Perceiving Synchrony: Determining Thermal-Tactile Simultaneity Windows

Takuya Jodai, Lynette A. Jones, *Fellow, IEEE*, Masahiko Terao, and Hsin-Ni Ho, *Member, IEEE*

***Abstract*—In cutaneous displays in which both tactile and thermal signals are presented, it is important to understand the temporal requirements associated with presenting these signals so that they are perceptually synchronous. Such synchrony is important to provide realistic touch experiences in applications involving object recognition and social touch interactions. In the present experiment the temporal window within which tactile and warm thermal stimuli are perceived to occur at the same time was determined. A Simultaneity Judgment Task was used in which pairs of tactile and thermal stimuli were presented on the hand at varying stimulus onset asynchronies, and participants determined whether the stimuli were simultaneous or not. The results indicated that the average simultaneity window width was 1041 ms. The average point of subjective simultaneity (PSS) was −569 ms, indicating that participants perceived simultaneity best when the warm thermal stimulus preceded the tactile stimulus by 569 ms. These findings indicate that thermal and tactile stimuli do not need to be displayed simultaneously for the two stimuli to be perceived as being synchronous and therefore the timing of such stimuli can be adjusted to maximize the likelihood that they will both be perceived.**

***Index Terms*—Cutaneous displays, multimodal haptic interfaces, simultaneity judgments, simultaneity window, thermal sensing.**

I. Introduction

Touch provides critical information about objects and surface texture during manual exploration and conveys emotions that are essential for interpersonal communication [1]. However, direct physical contact is not always possible when people are remotely located, experiencing health issues, or socially isolated. Addressing this gap, recent technological advancements have led to the development of cutaneous displays capable of digitally replicating and transmitting cutaneous sensations. These displays have the potential to expand the capabilities of current audiovisual communication systems and enhance the communication experience for users of mobile devices, wearable technology, and virtual reality.

Tactile contact is a multifaceted experience, encompassing both mechanical and thermal elements. Mechanical interaction with the touched surface leads to skin deformation, while thermal interaction results in changes in skin temperature. These physical changes activate specific mechanoreceptors and thermal receptors within the skin, giving rise to tactile and thermal sensations which are instrumental in discerning the state, texture, and material properties of the touched surfaces. Accordingly, a holistic digital touch experience should be able to capture these rich sensory experiences, offering simultaneous and synergistic thermal and tactile feedback. When used to assist with object recognition in teleoperation and virtual environments, thermal feedback can provide information about the material composition of objects, while tactile feedback can convey cues related to surface texture [2], [3]. In social touch applications, the addition of thermal feedback offers cues associated with psychological warmth and animacy [4], [5].

Several studies have explored the integration of thermal and tactile feedback within a single display, focusing primarily on hardware development and control algorithms [6], [7]. However, simply integrating thermal and tactile feedback in a display is not sufficient due to significant challenges in effectively presenting temperature and tactile information. Recent studies have shown that concurrent tactile stimulation can influence thermal identification: vibrotactile stimuli often mask the perception of thermal stimuli when presented simultaneously [8]. Furthermore, the temporal and spatial properties of the thermal and tactile senses differ markedly; the thermal sense is slower and more spatially diffuse compared to the tactile sense. Therefore, the perceptual outcome of presenting thermal and tactile feedback concurrently is not straightforward. These challenges indicate that systematic investigation of the sensory interactions between thermal and tactile inputs is crucial for such feedback to be effectively implemented for communication purposes.

The tactile and thermal sensory systems are independent modalities in terms of their underlying neurophysiological structures. They possess distinct receptors, separate ascending pathways to the brain, and different cortical processing areas.

Received 20 March 2024; revised 24 July 2024; accepted 22 August 2024. Date of publication 3 September 2024; date of current version 19 December 2024. The work of Lynette A. Jones was supported by the National Science Foundation under Grant IIS-2006152. The work of Masahiko Terao and Hsin-Ni Ho was supported by the Telecommunications Advancement Foundation, Japan. The work of Lynette A. Jones, Masahiko Terao, and Hsin-Ni Ho was supported by ULVAC-Hayashi MISTI Seed Fund, MIT-Japan Program. The work of Hsin-Ni Ho was supported by the JSPS KAKENHI under Grant 22H03679. This article was recommended for publication by Associate Editor A. Moscatelli and Editor-in-Chief D. Prattichizzo upon evaluation of the reviewers' comments. *(Corresponding author: Hsin-Ni Ho.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Research Ethics Review Committee of Faculty of Design, Kyushu University, under Application No. 696.

Takuya Jodai and Hsin-Ni Ho are with the Faculty of Design, Kyushu University, Fukuoka 819-0395, Japan (e-mail: jtakuya625@gmail.com; hohsinni@design.kyushu-u.ac.jp).

Lynette A. Jones is with the Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: ljones@mit.edu).

Masahiko Terao is with the Research Institute for Time Studies, Yamaguchi University, Yamaguchi 753-0841, Japan (e-mail: terao@yamaguchi-u.ac.jp).

Digital Object Identifier 10.1109/TOH.2024.3452102

Mechanoreceptors, characterized by their distinct morphologies, are situated within both the epidermal and dermal layers of the skin. In contrast, thermal receptors, which are free nerve endings, exhibit a differentiated distribution: cold receptors are found in the epidermis, whereas warm receptors are located in the dermis [9]. The somatosensory cortex processes tactile sensations [10], whereas the insula is primarily responsible for thermal sensations [11]. The neural transmission latency for tactile stimuli is much shorter than that for thermal stimuli, with 20–60 ms for tactile stimulation [12], 140–200 ms for cold stimulation [13], and 280–356 ms for warm stimulation [14]. This means that simultaneous tactile and thermal cues will not reach the cortex at the same time and so are not necessarily perceived as concurrent.

From a perceptual viewpoint, there are also considerable differences in their temporal and spatial properties [10]. Reaction times for tactile stimuli are much faster than those for thermal stimuli. On the fingertip, the simple reaction time for tactile stimuli has been reported to be 182 ms (SD: 16 ms) [15], whereas for thermal stimuli reaction times are much slower and differ for warmth and cold [16]. The reaction time has been estimated to be approximately 938 ms (SD: 266 ms) for warm stimuli and 529 ms (SD: 87 ms) for cold stimuli [17] when they are applied to the hand. 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 (1-2m/s) [18]. These afferent fibers are in turn much slower than those of mechanoreceptor afferents, whose conduction velocities are approximately 80m/s [10].

For spatial processing, it is known that the thermal sensitivity of skin differs from that for 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 [19]. Thermal and tactile sensations also differ in their spatial resolution. The thermal sense is diffuse and incapable of providing precise spatial information, primarily because it integrates spatially separate inputs. Consequently, our capacity to localize and distinguish spatially distinct thermal inputs is limited [20], [21]. Studies have shown that the localization error for thermal stimuli is much larger than that for tactile stimuli [22], [23], and that localization accuracy is greater for cold as compared to warm stimuli [24]. Based on these differences in thermal and tactile perception, it is important to understand the interactions that occur between thermal and tactile stimuli when they are presented simultaneously.

