Determination of the Thermal-tactile Simultaneity Window for Multisensory Cutaneous Displays*

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***Abstract*—Multisensory cutaneous displays have been developed to enhance the realism of objects touched in virtual environments. However, when stimuli are presented concurrently, tactile stimuli can mask thermal perception and so both these modalities may not be available to convey information to the user. In this study, we aim to determine the simultaneity window using the Simultaneity Judgment Task. A device was created that could present both tactile and thermal stimuli to the thenar eminence of the participant's left hand with various stimulus onset asynchronies (SOA). The experimental results indicated that the simultaneity window width was 639 ms ranging from -561 ms to 78 ms. The point of subjective simultaneity (PSS) was at -242 ms, indicating that participants perceived simultaneity best when the thermal stimulus preceded the tactile stimulus by 242 ms. These findings have implications for the design of stimulus presentation in multisensory cutaneous displays.**

***Index Terms*—multisensory cutaneous displays, multimodal haptic interfaces, simultaneity window, simultaneity judgments**

I. Introduction

A. Background

Realistic object reproduction is important in enhancing immersion and realism in virtual environments. Generally, when creating virtual objects, information from a number of sensory modalities is integrated to improve the bandwidth of information transmission and to provide a more realistic representation of the object. Recently, with the development of multisensory displays that present visual and auditory cues to the user, there has been increased interest in incorporating tactile and thermal sensory information in these displays [1], [2], [3], [4]. One of the challenges associated with presenting tactile and thermal cues concurrently is the considerable difference between the two senses in the time taken to process information. Reaction times for tactile stimuli are much faster than those for thermal stimuli [5], [6] which means that simultaneous tactile and thermal cues will not necessarily be perceived as concurrent. There has been relatively little research on intersensory synchrony in the somatosensory system which is important for the design of effective multisensory displays.

*Research supported by the JSPS KAKENHI Grant Number 22H03679 (HNH), ULVAC-Hayashi MISTI Seed Fund, MIT-Japan Program (HNH, LAJ and MT), and the National Science Foundation under grant IIS-2006152 (LAJ)

The thermal and tactile sensory modalities are completely independent in terms of their underlying neurophysiological structure. From a perceptual viewpoint, there are also considerable differences in their temporal and spatial resolution. The response time for tactile sensation is estimated to be approximately 140-270 ms [5]. On the fingertip, the simple reaction time for tactile stimuli has been reported to be 182 ms (SD: 16 ms) [7], whereas for thermal stimuli reaction times are much slower and differ for warmth and cold [6]. When the hand is warmed the reaction time has been estimated to be approximately 938 ms (SD: 266 ms) and when the skin is cooled it is 529 ms (SD: 87 ms) [8]. These varying reaction times are due in part to differences in neural transmission velocities, with the conduction velocity of cold afferent fibers (5-15 m/s) being considerably faster than that of warm afferent fibers (1-2 m/s) [9]. These afferent fibers are in turn much slower than those of mechanoreceptor afferents, whose conduction velocities are about 80 m/s [10]. For spatial processing, it is known that the thermal sensitivity of skin differs from that of touch. In particular, on the hand tactile sensitivity increases in a proximal to distal direction, whereas thermal sensitivity increases in a distal to proximal direction, which means that the skin on the wrist is more sensitive to changes in temperature than the skin on the fingertips [11]. Based on these differences in thermal and tactile perception, it is important to understand the interaction between thermal and tactile stimuli when they are presented simultaneously.

Although the tactile and thermal sensory systems are independent, interactions occur between the two that influence how stimuli are perceived. Singhal and Jones [12] showed that concurrent vibration affected the ability to recognize cool stimuli more than warm stimuli, and that such vibrations could mask the perception of changes in skin temperature. These interactions need to be considered when designing multisensory cutaneous displays, in that under some conditions stimuli may not be perceived at all.

B. *Research Question*

In the present research, we focus on the perception of simultaneity of thermal and tactile stimuli, that is, the window within which stimuli are perceived to occur at the same time. By defining a window of stimulus simultaneity, it should be possible to provide guidance to designers of multisensory cutaneous displays in terms of specifying presentation intervals that create a more realistic impression of an object and avoid the effects of phenomena such as masking.

