Error bars indicate standard error. Asterisks indicate results of post-hoc Wilcoxon signed-rank tests.

sensation of the Cold task ($\chi^2 = 48.98, p = 0.000$), general presence of the Cold task ($\chi^2 = 25.87, p = 0.000$), spatial presence of the Cold task ($\chi^2 = 22.06, p = 0.010$), realness of the Cold task ($\chi^2 = 32.44, p = 0.000$), wind sensation of the Hot task ($\chi^2 = 34.06, p = 0.000$), and realness of the Hot task ($\chi^2 = 27.09, p = 0.000$).

We conducted post-hoc Wilcoxon signed-rank tests with the Benjamini–Hochberg procedure for the five dependent variables. In addition, to discuss the inducement of pseudo-wind perception, Two One-Sided Tests (TOST) using the non-parametric methods of the Wilcoxon signed-rank test were conducted to verify the equivalence of the wind sensation with conventional methods (Physical Wind condition). For the wind sensations, we adopted the additional Bonferroni procedure for these two post-hoc tests to avoid type I errors. The results of the statistical tests are described below.

a: WIND SENSATION OF COLD TASK

The wind sensations under the Thermal, Vibro-Thermal, and Physical Wind conditions were significantly higher than those under the None and Vibro conditions. In addition, the wind sensations under Thermal ($V = 3.00, p = 0.031$) and Vibro-Thermal conditions ($V = 6.00, p = 0.024$) were significantly equivalent to that in the Physical Wind condition, setting equivalence bounds to the standard deviation under the Physical Wind condition.

b: GENERAL PRESENCE OF COLD TASK

The general presences under the Thermal, and Vibro-Thermal conditions were significantly higher than those under the None and Vibro conditions. The general presence under the Physical Wind condition was significantly higher than that under the None condition.

c: SPATIAL PRESENCE OF COLD TASK

The spatial presence under the Thermal condition was significantly higher than those under the None and Vibro conditions. The spatial presence under the Vibro-Thermal condition was significantly higher than that under the Vibro condition.

d: REALNESS OF COLD TASK

The realness under the Thermal, Vibro-Thermal, and Physical Wind conditions was significantly higher than that under the None and Vibro conditions.

e: WIND SENSATION OF HOT TASK
The wind sensation under the Physical Wind condition was significantly higher than those under the None, Vibro, Thermal, and Vibro-Thermal conditions. The wind sensation values under the Vibro, Thermal, Vibro-Thermal conditions were significantly higher than that under the None condition. The wind sensation under the Vibro-Thermal condition was significantly higher than that under the Vibro condition.

f: GENERAL PRESENCE OF HOT TASK
The general presence under the Physical Wind condition was significantly higher than that under the None condition.

g: REALNESS OF HOT TASK
The realness under the Physical Wind condition was significantly higher than that under the None, Vibro, Thermal and Vibro-Thermal conditions. The realness under the Vibro-Thermal condition was significantly higher than that under the None condition.

D. DISCUSSION
a: WIND SENSATION
First, we discuss the results of the wind sensations. For both cold and hot tasks, the mean value of wind sensation was higher in the order of the None, Vibro, Thermal, Vibro-Thermal, and Physical Wind conditions. The lowest mean values of wind sensations were 1.81 for the Cold task under the None condition and 2.25 for the Hot task under the None condition. This suggests that the audio-visual stimuli alone were insufficient to experience the wind. The reason may be that it is rare to see the wind directly and the input of wind to visual modality is small. The mean values of wind sensation under the Physical Wind conditions were 6.81 in the Cold task and 7.38 in the Hot task and were significantly higher than those under None condition, consistent with results in previous studies on wind display. However, the values were not 10, which is the maximum value, and the physical wind did not present a fully realistic wind experience. The reason may be that the wind from the fan was not perfectly matched with the VR space. For example, it is difficult to perfectly reproduce the area where the wind hits from the wind source in the VR space. In the open-ended answers, one respondent commented, "I thought the wind would feel more real if the video was more realistic."