There has been relatively little research on understanding the temporal requirements associated with presenting tactile and thermal cues simultaneously in displays. Although it has been shown that thermal cues can be completely masked by high intensity vibration when presented concurrently, they do become perceptible when a brief delay is added to the onset of the vibratory stimulus relative to the thermal cue [8]. This suggests that the timing of stimuli can be adjusted to maximize the likelihood that they will both be perceived, but at the same time are perceptually synchronous. The temporal window within which stimuli are perceived to occur at the same time is known as the simultaneity window. It has been extensively studied in vision and audition, where it has been important to understand how delays impact perceptual reliability and saliency [25]. For audiovisual stimuli related to speech perception, for example, perceived simultaneity is maximal if visual cues precede the auditory signals by approximately 120 ms [26], [27].

With the pervasive use of virtual buttons and keys on touchscreens comes the requirement to understand the temporal features required when presenting audio and tactile cues so that there is a realistic user experience. The presence of perceptually synchronous audio cues has been shown to enhance the perceived quality of such touch interfaces [28], [29]. In an experiment involving virtual buttons, Brahimaj et al. [30] reported that when an audio signal was presented first, a delay of 40 ms resulted in the audio and tactile cue being perceived as being synchronous, whereas when the haptic cue was presented first synchronicity was perceived at a delay of 109ms. This increased sensitivity to delays in the tactile modality was interpreted in terms of daily experience in which we generally feel the tactile cue associated with contacting a button or switch prior to hearing any response. It was proposed that these threshold values could be used in the design of virtual buttons, with the caveat that audio cues should not be presented prior to tactile cues given the stringent temporal requirements for perceived audio-tactile synchronicity.

There has also been research on the perceptual simultaneity of different tactile cues such as vibration and impact forces, which is relevant to rendering multimodal haptic feedback. Park and Choi [31] found that the point of subjective simultaneity (PSS) for vibration and force pulses delivered by a handheld device varied as a function of the frequency (40–250 Hz) and duration (50–200 ms) of the vibration. The PSS decreased as the frequency increased from 40 to 250Hz. However, the order of the two stimuli for perceived simultaneity (i.e. whether vibration or the force pulse came first) varied with both frequency and duration.

To provide a realistic touch experience, cutaneous displays should offer synergistic thermal and tactile sensations. This is particularly important in applications involving object recognition and social touch interactions, where touch typically involves contact with a surface, entailing concurrent thermal and tactile inputs. In daily experience, we do not perceive a delay in thermal information, despite the longer processing time as compared to tactile information. This suggests that the brain compensates for these delays, forming a unified perception of the touched surface. Understanding this temporal integration is crucial for designers of cutaneous displays, particularly when specifying presentation intervals that create a realistic impression of a surface and to avoid effects such as masking.

The focus of the present research is on the perception of simultaneity for thermal and tactile stimuli and in particular determining the temporal window within which they are perceived to occur at the same time. In a recent study, we investigated the simultaneity window for a cooling stimulus delivered to the hand concurrently with a tactile input [32]. Specifically, we determined the time interval within which these inputs are perceived as simultaneous and merged into a single perceptual event. The simultaneity window's width was 639 ms, ranging from −561 ms to 78 ms and 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. In the experiment described in this paper we have further explored tactile-thermal interactions by measuring the simultaneity window for a warm thermal stimulus and tactile pulse. Given the differences in neural conduction velocity and transmission latency between the cold and warm sensory systems, we expect that the simultaneity window and PSS for warm tactile stimuli will differ from those measured for cold tactile inputs. It is also possible that the properties of the simultaneity window itself vary for cold and warmth.

II. Device Development

A cutaneous display that can present both thermal and tactile stimuli to the thenar eminence on the hand was used in the experiment. The stimuli were generated and the display controlled using data acquisition modules (DAQ) (AIO-160802AY-USB, Contec Inc). The DAQ driver (API-AIO (WDM), V7.70, Contec Inc) enabled command execution in Python3 within the Anaconda framework. The display was programmed to output an analog signal for temperature and a digital signal for tactile stimulation at varying intervals of stimulus onset. Two thermal outputs were generated: a warming stimulus of +5 °C for each experimental trial and a constant stimulus during the inter-trial interval that ensured that the participant's baseline skin temperature was maintained. To ensure safety, the system was designed with safeguards to avoid temperature deviations below 15 °C or above 45 °C, both of which result in pain and potential skin damage [19].

A. Apparatus

1) Peltier Module: A 30-mm square Peltier device (430533-502, Laird Thermal Systems, Inc.) with a central hole (14.4 mm diameter) was chosen to present thermal stimuli, as this enabled the co-location of tactile and thermal stimulation. To dissipate heat from the Peltier module's backside, an air-cooled heat sink was utilized. A 14.1 mm × 16.0 mm hole was cut in the middle of the heat sink to fit the solenoid used to deliver tactile stimulation (see Fig. 1). The solenoid was fixed to the heat sink using a clay-like adhesive together with double-sided tape. To safeguard against excessive thermal exposure to other areas of the hand, felt material was applied to the surface of the display, effectively bridging the space between the heat sink and the Peltier module.

2) Thermisors: Three thermistors (56A1002-C8, Alpha Technics) each with a diameter of 457 μm and a length of 3.18 mm were used to record temperature. Thermistor T1 recorded the temperature of the Peltier module and was covered with a buffer material to avoid direct skin contact. Thermistors T2 and T3 measured the skin temperature of the participant and the temperature at the point where the skin made contact with the device, respectively. T2 was placed proximal to the Peltier module, and served as a baseline reference for skin temperature, unaffected by the thermal display's temperature fluctuations. T3 was placed on top of the device to record the skin-interface temperature (see Fig. 1).

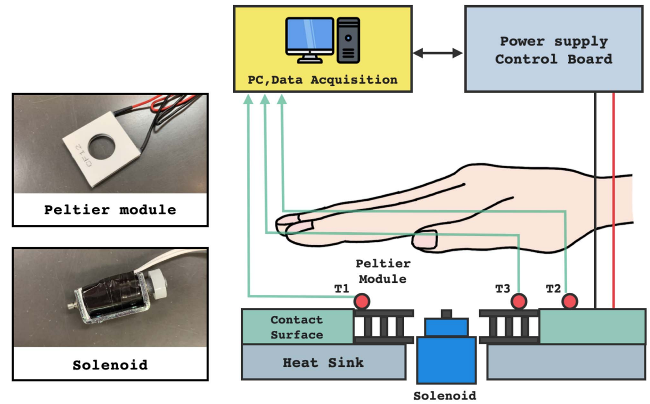

Fig. 1. Schematic illustration of the experimental setup with the Peltier module and solenoid shown. The hand is positioned above the display and the locations of the three thermistors T1, T2, and T3 are indicated. Adapted from [32].

3) Solenoid: Tactile stimulation was provided by a solenoid designed for pulsed stimulation (Model CB0730, Takaha Kiko Co., Ltd). The tip of the solenoid had a diameter of 3.5mm, a length of 9mm, and a range of motion of 3mm.

B. Stimuli

1) Thermal Stimuli: A warming stimulus of +5 °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 1.41 °C/s. The +5 °C value was selected based on pilot studies in which some participants reported heat pain (a stinging sensation) at higher amplitudes.

2) Tactile Stimuli: The solenoid was used to present a single pulse that deformed the skin. The pulse duration was 10ms, with a force of approximately 1.4N, which was readily perceived.