II. Device Development

A multisensory cutaneous display was built to present thermal and tactile stimuli to the thenar eminence of the participant's hand. Data Acquisition modules (DAQ) (AIO-160802AY-USB, Contec Inc) were used for stimulus generation and to control the display. The DAQ driver (API-AIO (WDM), V7.70, Contec Inc) was used to command the operation in Python3 in the Anaconda environment. The outputs to the display were an analog temperature output and a digital tactile output that were presented at different time intervals. Two temperature outputs were created, one a cooling stimulus of -7 °C for the experiment, and the other a constant stimulus to maintain skin temperature at a baseline level. Safety measures were added to prevent temperature fluctuations below 15 °C and above 45 °C, which are painful and can cause tissue damage [13].

A. *Apparatus*

1) Peltier module: A Peltier module with a hole in the center was selected to present the thermal stimuli so that the tactile and thermal stimuli could be co-located. It was 30 mm square with a 14.5 mm diameter hole. An air-cooled heat sink was used to facilitate heat dispassion from the back side of the Peltier module. A 14.1 mm × 16.0 mm hole was drilled in the center of the heat sink to accommodate the solenoid used to present tactile stimuli (see Fig. 1). A clay-like adhesive and double-sided tape (Choko Co., Ltd) secured the solenoid to the heat sink. Felt was placed on the surface of the display to fill the gap between the heat sink and the Peltier module and prevent excessive heat stimulation on other parts of the hand.

2) Thermisors: Three thermistors (56A1002-C8, Alpha Technics) with a diameter of 457 μm and a length of 3.18 mm were used to measure temperature. The thermistors are small in size and volume, with a fast response. Thermistor T1 measured the temperature of the Peltier module and was covered by a buffer material to isolate it from the hand. Thermistors T2 and T3 measured the participant's skin temperature and the skin-device interface temperature, respectively. T2 was placed proximal to the Peltier module and provided a reference baseline skin temperature that was not affected by changes in the temperature of the thermal display. T3 was placed directly on top of the device and recorded the skin-interface temperature (see Fig. 1).

3) Solenoid: For tactile stimulation, a solenoid that could provide pulsed stimulation was used (CB0730, Takaha Kiko Co., Ltd). The dimensions of the solenoid were: tip diameter 3.5 mm, tip length 9 mm, and 3 mm range of motion. The solenoid delivered a force of approximately 1.4 N which was clearly perceptible.

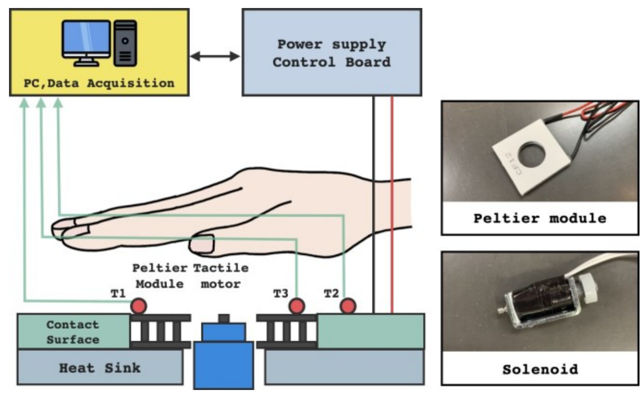

Fig. 1. Schematic illustration of the experimental set-up with the Peltier module and solenoid shown. The hand is positioned above the display and the locations of the three thermistors T1, T2 and T3 are indicated.

B. *Stimuli*

1) Thermal stimuli: A cooling stimulus of -7 °C from the participant's baseline skin temperature was presented using the Peltier module. It was controlled using PI feedback control. The rate of temperature change was approximately 2.5 °C/s. Cooling stimuli were selected because people are generally more sensitive to decreases than increases in skin temperature [14]. Furthermore, the masking effect from concurrent vibration has been shown to impact the ability to recognize cool stimuli more than warm stimuli [12]. As a result, it is important to understand the simultaneous perception of cool and tactile stimuli for effective display design.