In the cold task, the mean values of wind sensation under the Thermal, Vibro-Thermal, and Physical Wind conditions were significantly higher than those under all other conditions, and there were no significant differences between them. This means that thermal presentation is effective for cold wind sensation in the VR space. This is consistent with the results of study 1. There were no significant differences in wind sensation between None and Vibro conditions and between Thermal and Vibro-Thermal conditions, suggesting that vibrotactile presentation does not have an effect on cold wind sensation. Almost no effects of the vibrotactile stimuli alone may be the result of suppression of the haptic sensation by the addition of audio-visual stimuli in the VR space. It has been confirmed that the addition of an input to a modality can suppress an input to another modality [55], [56], [57]. There were significant equivalences between the Thermal and Physical Wind conditions and between the Vibro-Thermal and Physical Wind conditions, suggesting that visuo-audio-haptic stimuli with cross-modal effects can induce pseudo-wind perception of cold wind. In the open-ended answers, a respondent said, "I was surprised that the stimuli by the belt felt more like a breeze than the breeze from the fan."

In contrast, in the Hot task, the mean value under the Physical Wind condition is significantly higher than that under all other conditions, indicating that even under the Vibro-Thermal condition, wind sensation was not sufficiently presented in the Hot task. The value under the None condition was significantly lower than that under all other conditions. This indicates that in the case of the Hot task, not only thermal but also vibrotactile stimuli are effective for hot wind sensation. At the same time, there was a significant difference between Vibro-Thermal and Vibro conditions and no significant difference between Vibro-Thermal and Thermal conditions, suggesting that the effect of vibrotactile stimuli on hot wind sensation is smaller than that of thermal stimuli.

b: DIFFERENCE BETWEEN COLD AND HOT WIND SENSATIONS
Regarding specific values of wind sensation, the results in the Cold task were 6.81 under the Physical Wind condition, and 5.75 under the Vibro-Thermal condition. The corresponding results in the Hot task were 7.38 and 4.75, and the difference between them was larger than that in the Cold task. These differences between the results of Cold and Hot tasks are because of the differences in the weight of the thermal perception in wind perception. Wind perception is based on multiple stimuli; audio-visual cues, thermal stimuli, vibrotactile stimuli, pressure, and shaking hair. The hot wind is closer to skin temperature than the cold wind, and the contribution of thermal stimuli to the wind perception can be smaller. Therefore, in the Hot task, the contribution of vibrotactile stimuli was relatively high, and the vibrotactile stimuli had a significant effect on pseudo-wind perception. According to a previous study, the closeness of the temperature to skin temperature implies high sensitivity of the vibrotactile sensation [58]. Thus, in presenting the hot wind, the tactile stimuli design should be changed from that of cold wind.

c: PRESENCE SCORE
In terms of the IPQ scores, from the results of the post-hoc Wilcoxon signed-rank test, in the Cold task, the values of the general presence under the Thermal, Vibro-Thermal, and Physical Wind conditions were significantly higher than that under the None condition, and there are no significant differences. This indicates that the presence of the cold wind experience in virtual reality can be enhanced by thermal stimuli.

The general presence under the physical wind condition in the Cold task was not at its maximum, different from the wind sensation. This may be because of the decrease in the involvement of the electric fan, which is discussed later.

As for the spatial presence in the Cold task, there were also significant differences between the Thermal and None conditions. The spatial presence involves patterns of actions in perceiving environment [59]; however, the participants were instructed to maintain their postures and not move. Therefore, in this experiment, the high spatial presence means that the VR space was perceived as a space surrounding the participants, and not only pictures without other modalities. Thus, this result suggests that the feeling present in space could be presented by the sensation of cold wind with thermal stimuli.

As for the involvement, the values of the involvement under the Vibro, Thermal, and Vibro-Thermal conditions were higher than those under the None and Physical Wind conditions. As a low involvement indicates conflicting sensory inputs [54], this result suggests that the stimuli of the belt-type device under Vibro, Thermal, and Vibro-Thermal conditions were not highly conflicting. Under the Physical Wind condition, since they perceived the wind as coming from an actual wind source, they paid attention to the actual wind source and were likely to notice the difference between the virtual wind and the physical wind, which may have led to a conflict. Concurrently, one respondent to the open-ended question stated that, "Some of the stimuli from the device made me feel the wind. However, I felt that some of them were not convincing because I had the perception that it was caused by a device."