C. Improved Accuracy With Consideration of Delays

The ability to detect a change in temperature varies as a function of the rate at which skin temperature changes. If the skin is warmed at rates below 0.1 °C/s, the threshold for detecting an increase in temperature is considerably higher than that measured for faster rates of warming [33]. However, when the rate is above 0.1 °C/s, thresholds remain constant. It has also been shown that reaction times are not significantly affected by the rate at which temperature changes over the range of 1.5 to 6.7 °C/s [34]. These perceptual properties are important to the design of the experiment since precise control of the timing of each stimulus is required. Several delays are unavoidable due to limitations in hardware and software. Delays occur between the program command and the DAQ output (D1), between the output from the DAQ and the Peltier module's or solenoid's response (D2), and then the device's actual change in skin temperature or contact force (D3). Given that this study aims to determine the simultaneity window, these delays must be factored into accurate estimations of this window.

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

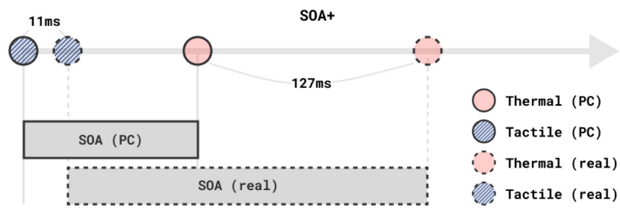

Fig. 2. Schematic illustration of the relationship between the SOA specified in the program and the SOA on the skin when a positive value is assigned to the SOA, accounting for computer response and delays. Adapted from [32].

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

The command execution time, D1, was measured using the standard Python library. The delay associated with the tactile stimulus, D2, was measured using a high-speed camera recording at 1000 frames per second. It was set to 10ms, the timing difference between the DAQ output and the solenoid's movement to reach the halfway point. For thermal stimulation, D2, it 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 set at 0 ms for both tactile and thermal stimuli. The former estimate was based on measurements made by Ujitoko et al. [35] who showed that when a silicone rubber sheet was indented by a solenoid, the deformation started when the solenoid was activated (i.e., 0 ms). Accordingly, it was assumed that the skin deformation delay is negligibly small. The thermal stimulation presented by the Peltier module was assumed to change skin temperature essentially simultaneously, so D3 was set to 0 ms in this analysis [36].

2) *Defining Stimulus Onset Asynchronies (SOA) for Skin Responses:* In this experiment, the SOA was defined 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 shown in Figs. 2 and 3. To present the stimulus at the specified SOA, the relationship between the SOA set in the program (SOA program) and the SOA on the skin (SOA) is defined taking into account the D1, D2, and D3 delays, as shown in (1):

$$\mathrm{SOA_{program}} = \mathrm{abs}\left\{\mathrm{SOA} - (127 - 11)\mathrm{ms}\right\} \quad (1)$$

where SOA can be positive or negative.

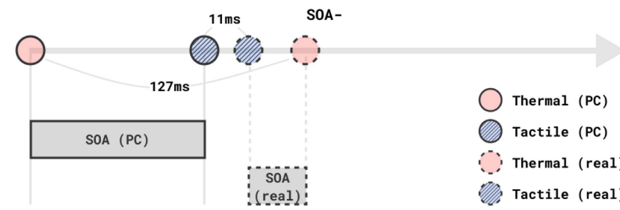

Fig. 3. Schematic illustration of the relationship between the SOA specified in the program and the SOA on the skin when a negative value is assigned to the SOA, accounting for computer response and delays. Adapted from [32].

III. MATERIALS AND METHODS

A. Outline of Experiment

The thermal-tactile simultaneity window was estimated using the Simultaneity Judgment (SJ) task which entails presenting pairs of thermal and tactile stimuli with varying SOA. During the experiment, participants were required to determine on each trial whether the stimuli were "simultaneous" or "not simultaneous". Each participant conducted 220 simultaneity judgments, spread across 11 SOAs with 20 repetitions. The primary goal was to construct a bell-shaped probability curve of judgments based on binary outcomes (i.e., simultaneous and not simultaneous), from which the simultaneity window could be determined. This window was defined as the width of the fitted function at the 50% simultaneity response level.

B. Participants

Thirteen participants (five women) took part in the study. They ranged in age from 21 to 31 years, with a mean age of 22.9 years (SD: 2.52 years). All participants were in good health, with no reported skin conditions or hand injuries, and normal thermal and tactile perception. Prior to participation, each individual signed an informed consent form, which had been approved by Kyushu University's Ethics Committee.

C. Apparatus

The cutaneous display described in Section II was used to deliver thermal and tactile stimuli to the thenar eminence on the left (non-dominant) hand as the thenar eminence has the highest thermal sensitivity in the hand [37]. The participant's skin temperature, the device temperature, and the skin-device interface temperature were sampled every 15ms. The presentation of stimuli, recording of participants' responses, and adherence to the experimental procedure were all managed by a custom-written program developed with the DAQ and its associated driver. To prevent any potential reduction in skin temperature caused by airflow from the air-cooling fan, a partition, and base were constructed from styrofoam as depicted in Fig. 4.

D. Thermal and Tactile Stimuli

The thermal stimulus intensity (ΔT) was +5 °C relative to each participant's baseline skin temperature. Owing to constraints associated with the PI control, the increase in temperature experienced by participants averaged 4.57 °C (SD: 0.20

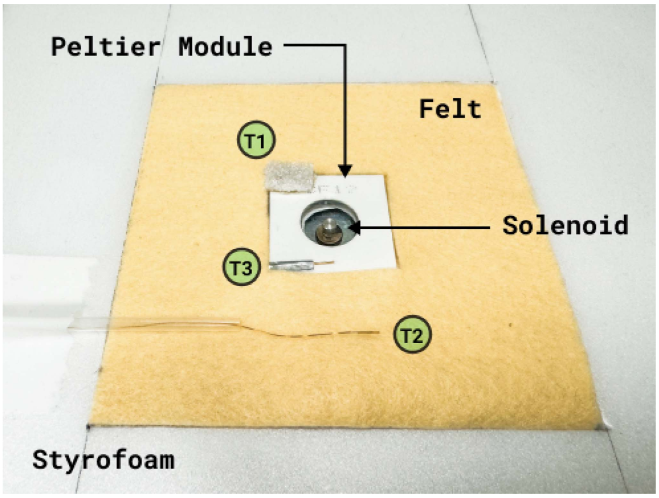

Fig. 4. Setup used in the experiment, with the solenoid in the center of the Peltier module. The area surrounding the Peltier module is covered with felt to ensure participant comfort. White Styrofoam is used to block air flow. T1, T2, and T3 indicate the positions of each thermistor. Adapted from [32].