2) Tactile stimuli: The solenoid was used to present a single pulse that indented the skin. The pulse duration was 10 ms, with a force of approximately 1.4 N.

C. *Improved accuracy with consideration of delays*

The ability to detect a change in skin temperature is affected by the rate at which skin temperature decreases. For example, cold thresholds remain constant at rates of 0.1 °C/s and above, but increase rapidly at slower rates of temperature change [15]. Yarnitsky and Ochoa [16] reported that the rate at which temperature changes does not affect reaction times over the range of 1.5 to 6.7 °C/s. These findings have implications for our study, where we are presenting pairs of stimuli with varying SOA, and precise control of the temporal parameters of presentation is required. Several delays are unavoidable due to hardware and software limitations. For example, there are delays between the program command and the DAQ output (D1), the DAQ output and the Peltier device's or solenoid's response (D2), and the device's response and the change in skin temperature or contact force (D3). As the purpose of this study is to determine the simultaneity window, these delays must be considered in deriving accurate simultaneity window estimations.

1) Delay estimation: Table. I shows the estimation of each delay.

TABLE I
ESTIMATION OF THREE TYPES OF DELAYS

Stimuli	***D1***	***D2***	***D3***
Tactile	1 ms	10 ms	0 ms
Thermal	7 ms	120 ms	0 ms

D1, the command execution time, was measured using the standard Python library. For the tactile stimulus, D2, was measured with a high-speed camera with 1000 ms resolution and set at 10 ms, which included 7 ms for LED-solenoid activation and 3 ms for solenoid movement to the halfway point. For thermal stimulation, D2, was the time difference between the DAQ output and the onset of the temperature change, which was estimated by applying a discrete derivative on the temperature curve and a moving average with a window size of seven to eliminate noise. The onset of the temperature change was defined as the point where the derivative exceeded a specified value in the steady-state temperature. The delay was estimated to be 120 ms based on four pre-acquired data sets. D3 was estimated to be 0 ms for both tactile and thermal stimuli. In measuring the deformation of a rubber sheet using a solenoid, the deformation started from the start time of solenoid operation (0 ms) [17]. Accordingly, we assumed the delay of skin deformation to be negligibly small. The thermal stimulation presented by the Peltier module was assumed to change skin temperature instantaneously, so D3 was set to 0 ms in this analysis.

2) Defining SOA for skin responses: In this study, we define the SOA with respect to sensing by the skin. A positive (negative) SOA indicates the tactile (thermal) stimulus is presented prior to the thermal (tactile) stimulus. The relationship between the SOA specified in the SOA program and the SOA on the skin is as shown in Fig. 2 and Fig. 3. To present the stimulus at the desired SOA, the relationship between the SOA set in the program (SOA program) and the SOA on the skin (SOA) is defined taking into consideration the D1, D2, and D3 delays, as shown in Eq (1):

$$\mathrm{SOA}_{\mathrm{program}} = \mathrm{abs}\{\mathrm{SOA} - (127 - 11)\mathrm{ms}\} \qquad (1)$$

where SOA can be positive or negative.

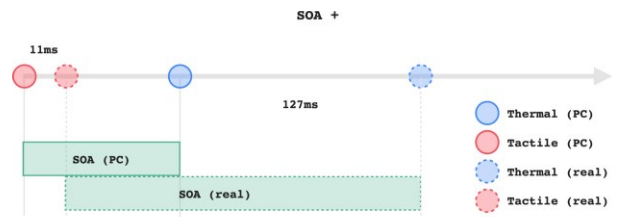

Fig. 2. Schematic illustration of the relationship between the SOA specified in the PC program and the SOA on the skin when a positive value is assigned to the SOA, accounting for computer response and delays.

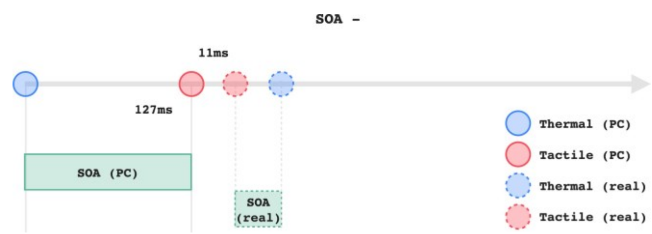

Fig. 3. Schematic illustration of the relationship between the SOA specified in the PC program and the SOA on the skin when a negative value is assigned to the SOA, accounting for computer response and delays.