The realness under the Thermal, Vibro-Thermal and Physical Wind conditions was significantly higher than those under the None and Vibro conditions in Cold task. This indicates that thermal stimuli can improve the reality of cold wind experience. The realness under only the Vibro-Thermal and Physical Wind conditions was significantly higher than that under the None condition in Hot task, suggesting that cross-modal effects induced by audio-visual and vibro-thermal presentations can enhance the reality of VR experiences in hot wind. The difference of realness between cold and hot winds can be due to the closeness between the skin and wind temperatures as well as those of wind sensation.

d: SUMMARY

The results of study 2 suggest that cross-modal reproduction of thermal, visual, and auditory stimuli can enhance wind sensation and realness for cold winds, and that cross-modal reproduction of vibrotactile, thermal, visual, and auditory stimuli can enhance wind sensation and realness for hot winds. Further, we found that there were differences in vibrotactile and thermal contribution between cold and hot wind sensations; the contribution of thermal modalities to pseudo-wind perception was larger for cold wind. This can be due to the difference in tactile sensitivity caused by the difference between wind and skin temperatures. Therefore, it is important to change the design of tactile stimuli for pseudo-wind perception based on the wind temperature.

VI. LIMITATIONS AND FUTURE STUDIES

This first study on pseudo-wind perception is limited in terms of the display area. A future study can include expansion of the area where the stimuli are provided to other body parts, such as the face, legs, and neck. The effects when the stimuli are provided on the area should be studied. Another limitation of the proposed method is the extent to which various wind properties, such as wind power, wind direction, and wind temperature, can be presented.

VII. CONCLUSION

This paper proposed achieving hot and cold wind sensations by cross-modal effects without the use of physical wind. We developed a belt-type device to present vibrothermal stimuli and investigated tactile stimuli suitable for pseudo-wind perception in study 1. From the results, we found that vibrotactile and thermal stimuli based on the actual measurements on the skin receiving wind can effectively induce the tactile sensation of wind. Next, we conducted study 2 to evaluate pseudo-wind perception and wind experience with visuo-audio-haptic stimuli. The results show that the wind sensation and realness with the thermal stimuli in addition to audio-visual stimuli are significantly higher than those without haptic stimuli in cold wind, and that the wind sensation and realness of hot wind with the vibro-thermal stimuli in addition to audio-visual stimuli are significantly higher than those without haptic stimuli. In the case of cold wind, the wind sensation with the visuo-audio-haptic stimuli was significantly equivalent to that with the physical wind. These results indicate that providing thermal stimuli in addition to audio-visual stimuli can induce pseudo-wind perception of cold wind and that visuo-audio-haptic reproduction can enhance the reality of the VR experience with winds The results also suggest that the design of tactile stimuli needs to be different for cold and hot winds because of the differences in the contribution of the vibrotactile stimuli. We believe that our new methods of presenting wind sensation without wind further expand the range of VR applications in flight, driving, and sightseeing.

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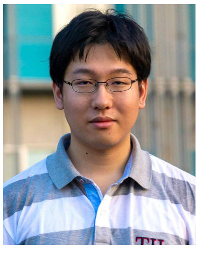
JURO HOSOI received the bachelor's degree in engineering from The University of Tokyo, Tokyo, Japan, in 2021, where he is currently pursuing the master's degree with the Department of Frontier Sciences. His current research interest includes reproducing various tactile sensations.

YUKI BAN (Member, IEEE) received the M.S. and Ph.D. degrees in information science and technology from The University of Tokyo, Tokyo, Japan, in 2013 and 2016, respectively. He was a Researcher at Xcoo Inc., from 2016 to 2017. He is currently an Project Lecturer with the Department of Frontier Sciences, The University of Tokyo. His current research interest includes modifying spatial perception using visuo-haptic interaction.



KENICHI ITO received the Master of Environmental Studies degree from the Graduate School of Frontier Sciences, The University of Tokyo, Tokyo, Japan, in 2021, where he is currently pursuing the doctoral degree with the Graduate School of Frontier Sciences. His research interests include improving presence and immersion of virtual reality by presenting the feelings of wind. He received the JSPS Research Fellowship for Young Scientists (DC1) from the Japan Society for the Promotion of Science, from 2021 to 2024.

SHIN'ICHI WARISAWA (Member, IEEE) is currently a Professor with the Department of Frontier Sciences, The University of Tokyo. From 1994 to 2000, he was an Assistant Professor at the Tokyo Institute of Technology. Since 2000, he has been with The University of Tokyo. He was a Visiting Researcher at the Massachusetts Institute of Technology, from 2010 to 2011, and a Visiting Professor with Université Jean Monnet, in 2016. His current research interests include wearable/ambient human health monitoring, nano/micro sensing devices fabrication, and sensing information technology application for human well-being.