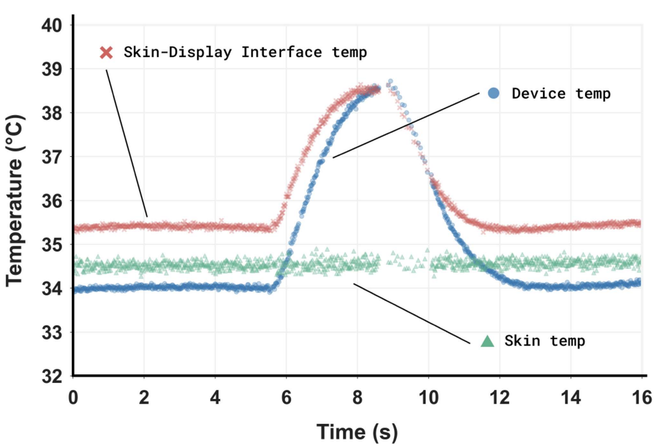

Fig. 5. Temperatures measured at each location as the thermal stimulus is presented. Blue is the device temperature (T1), green is the skin temperature at a location away from the Peltier module (T2), and red is the skin-display interface temperature (T3).

°C). The mean rate of temperature change was 1.41 °C/s (SD: 0.06 °C). The participants' baseline temperature was maintained at a constant level for 9 s prior to each stimulus presentation. Fig. 5 shows the temperatures measured by each thermistor during stimulus presentation.

E. SOA

Eleven SOA ranging from −2000 ms to +1000 ms with a center of −500 ms were used in the experiment. Positive SOA indicate that the tactile stimulus preceded the thermal stimulus, whereas negative SOA indicate that the thermal stimulus came first. The SOA were −2000 ms, −1500 ms, −1100 ms, −800 ms, −600 ms, −500 ms, −400 ms, −200 ms, 100 ms, 500 ms, and 1000 ms. These values were selected based on the results from a pilot study that measured the point of subjective simultaneity (PSS). To prevent missing critical data for estimating the simultaneity window, more observation points were placed near the expected PSS value of −500 ms. The maximum and minimum SOA values were defined as those determined to be out of synchrony on at least 95% of the trials, based on the results from the pilot experiment.

F. Procedure

Before commencing the experiment, the procedure was explained to each participant, both verbally and in writing. The mean skin temperature of the participants at the beginning of the experiment was 33.1 °C (SD: 1.20 °C). To maintain as consistent an initial skin temperature as possible, the participant's left palm was placed on a rubber heater, maintained at 33 °C, during the explanation phase. Participants then positioned their left hand comfortably on the device, ensuring that the thenar eminence was in the center, on top of the Peltier module and the solenoid. All thermistors were checked to confirm that they were under the palmar surface. During the experiment, participants wore noise-cancellation headphones (Soundcore Life Q20, Anker Inc) playing white noise. This obscured operational sounds such as solenoid clicks and ambient noise, thereby aiding concentration on the task. Additionally, auditory cues were played during each trial to indicate the start of the trial and the response time.

After explaining the procedure, a practice session was conducted using 8 SOA randomly selected from the 11 thermal and tactile stimulus pairs used in this experiment. In the practice session, the experimenter verified whether participants were able to perceive the stimuli, respond suitably, and adhere to the experimental protocol.

The main experiment comprised 220 trials, segmented into five sections, each containing 44 trials of approximately 10 minutes duration. Breaks of 2 and 5 minutes were allocated between the sections during the experiment. Each trial encompassed three phases: (1) device temperature adjustment to match the participant's skin temperature; (2) presentation of both stimuli (tactile and thermal) according to a pre-determined randomized SOA; if the SOA was positive, the tactile stimulus was presented first, and vice versa for a negative SOA, and (3) response phase. Different sound cues signaled the initial and response phases. Participants recorded their responses on a numeric keypad, pressing "1" for simultaneous stimuli and "2" for non-simultaneous stimuli. The next trial began following the participant's response.

IV. Results

The proportion of simultaneity judgments was derived from the binary responses of participants for each SOA. We fitted the proportion of simultaneity judgments of each participant using the Gaussian function shown in (2). During the analysis, it was noted that the simultaneity judgment percentages for two participants were consistently below 50%. Consequently, data from these participants were excluded from subsequent analyses.

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

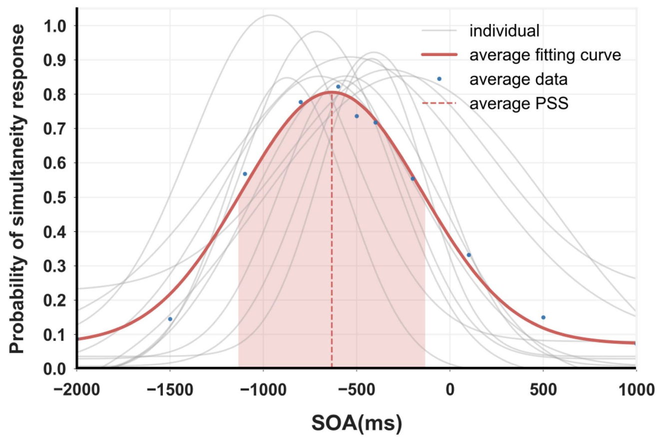

Fig. 6. Results from the Simultaneity Judgement Task when tactile inputs are delivered concurrently with warm stimuli. The gray lines indicate the functions fitted to the individual participants' simultaneity judgments. The blue dots represent the group mean simultaneity judgment at each SOA tested, and the solid red line is the line fitted to those mean values. The red dotted line and the shaded area in red indicate the PSS and the simultaneity window derived from the group mean data, respectively.

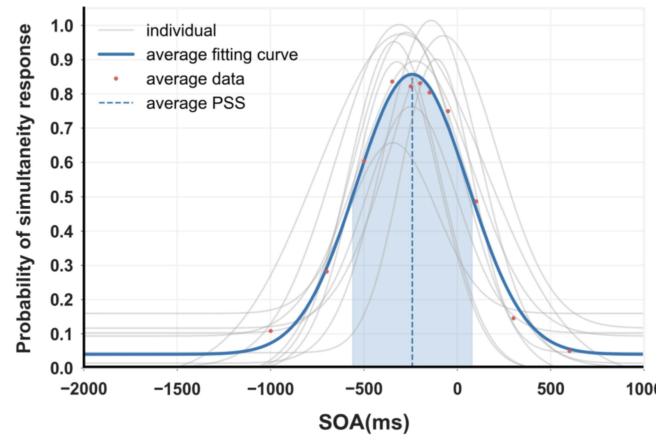

Fig. 7. Results from the Simultaneity Judgement Task when tactile inputs are delivered concurrently with cold stimuli. The gray lines indicate the functions fitted to the individual participants' simultaneity judgments. The red dots represent the mean simultaneity judgment at each SOA tested, and the solid blue line is the line fitted to those mean values. The blue dotted line and the shaded area in blue indicate the PSS and the simultaneity window derived from the group mean data, respectively. Adapted from [32].

To achieve the optimal fit for the data, we utilized a nonlinear least-squares method via the curve_fit function from the SciPy library in Python. This enabled the estimation of several parameters including the amplitude (A), mean (μ), standard deviation (σ), and a fitting adjustment parameter (B). An upper limit was set to ensure that the maximum value of A was close to 1. The fitting was conducted with x values spanning from −2000 ms to +1000 ms, incremented in steps of 1ms.