III. PERCEPTUAL EXPERIMENT

A. Outline of Experiment

To investigate the thermal-tactile simultaneity window, we used a Simultaneity Judgment (SJ) task that involved presenting pairs of thermal stimuli and single-pulse tactile stimuli at 11 different Stimulus Onset Asynchronies (SOA). During the experiment, participants were required to determine whether the stimuli were "simultaneous" or "not simultaneous". A total of 220 simultaneity judgments per participant were made across the 11 SOAs, with the aim of deriving a bell-shaped judgment probability curve from the binary data (i.e., simultaneous and not simultaneous). The main objective of the study was to identify the simultaneity window, which was defined as the width of the fitted function at the 50% simultaneous response level.

B. Participants

Twelve participants (four women) participated in the study. They ranged in age from 21 to 30 years, with a mean age of 22.8 years (SD: 2.30 years). Each participant was healthy and did not have any skin condition or injury to the hands and no impairment in thermal or tactile perception. All participants signed an informed consent form approved by the Ethics Committee at the university.

C. Apparatus

The experiment used the multisensory cutaneous display described in the previous section to present thermal and tactile stimuli to the thenar eminence of the participant's left hand. The participant's skin temperature, the device temperature, and the skin-device interface temperature were recorded every 15 ms using the three thermistors. All stimulus presentations, recording of responses, and the experimental protocol were controlled by a program written using the DAQ and its driver. In order to prevent the participant's skin temperature from decreasing due to air flow generated by the air-cooling fan during the experiment, a partition and base were attached using styrofoam as shown in Fig. 4.

D. Thermal and Tactile Stimuli

The intensity of the thermal stimulus (ΔT) was set to be -7 °C from each participant's baseline skin temperature. Due to limitations in the PI controller, the final output ΔT stabilized at -6 °C. The rate of temperature change was approximately 2.5 °C/s. Prior to the onset of the temperature change, the participant's skin temperature was maintained at the baseline skin temperature for 9 s. Fig. 5 shows the actual thermal stimuli presented.

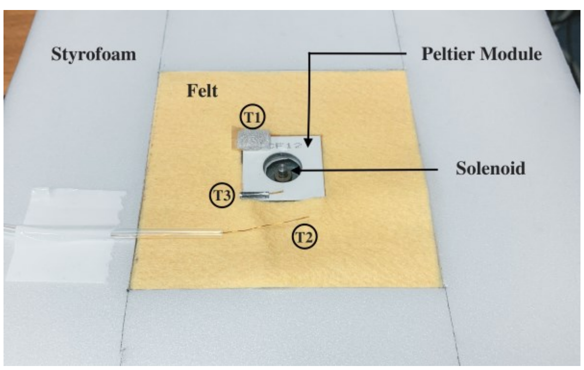

Fig. 4. Setup used in the experiment, with the solenoid positioned in the center of the Peltier module that is covered with felt around the periphery. White styrofoam is used to block air flow. T1, T2, and T3 indicate the position of each thermistor.

E. SOA

Eleven SOAs ranging from -1000 ms to +600 ms with a center of -200 ms were selected. Positive SOAs indicate the tactile stimulus preceded the thermal stimulus, while negative SOAs indicate the thermal stimulus preceded the tactile stimulus. The SOAs were -1000 ms, -700 ms, -500 ms, -350 ms, -250 ms, -200 ms, -150 ms, -50 ms, 100 ms, 300 ms, and 600 ms. The selection of the SOAs was based on the results from a pilot study that measured the point of subjective simultaneity (PSS) and aimed to prevent missing information by placing more observation points near the expected simultaneity window. The maximum and minimum SOA values were defined as those determined to be 95% or more out of synchrony based on the results from the pilot experiment.