The results are shown in Fig. 6. The curves fitted to the individual data for the 11 participants are represented by gray lines. The range of R^2, which indicates the goodness of fit of these curves, is 0.87−0.99. The curve fitted to the group mean data is represented by a solid red line, along with the window of simultaneity estimated from the group mean data. One of the objectives of the present experiment was to determine whether the PSS and the simultaneity window measured for warm stimuli delivered concurrently with tactile inputs differed substantially from those measured for cold stimuli presented synchronously with tactile inputs. The results from the earlier experiment using cold stimuli are shown in Fig. 7. A comparison of Figs. 6 and 7 reveals that, while the PSS for both warm and cold stimuli occurs on the thermal leading side, there is greater individual variation in the timing of the PSS for warm stimuli than for cold stimuli. Additionally, the simultaneity window for warm stimuli is wider compared to that for cold stimuli.

Fig. 8 presents a comparison between warm and cold stimuli, in terms of the PSS, the simultaneity window, and the proportion of simultaneity judgments made at the PSS. The mean PSS for warm stimuli is −569 ms (SEM = 76 ms), in contrast to −245 ms (SEM = 29 ms) for cold stimuli. A one-sample t-test indicated that the PSS is significantly different from zero in both the warm ($t(10) = -8.59$, $p < 0.001$) and cold conditions ($t(10) = -8.40$, $p < 0.001$). Given that the warm and cold conditions involved different groups of participants, an independent samples t-test was performed to compare the PSS between these conditions. The results indicated a statistically significant difference ($t(20) = 4.41$, $p < 0.001$, Cohen's $d = 0.59$) between the PSS measured for warmth and cold. These findings show that to achieve the perception of simultaneity, thermal stimuli must precede the tactile inputs. Furthermore, warm stimuli must precede tactile inputs by over 300 ms more than that for cold stimuli to achieve this perception of simultaneity. The simultaneity window, defined as the width of the fitted function at the 50% simultaneous response level, is 1041 ms (SEM = 105 ms) for warm stimuli and 626 ms (SEM = 55 ms) for cold stimuli. An independent samples t-test was performed to compare the window width between warm and cold conditions. The results indicate a wider simultaneity window for warm stimuli compared to cold stimuli when presented concurrently with tactile inputs ($t(20) = -3.49$, $p = 0.001$, Cohen's $d = 0.53$). Lastly, the group mean proportion of simultaneity judgments at the PSS is 0.89 (SEM = 0.02) for warm stimuli and 0.91 (SEM = 0.03) for cold stimuli. No significant difference was found between these proportions.

Note that the results derived from fitting the group mean data are also presented in Figs. 6 and 7. The PSS and simultaneity window width were estimated at −633 ms and 1001 ms for warm stimuli, and −242 ms and 639 ms for cold stimuli, respectively. These values slightly deviate from the PSS and simultaneity window calculated from the individual participants' data, which are −569 ms and 1041 ms for warm stimuli, and −245 ms and 626 ms for cold stimuli, as shown in Fig. 8. Although both fitting approaches are used to characterize the PSS and the simultaneity window in the literature, the mean values calculated from individual data offer a more accurate estimation for our dataset. A detailed examination of the individual curves for warm stimuli, illustrated in Fig. 6, reveals significant variation in the PSS across participants. Consequently, utilizing group mean data (represented by the red solid line) yields an estimation of PSS

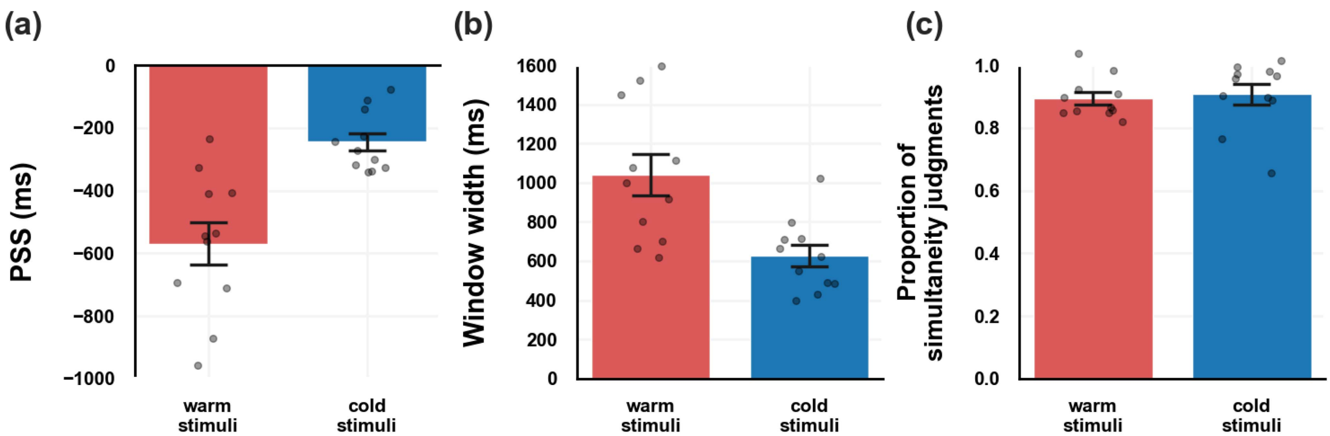

Fig. 8. Group means from fitting the individual data (shown as grey circles): (a) PSS, (b) window width, and (c) proportion of simultaneity judgments at the PSS when a tactile stimulus was presented with a warm stimulus (red bars) or a cold stimulus (blue bars). The error bars represent the standard errors of the means. Data for cold stimuli are from [32].

that does not match the higher levels of simultaneity judgment observed in the individual curves. This discrepancy indicates that the group mean data-based results may not fully capture the simultaneity perception of our participants, suggesting a more precise representation is achieved through analyzing the individual data.

In addition to the 50% window, other measures such as the standard deviation (SD) and the Full Width at Half Maximum (FWHM) window have been utilized in various experiments to estimate the simultaneity window [38], [39]. The SD, which indicates the dispersion of data around the mean for a Gaussian distribution, offers a more conservative estimate of the time interval for perceiving simultaneity due to its considerably narrower range compared to the 50% window [25]. In contrast, the FWHM, defined as the spectral width at 50% of the intensity of the maximum peak, calculated using (3), provides a broader perspective.

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

Specifically, when the maximum probability of simultaneity judgments does not reach unity, the simultaneity window estimated by the FWHM proves to be wider than that determined by the 50% criterion. Considering the present data, the SD is 473 ms (SEM = 49 ms), the 50% window is 1041 ms (SEM = 105 ms), and the FWHM is 1115 ms (SEM = 116 ms) for warm stimuli. For cold stimuli, the SD is 279 ms (SEM = 22 ms), the 50% window is 626 ms (SEM = 55 ms), and the FWHM is 658 ms (SEM = 51 ms).

V. Discussion

A. Principal Findings

To the best of our knowledge, the experiment described here, along with the one in our recent study [32], are the first to investigate the perception of thermal-tactile simultaneity, and in particular how these differ for warm and cold stimuli delivered concurrently with tactile stimuli. The substantial differences between warmth and cold when presented concomitantly with tactile stimuli are consistent with the known variations in the temporal properties of the thermal senses, in particular the different conduction velocities of afferent fibers innervating the receptors [40] and the relative locations of warm and cold thermoreceptors in the skin [9], as detailed in the Introduction.

These findings indicate that thermal and tactile stimuli do not need to be displayed simultaneously for the two stimuli to be perceived as being presented at the same time, that is, the PSS does not need to be zero. Provided that the time difference between the thermal and tactile stimuli is within the simultaneity window, they can still be perceived as being simultaneous. This implies that the timing of stimuli can be adjusted to maximize the likelihood that they will both be perceived, but at the same time perceptually synchronous. In studies of multi-somatosensory perception, it has been shown that the ability to perceive independent channels of communication can be influenced by the concurrent presentation of other sensory cues [8], [41]. In particular, when the peaks of a thermal stimulus coincide with the falling or rising edge of a vibration pulse, the perception of changes in skin temperature is masked. These changes do become perceptible, however, if a brief delay is introduced at the onset of the vibratory stimulus relative to that of the thermal stimulus [8].

B. Differences Between Warmth and Cold

For both warm and cold stimuli, the PSS shifted towards the thermal leading side. Specifically, to achieve the perception of simultaneity, warm stimuli needed to precede the tactile inputs by over 300 ms more than that for cold stimuli. These findings are consistent with the concept that the brain accommodates the differences in processing speed across modalities. Studies on audio-visual [42], [43], visual-tactile [44], and audio-tactile simultaneity [45], [46] have also shown that people perceive simultaneity when the sensory modality with the slower transmission speed precedes the modality with faster transmission. For audio-visual stimuli such as watching a person speak, simultaneity is maximal when the visual stimulus precedes the audio by 120 ms [47], although it has been reported that asynchronies can be detected at times as short as −27 and 38 ms [48]. For audio-tactile stimuli the point of subjective simultaneity is shifted towards audio delays of 7 ms (−13 to 28 ms) [46].

The width of the simultaneity window was much greater for warm than for cold stimuli. This disparity is likely because the sense of cold is better at detecting transient temperature change than the sense of warmth, as detailed in [16] and [49]. Therefore it is more challenging to pinpoint the onset of warm stimuli, a critical factor in the simultaneity judgment task which hinges on accurately comparing the onset of two stimuli. As a result, a larger temporal gap is necessary for participants to discern asynchrony in scenarios involving warm stimuli, resulting in a wider simultaneity window. When compared to the widths of the simultaneity windows for other crossmodal stimuli, the thermal-tactile simultaneity windows for both warm and cold stimuli are significantly wider. This suggests that participants encounter difficulties in making simultaneity judgments for thermal and tactile stimuli. One contributing factor to this phenomenon may be the distinct temporal profiles of the stimuli used. The tactile stimulus was a short 10 ms, 9.63 kPa pressure impulse that had a clear onset, in contrast to the thermal stimuli, which exhibited a rate of change of 2.5 °C/s for cold and 1.4 °C/s for warmth (see Fig. 5). These specific profiles were chosen to replicate the mechanical and thermal changes experienced during brief contact with a surface. Consequently, our findings regarding the PSS and the width of the simultaneity window are expected to mirror experiences of everyday touch. It is important to note that the present experiment employed passive touch for better control of timing. Further research is required to explore these phenomena in an active touch setting.

The participants' judgments of thermal-tactile simultaneity were much more variable when the concurrent thermal stimulus was warm as compared to cold as depicted in Figs. 6 and 7. It would appear that the increases in skin temperature were not as perceptibly salient as decreases in skin temperature and that the rates at which the skin cooled or warmed differed. The thresholds for detecting a change in temperature on the thenar eminence are 0.11 °C (at 1.9 °C/s) for cooling and 0.20 °C for warming (at 2.1 °C/s) [37]. At slower rates, between 0.1 and 0.3 °C/s, the rate of change in temperature has no effect on either warm or cold thresholds [33], but at faster rates (i.e., 1.4–3.9 °C/s) warm, but not cold, thresholds have been shown to increase [50]. In other contexts, such as measurements of warm and cold thresholds, it has been found that warm thresholds are consistently more variable than cold thresholds [51], [52], [53] The intensities of the warm and cold stimuli also differed in terms of the absolute difference from baseline skin temperature, at +5 °C and −7 °C respectively. However, Dufour et al. [9] have shown that even when the absolute differences from baseline temperature are identical, cold stimuli are perceived as more intense than warm stimuli, so matching absolute stimulus amplitude does not ensure similar perceived intensities. It is important to note that these findings relate to warm stimuli within the non-noxious thermal range, and that the point of perceived simultaneity may change when thermal stimuli are above 42 °C, which is the threshold for heat-pain.

C. Implications

These findings are relevant to the implementation of cutaneous displays in virtual reality (VR) and augmented reality (AR) environments, and in particular understanding the degree of user tolerance for delays in the sensory cues rendered. A lack of synchronization can result in a loss of a sense of immersion and feelings of cybersickness. The recent emphasis on developing metrics for assessing the quality of experience (QoE) of such environments in addition to the Quality of Service (QoS) has highlighted the importance of understanding the factors that impact the experience of the user [54]. In the context of VR environments, delays in the order of 3–60 ms have been proposed as acceptable for haptic cues, but there do not appear to be any data regarding acceptable user delays when incorporating both tactile and thermal cues in the VR environments [55].

VI. Conclusion

This study's findings reveal that in thermal-tactile simultaneity perception, the PSS is biased towards the thermal leading side, with the simultaneity window extending to 1041 ms for warm stimuli and 626 ms for cold stimuli. These window widths are significantly wider than those observed for other crossmodal stimuli, highlighting the remarkable capacity of the human brain to integrate thermal and tactile sensations despite the inherent delays in their arrival and processing times. This integration takes account of the distinct spatiotemporal characteristics of the two senses and results in a coherent perceptual experience within a relatively wide time window. Future research will investigate how the spatial arrangement of thermal and tactile stimuli affects simultaneity perception. Determining the optimal placement of multiple actuators on the skin is a significant design challenge for the development of cutaneous displays. In addressing these complexities, we aim to derive guidelines for the effective combination of thermal and tactile feedback, thereby enhancing the realism of object perception in virtual environments.

References

[1] F. McGlone, J. Wessberg, and H. Olausson, "Discriminative and affective touch: Sensing and feeling," *Neuron*, vol. 82, no. 4, pp. 737–755, May 2014, doi: 10.1016/j.neuron.2014.05.001.

[2] Y. Ujitoko, Y. Ban, and K. Hirota, "GAN-based fine-tuning of vibrotactile signals to render material surfaces," *IEEE Access*, vol. 8, pp. 16656–16661, 2020, doi: 10.1109/ACCESS.2020.2968185.

[3] L. A. Jones and A. Singhal, "Sensory interactions in cutaneous displays," in *Proc. IEEE World Haptics Conf.*, 2019, pp. 545–550, doi: 10.1109/WHC.2019.8816078.

[4] L. E. Williams and J. A. Bargh, "Experiencing physical warmth promotes interpersonal warmth," *Science*, vol. 322, no. 5901, pp. 606–607, 2008, doi: 10.1126/science.1162548.

[5] A. E. Block and K. J.. Kuchenbecker, "Softness, warmth, and responsiveness improve robot hugs," *Int. J. Social Robot.*, vol. 11, pp. 49–64, 2019, doi: 10.1007/s12369-018-0495-2.

[6] S. Gallo, L. Cucu, N. Thevenaz, A. Sengul, and H. Bleuler, "Design and control of a novel thermo-tactile multimodal display," in *Proc. IEEE Haptics Symp.*, 2014, pp. 75–81, doi: 10.1109/HAPTICS.2014.6775436.