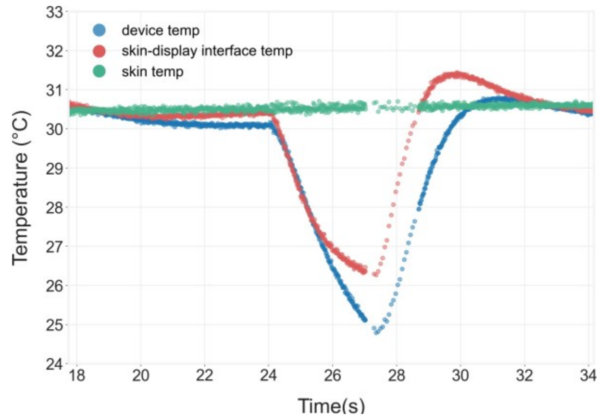

Fig. 5. Temperature stimulus presented in the experiment. Blue is the device temperature (T1), green is the skin temperature at a location away from the Peltier module (T2), and red is skin-display interface temperature (T3).

F. Procedure

Before the start of the experiment, participants received a written and oral explanation of the procedure and an outline of the experiment. Participants' skin temperatures at the beginning of the experiment averaged 31.8 °C (SD: 1.41 °C). While the experiment was being explained, the participant's left palm was kept on a rubber heater set at 33 °C to keep the initial skin temperature as uniform as possible. Participants were instructed to place their left hands in a comfortable position, with the thenar eminence in the center of the device. They were asked to ensure that their palm was in contact with the surface of the device. They also checked to make sure that all thermistors were beneath the palmar surface. Participants wore noise-canceling headphones (Soundcore Life Q20, Anker Inc) during the experiment. The headphones played white noise at an appropriate volume. This was introduced to mask sounds, such as solenoid clicks and ambient noise associated with device operation, and to help participants concentrate on the task. An auditory cue was also played on each trial to inform participants of the start time and response time.

After explaining the procedure, a practice section was conducted in which thermal and tactile stimulus pairs with extreme time differences (SOA= -1500 ms and 1500 ms) were repeated eight times. During the practice session, the experimenter checked to see if participants could perceive the stimuli, respond in an appropriate manner, and otherwise follow the experimental procedure.

The main experiment consisted of 220 trials, divided into five sections each with 44 trials, each lasting approximately 10 minutes. During the experiment, participants took 2-minute and 5-minute breaks between each section. Each trial was divided into 3 stages: (1) device temperature adjustment to match the participant's skin temperature, (2) presentation of both stimuli (tactile and thermal) according to a predetermined randomized SOA; if the SOA was positive, the tactile stimulus was presented first, and vice versa for a negative SOA, and (3) response phase. The initial and response phases were signaled by different sounds. Participants made their responses using a numeric keypad, with ”1” indicating simultaneity and ”2” indicating no simultaneity. The next trial was initiated after the participant’s response was entered.

IV. Results

A. Simultaneity window

The percentage of simultaneity judgments was calculated from the participants’ binary data responses for each SOA. The response distribution was fitted by the Gaussian function shown in Eq (2). In the experiment, the percentage of simultaneity judgments for one participant was always less than 50%, and so this participant was excluded from further data analysis.

$$f(x) = A \cdot \exp\left\{-\frac{(x-\mu)^2}{2.0\cdot\sigma^2}\right\} + B \tag{2}$$

The Gaussian function was used as the fitting model to describe the data in Eq. 2. To obtain the best fit to the data, a nonlinear least-squares method was used through the curve_fit function in the scipy library in Python. This allowed for the estimation of the amplitude (A), mean (μ), standard deviation (σ), and fitting adjustment parameter (B). To ensure that the maximum value of A was close to 1, an upper limit was set. The fit was obtained using x values ranging from -1200 ms to +1200 ms, with a 1 ms increment.

The average fitting curve and PSS for all but one of the 11 participants are shown in Fig. 6 together with the window of simultaneity. The PSS was -242 ms, indicating that participants felt the most simultaneity when the thermal stimulus preceded the tactile stimulus by -242 ms. The proportion of judgments at this point was 0.86, indicating that the two stimuli were not 100% simultaneously perceived at the PSS. The simultaneous window defined by the width of the fitted function at the 50% simultaneous response level is 639 ms with a range from -561 ms to 78 ms.