[7] G.-H. Yang, K.-U. Kyung, M. A. Srinivasan, and D.-S. Kwon, "Quantitative tactile display device with pin-array type tactile feedback and thermal feedback," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2006, pp. 3917–3922, doi: 10.1109/ROBOT.2006.1642302.

[8] A. Singhal and L. A. Jones, “Perceptual interactions in thermo-tactile displays,” in *Proc. IEEE World Haptics Conf.*, 2017, pp. 90–95, doi: 10.1109/WHC.2017.7989882.

[9] A. Dufour, O. Després, T. Pebayle, and S. Lithfous, “Thermal sensitivity in humans at the depth of thermal receptor endings beneath the skin: Validation of a heat transfer model of the skin using high-temporal resolution stimuli,” *Eur. J. Appl. Physiol.*, vol. 120, pp. 1509–1518, 2020.

[10] F. McGlone and D. Reilly, “The cutaneous sensory system,” *Neurosci. Biobehavioral Rev.*, vol. 34, no. 2, pp. 148–159, 2010, doi: 10.1016/j.neubiorev.2009.08.004.

[11] A. D. Craig, K. Chen, D. Bandy, and E. M. Reiman, “Thermosensory activation of insular cortex,” *Nature Neurosci.*, vol. 3, no. 2, pp. 184–90, 2000.

[12] M. Guidotti, C. Beaurieux, P. Marionnaud, F. Bonnet-Brilhault, C. Wardak, and M. Latinus, “Skin type and nerve effects on cortical tactile processing: A somatosensory evoked potentials study,” *J. Neuriophysiol.*, vol. 130, no. 3, pp. 547–556, 2023, doi: 10.1152/jn.00444.2022.

[13] C. Maihofner, M. Kaltenhauser, B. Neundorfer, and E. Lang, “Temporo-spatial analysis of cortical activation by phasic innocuous and noxious cold stimuli- A magnetoencephalographic study,” *Pain*, vol. 100, pp. 281–290, 2002.

[14] A. B. Chatt and D. R. Kenshalo, “Cerebral evoked responses to skin warming recorded from human scalp,” *Exp. Brain Res.*, vol. 28, pp. 449–455, 1977.

[15] J. A. Leonard, “Tactual choice reactions: I,” *Quart. J. Exp. Psychol.*, vol. 11, no. 2, pp. 76–83, 1959, doi: 10.1080/17470215908416294.

[16] H.-N. Ho, K. Sato, S. Kuroki, J. Watanabe, T. Maeno, and S. Nishida, “Physical-perceptual correspondence for dynamic thermal stimulation,” *IEEE Trans. Haptics*, vol. 10, no. 1, pp. 84–93, First Quarter 2017, doi: 10.1109/TOH.2016.2583424.

[17] H. Fruhstorfer, H. Guth, and U. Pfaff, “Thermal reaction time as a function of stimulation site,” *Pflugers Archiv.*, vol. 335, 1972, Art. no. R49.

[18] D. Filingeri, “Neurophysiology of skin thermal sensations,” *Comp. Physiol.*, vol. 6, pp. 1429–1491, 2016, doi: 10.1002/cphy.c150040.

[19] I. Darian-Smith, “Thermal sensibility,” in *Handbook of Physiology: The Nervous System*, Bethesda, MD, USA: Amer. Physiological Soc., 1984, pp. 879–913.

[20] W. S. Cain, “Spatial discrimination of cutaneous warmth,” *Amer. J. Psychol.*, vol. 86, pp. 169–181, 1973.

[21] L. E. Marks and J. C. Stevens, “Spatial summation of warmth: Influence of duration and configuration of the stimulus,” *Amer. J. Psychol.*, vol. 86, pp. 251–267, 1973.

[22] P. W. Nathan and R. C. Rice, “The localization of warm stimuli,” *Neurology*, vol. 16, no. 6, pp. 533–533, 1966, doi: 10.1212/WNL.16.6.533.

[23] M. L. Simmel and A. Shapiro, “The localization of non tactile thermal sensations,” *Psychophysiol.*, vol. 5, no. 4, pp. 415–425, 1969, doi: 10.1111/j.1469-8986.1969.tb02841.x.

[24] L. A. Jones and H.-N. Ho, “Incorporating thermal feedback in cutaneous displays: Reconciling temporal and spatial disparities,” in *Proc. Int. Workshop Haptic Audio Interaction Des.*, 2022, pp. 48–58.

[25] J. Vroomen and M. Keetels, “Perception of intersensory synchrony: A tutorial review,” *Attention Perception Psychophysics*, vol. 72, no. 4, pp. 871–884, 2010, doi: 10.3758/APP.72.4.871.

[26] M. Keetels and J. Vroomen, “Perception of synchrony between the senses,” in *The Neural Bases of Multisensory Processes*, Boca Raton, FL, USA: CRC Press, 2012, pp. 147–178.

[27] M. Zampini, D. I. Shore, and C. Spence, “Audiovisual temporal order judgments,” *Exp. Brain Res.*, vol. 152, pp. 198–210, 2003.

[28] M. E. Altinsoy and S. Merchel, “Audiotactile feedback design for touch screens,” in *Proc. Int. Conf. Haptic Audio Interaction Des.*, 2009, pp. 136–144.

[29] M. E. Altinsoy, “Perceptual features of everyday push button sounds and audiotactile interaction,” *Acoustical Sci. Technol.*, vol. 41, no. 1, pp. 173–181, 2020.

[30] D. Brahimaj, M. Ouari, A. Kaci, F. Giraud, C. Giraud-Audine, and B. Semail, “Temporal detection threshold of audio-tactile delays with virtual button,” *IEEE Trans. Haptics*, vol. 16, no. 4, pp. 491–496, Fourth Quarter 2023.

[31] C. Park and S. Choi, “Perceptual simultaneity between vibrotactile and impact stimuli,” in *Proc. IEEE World Haptics Conf.*, 2023, pp. 148–155.

[32] T. Jodai, M. Terao, L. A. Jones, and H.-N. Ho, “Determination of the thermal-tactile simultaneity window for multisensory cutaneous displays,” in *Proc. IEEE World Haptics Conf.*, 2023, pp. 230–236, doi: 10.1109/WHC56415.2023.10224482.

[33] D. R. Kenshalo, C. E. Holmes, and P. B. Wood, “Warm and cool thresholds as a function of rate of stimulus temperature change,” *Perception Psychophysics*, vol. 3, pp. 81–84, 1968.

[34] D. Yarnitsky and J. L. Ochoa, “Warm and cold specific somatosensory systems: Psychophysical thresholds, reaction times and peripheral conduction velocities,” *Brain*, vol. 114, no. 4, pp. 1819–1826, 1991, doi: 10.1093/brain/114.4.1819.

[35] Y. Ujitoko, R. Tokuhisa, S. Sakurai, and K. Hirota, “Impact vibration source localization in two-dimensional space around hand,” *IEEE Trans. Haptics*, vol. 14, no. 4, pp. 862–873, Fourth Quarter 2021, doi: 10.1109/TOH.2021.3085756.

[36] D. M. Rowe, *CRC Handbook of Thermoelectrics*. Boca Raton, FL, USA: CRC Press, 2018.

[37] J. C. Stevens and K. C. Choo, “Temperature sensitivity of the body surface over the life span,” *Somatosensory Motor Res.*, vol. 15, pp. 13–28, 1998.

[38] A. Basharat, M. S. Adams, W. R. Staines, and M. Barnett-Cowan, “Simultaneity and temporal order judgments are coded differently and change with age: An event-related potential study,” *Front. Integrative Neurosci.*, vol. 12, Apr. 2018, Art. no. 15, doi: 10.3389/fnint.2018.00015.

[39] E. Van der Burg, J. Cass, and D. Alais, “Window of audio-visual simultaneity is unaffected by spatio-temporal visual clutter,” *Sci. Rep.*, vol. 4, 2014, Art. no. 5098, doi: 10.1038/srep05098.

[40] C. Leone et al., “Conduction velocity of the cold spinal pathway in healthy humans,” *Eur. J. Pain*, vol. 24, no. 10, pp. 1923–1931, 2020, doi: 10.1002/ejp.1640.

[41] Z. A. Zook, J. J. Fleck, and M. K. O’Malley, “Effect of tactile masking on multi-sensory haptic perception,” *IEEE Trans. Haptics*, vol. 15, no. 1, pp. 212–221, First Quarter 2022, doi: 10.1109/TOH.2021.3112509.

[42] C. Kayser, C. I. Petkov, and N. K. Logothetis, “Visual modulation of neurons in auditory cortex,” *Cereb. Cortex*, vol. 18, no. 7, pp. 1560–1574, 2008, doi: 10.1093/cercor/bhm187.

[43] M. Zampini, S. Guest, D. I. Shore, and C. Spence, “Audio-visual simultaneity judgments,” *Perception Psychophysics*, vol. 67, no. 3, pp. 531–544, 2005, doi: 10.3758/BF03193329.

[44] Y.-C. Chen, T. L. Lewis, D. I. Shore, C. Spence, and D. Maurer, “Developmental changes in the perception of visuotactile simultaneity,” *J. Exp. Child Psychol.*, vol. 173, pp. 304–317, 2018, doi: 10.1016/j.jecp.2018.04.014.

[45] T. Kaaresoja, S. Brewster, and V. Lantz, “Towards the temporally perfect virtual button: Touch-feedback simultaneity and perceived quality in mobile touchscreen press interactions,” *ACM Trans. Appl. Percep.*, vol. 11, no. 2, pp. 1–25, 2014, doi: 10.1145/2611387.

[46] M. E. Altinsoy, “Perceptual aspects of auditory-tactile asynchrony,” in *Proc. 10th Int. Congr. Sound Vib.*, 2003, pp. 3831–3838.

[47] N. F. Dixon and L. Spitz, “The detection of auditory visual desynchrony,” *Perception*, vol. 9, no. 6, pp. 719–721, 1980.

[48] D. J. Levitin, K. MacLean, M. Mathews, L. Chu, and E. Jensen, “The perception of cross-modal simultaneity (or “the Greenwich Observatory Problem” revisited),” in *Proc. Amer. Inst. Phys. Conf.*, 2000, pp. 323–329.

[49] A. S. Courtin, A. Delvaux, A. Dufour, and A. Mouraux, “Spatial summation of cold and warm detection: Evidence for increased precision when brisk stimuli are delivered over larger area,” *Neurosci. Lett.*, vol. 797, 2023, Art. no. 137050.

[50] A. Pertovaara and I. Kojo, “Influence of the rate of temperature change on thermal thresholds in man,” *Exp. Neurol.*, vol. 87, no. 3, pp. 439–445, 1985.

[51] L. M. Harding and A. R. Loescher, “Adaptation to warming but not cooling at slow rates of stimulus change in thermal threshold measurements,” *Somatosensory Motor Res.*, vol. 22, pp. 45–48, 2005.

[52] V. H. Lilliesköld and E. Nordh, “Method-of-limits; Cold and warm perception thresholds at proximal and distal body regions,” *Clin. Neuriophysiol. Pract.*, vol. 3, pp. 134–140, 2018.

[53] D. Filingeri, H. Zhang, and E. A. Arens, “Thermosensory micromapping of warm and cold sensitivity across glabrous and hairy skin of male and female hands and feet,” *J. Appl. Physiol.*, vol. 125, no. 3, pp. 723–736, 2018.

[54] I. Wechsung and K. De Moor, “Quality of experience versus user experience,” in *Quality of Experience: Advanced Concepts, Applications and Methods*, Cham, Switzerland: Springer Int. Publishing, 2014, pp. 35–54.

[55] S. Van Damme, M. Torres Vega, and F. De Turck, “Human-centric quality management of immersive multimedia applications,” in *Proc. IEEE 6th Conf. Netw. Softwarization*, 2020, pp. 57–64, doi: 10.1109/NetSoft48620.2020.9165335.

Takuya Jodai received the bachelor's degree in design in 2023. As a student, he focused on the integration of tactile and thermal sensations on the skin and the elucidation of their interactions, as well as the simultaneity of multimodal sensations. He joined the Faculty of Design, Kyushu University, Fukuoka, Japan, where he is currently a Technical Staff member with Ho Haptics Lab. In addition to his role with Kyushu University, he is also a Lead Designer with Adora Inc., Tokyo, Japan. His research interests include the study of haptic and thermal perception, the integration of tactile sensations on the skin, and the exploration of multimodal sensory interactions.

Lynette A. Jones (Fellow, IEEE) received the Ph.D. degree from McGill University, Montreal, QC, Canada. She is currently a Senior Research Scientist with the Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA. Her research interests include understanding how the skin senses the environment and determining how it can be used as a medium of communication. She also studies thermal perception, in particular examining how thermal feedback can be incorporated in multisensory displays. She was the Editor-in-chief of the World Haptics Conference Editorial Board from 2008 to 2011 and the Editor-in-Chief of IEEE TRANSACTIONS ON HAPTICS from 2014 to 2019.

Masahiko Terao received the Ph.D. degree from Kwansei Gakuin University, Hyogo, Japan, in 2011. He was a Research Fellow of the Japan Society for the Promotion of Science and was a Postdoctoral Fellow with The University of Tokyo, Tokyo, Japan. Since 2015, he has joined the Research Institute for Time Studies, Yamaguchi University, Yamaguchi, Japan. He is an expert in the visual system, with a particular interest in the spatial-temporal properties of vision. His research focuses on understanding how the brain integrates multiple sensory inputs to reconstruct the real world within the brain. To investigate this topic, he employs a multidisciplinary approach, including psychophysics, brain imaging, and virtual reality.

Hsin-Ni Ho (Member, IEEE) received the Ph.D. degree from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 2006. From 2007 to 2021, she was a Research Scientist with NTT Communication Science Laboratories, Kyoto, Japan. She is currently an Associate Professor with the Faculty of Design, Kyushu University, Fukuoka, Japan. She is an expert in thermal perception and thermal displays. Her research interests include understanding how the brain processes cutaneous inputs and integrates them with other sensory inputs to form a unified perception of touch events. She also studies the role of touch in social interactions. The primary goal of her work is to support the development of haptic interfaces designed for sharing tactile experiences and enhancing affective communication. She was a discovery Editor of the Journal "*Temperature*" from 2015 to 2021.