In this study, the 50% window and the FWHM (Full Width at Half Maximum) and SD of the fitted Gaussian curve were calculated. The 50% window is defined as the window between the 50% points of the response distribution obtained from the binary responses. The 50% response level, representing chance level, was the boundary for the simultaneity determination; the FWHM is calculated as the spectral width at 50% of the intensity of the maximum peak, using Eq (3):

$$FWHM = 2 \cdot \sigma\sqrt{2 \cdot \ln 2} \tag{3}$$

The SD indicates the spread of data in a Gaussian distribution, and some studies [20] consider the SD as a window of time integration. Fig. 7 shows the group means for these three types of windows. These data were calculated from fitting individual data rather than from the average of the 11 individuals’ data. The FWHM = 657.75 ms (SE: 51.26), the SD = 279.32 ms (SE = 21.76), and the 50% window = 625.91 ms (SE = 55.49).

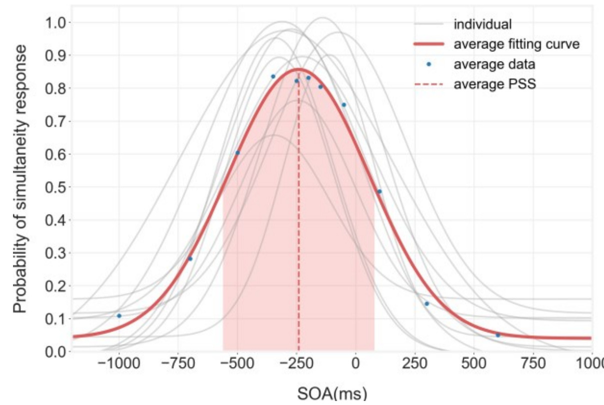

Fig. 6. Results from the Simultaneity Judgement Task. The solid red line is the line fitted to the plot of the percentage averages of the 11 participants’ simultaneity judgments and the blue dots are their data points. Gray indicates individual data. The red dotted line is the PSS, indicating the apex of the curve, and the width between the 50% points is shown in red.

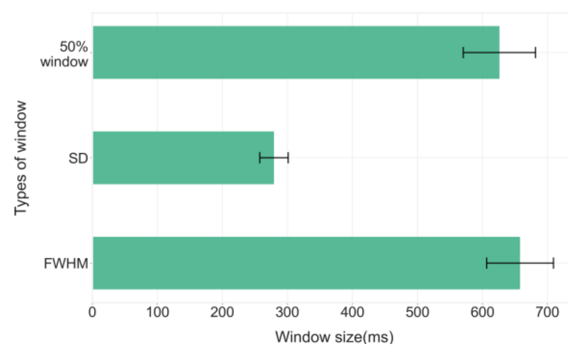

Fig. 7. Three window sizes, calculated based on fitting functions obtained from the response proportions of the 11 participants. The error bars are standard errors of the means (SEM).

V. Discussion

A. Principal findings

To the best of our knowledge, the present study is the first to investigate thermal-tactile simultaneity perception. We showed that the PSS is shifted to the thermal-leading side by 242 ms, and that the Simultaneity Window, that is, the time interval in which a human perceives the two stimuli as simultaneous, has a width of 639 ms, ranging from -561 ms to 78 ms. These findings indicate that simultaneous perception of thermal and tactile stimuli does not require the two stimuli to be physically presented at the same time (i.e., PSS = 0 ms). As long as the time difference between the thermal and tactile stimuli is within the simultaneity window, they can be perceived as simultaneous. By introducing a slight interval between thermal and tactile stimuli within this range, it is possible to create simultaneity while potentially avoiding the problem that tactile stimuli can mask thermal perception when presented at the same time.

In the present study, stimuli were presented only on the left hand of participants and one might speculate that the results could have been different if the right hand had also been tested. This seems unlikely as there is very little evidence of left-right differences in thermal sensitivity. Thermal threshold studies have shown that there is no statistically significant difference between cold and warm thresholds measured at a number of locations on the left and right sides of the body [18], [19].

In the design of multisensory cutaneous displays, it is important to provide concurrent, synergistic thermal and tactile feedback to create a coherent touch experience. When used to assist object recognition in teleoperated and virtual environments, thermal feedback can provide information about the material composition of objects and tactile feedback can convey surface texture cues. The thermal-tactile simultaneity window we found can therefore be used as a guideline for the effective integration of thermal and tactile feedback to create realistic impressions of objects in virtual environments.

B. Thermal-tactile temporal integration

The temporal properties of the thermal and tactile senses are profoundly different, as reviewed in Section 1A. It has been shown that the thermal modality has a slower transmission speed compared to the tactile modality [5], [6]. In the present study, we show that the PSS is shifted towards the thermal-leading side, suggesting that the brain accounts for these differences in sensory processing speed.

This finding aligns with previous research on audio-visual [20], [21], [22], visual-tactile [23], and audio-tactile simultaneity [24] [25], which demonstrated that people perceive simultaneity when the modality with the slower transmission speed precedes the modality with faster transmission. Kaaresoja et al. [24] reported that the PSS for audio-tactile and visual-tactile stimuli was 19 ms and 32 ms respectively, when measured in the context of pressing a virtual button on a touchscreen device. The time delay that is detectable between different modalities has also been measured in some of these earlier studies. For audio-haptic stimuli in which the haptic stimulus (mechanical impact of a hammer tap) occurs first, the average JND has been reported to be 24-42 ms [26].

The percentage of simultaneity judgments did not reach 100% in our data, suggesting participants had some difficulty in making simultaneity judgments. One possible reason is that the tactile and thermal stimuli we used had very different temporal profiles. While our tactile stimulus is a single impulse and has a clear onset, the thermal stimulus changed at a rate of 2.5 °C/s, taking 3 s to decrease by 6 °C (see Fig. 5). It is known that thermal sensitivity is influenced by the rate of change in temperature. The cold afferent fiber, the Aδ fiber, is approximately 100 times more sensitive to a rapid drop in temperature than to a slow change in temperature [13]. Thus, the gradual change in our thermal stimulus presumably influenced participants' performance in simultaneity judgments.

C. Considerations in using the FWHM, SD, and 50% point window for estimating the simultaneity window

The 50% response rate width was defined as the simultaneity window in this study. The feasibility of using the FWHM and the SD to estimate simultaneity windows was also explored. In some experiments, the FWHM or 50% of the maximum value has been defined as the simultaneity window [27], [28]. In our results, the 100% simultaneity judgments were not always near the PSS. With a maximum value of less than one, the 50% window and FWHM are different for a Gaussian distribution. Using the FWHM as a simultaneity window results in a wider time interval of perceived simultaneity, but with a greater proportion of non-simultaneous judgments at both ends. The SD is also a measure of distribution spread and a window of time integration [20]. It has a narrower range compared to the 50% point, leading to a more conservative estimate of the time interval for simultaneous perception.

D. Fitting averages of individual data as compared to group data

The group data, which is a result of integrating all 11 participants' responses, smooths and equalizes individual data, reducing the effect of bias. This can be considered an ideal human model. On the other hand, fitting individual data is biased toward the corresponding individual's responses. The ideal human model is more representative when the number of participants is small. Therefore, in this study, we adopted the ideal human model to derive the window of simultaneity. The window width was estimated to be 639 ms, ranging from -561 ms to 78 ms. For comparison, we also estimated the window size based on fitting individual data. The group mean simultaneity window size was 626 ms with a SE = 55.49 ms. The difference in the estimated window size is merely 13 ms.

VI. Conclusion

The results from this study indicate that in thermal-tactile simultaneity perception, the PSS is shifted to the thermal-leading side and the simultaneity window has a width of 639 ms, ranging from -561 ms to 78 ms. Our findings are consistent with previous findings of audio-visual, visual-tactile, and audio-tactile simultaneity, which indicate that simultaneity perception is biased to the modality that has a slower processing speed. For future work, we plan to measure the PSS for warming stimuli, which is expected to shift the PSS further to the thermal-leading side as the processing speed for warming stimuli is slower than that for cooling stimuli. This line of research can serve as a guideline for the effective integration of thermal and tactile feedback to create realistic impressions of objects in virtual environments.

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