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RESEARCH ARTICLE

ThermoSurf: Thermal Display Technology for Dynamic and Multi-Finger Interactions

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ABSTRACT Thermal feedback has been proven to enhance user experience in human-machine interactions. Yet state-of-the-art thermal technology has focused on the single finger or palm in static contact, overlooking dynamic and multi-finger interactions. The underlying challenges include incompatible designs of conventional interfaces for providing salient thermal stimuli for such interactions and, thereby, a lack of knowledge on human thermal perception for relevant conditions. Here we present the ThermoSurf, a new thermal display technology that can deliver temperature patterns on a large interface suitable for dynamic and multi-finger interactions. We also investigate how user exploration affects the perception of the generated temperature distributions. Twenty-three human participants interacted with the device following three exploration conditions: static-single finger, dynamic-single finger, and static-multi finger. In these experiments, the individuals evaluated 15 temperature differences ranging from −7.5 °C to +1.5 °C with an initial temperature of 38 °C. Our results showed that human sensitivity against thermal stimuli is significantly greater for static-single finger contact compared to the other tested conditions. In addition, this interaction type resulted in higher thermal discrimination thresholds than the ones reported in the literature. Our findings offer new perspectives on providing salient and consistent thermal feedback for future tactile interfaces.

INDEX TERMS Human–machine interaction, human thermal perception, thermal display, thermal feedback.

I. INTRODUCTION

Touch constitutes a substantial part of human interactions with their surrounding objects and other people. Nonetheless, humans spend considerable time in the virtual while interacting with smartphones, tablets, or computers. Yet, these interactions are far from natural as these devices are not well equipped to display effective tactile feedback.

Recent advances in the field of surface haptics showed the possibility of enabling tactile cues of friction and vibration on touchscreens [1]. However, displaying thermal cues on these devices has been rather overlooked, despite their importance in everyday interactions. Previous research showed evidence that thermal feedback has a significant role in conveying emotions [2], [3]. It can also improve realistic rendering of material properties [4], [5] and enhance user performance and comfort [6], [7], [8]. Imagine your smartphone could deliver effective thermal feedback. During a long-distance call with a loved one, you could lay your hand on the screen, and the person on the other side could feel the warmth of your skin besides perceiving your words and facial expressions. Or picture a game in which you run through a desert, and your teammate hands you an ice-cold beverage. The game could feel more immersive if this sudden temperature change is felt on your skin.

Creating such thermal effects on prevalent information displays requires achieving several features (e.g., transparent screen, large interaction area, low power consumption, easy integration, compact design, suitability for localized, distributed, and multi-finger interactions, ability to deliver multi-modal tactile feedback [1]) desired for surface haptic devices. Most state-of-the-art thermal displays use Peltier devices, which rely on electrical current to generate or remove heat [5]. These devices are generally closed-loop

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controlled, and their excessive heat is dissipated through heat sinks [9], [10], [11] as well as active fluid cooling systems [12], [13]. On such thermal display designs, the users touch either directly the surface of the Peltier elements [9], [10], [11] or the material that is heated or cooled by the Peltiers placed below [14]. As the commercially available Peltier devices are made of opaque ceramic substrates, these displays are not transparent, hence not suitable for concurrent visual feedback. More importantly, common thermal displays have a small interaction area that prohibits the capability of localized, distributed, dynamic, or multi-finger interactions.

Recently, two approaches were proposed to provide a large interaction area for thermal displays. The first technique relies on using individual heating elements (e.g., resistive wires) and liquid cooling to distribute temperature over a flat surface [15]. These elements are placed on a grid to attain localized thermal patterns by applying current to only the specified grid points. However, this approach does not offer power efficiency or compactness and does not ease integration and control. The second method uses multi-layered anisotropic materials whose layers contain a single heat beam. When multiple layers in various orientations are stacked together, the combined beams can create various thermal patterns [16]. This approach provides low power consumption and compactness but requires a complicated manufacturing process. Moreover, neither of the methodologies offers transparency, making them hard to integrate with the current touchscreens.

Probably due to the design challenges explained above [13], the state-of-the-art research on human thermal perception has mainly focused on the single finger or palm in static contact with a natural material or a thermal display [6], [9], [10]. However, real-life interactions with objects also include sliding and/or multi-finger contact, which affects the resulting finger-surface contact dynamics [17] and possibly the thermal sensitivity. Thus, our knowledge of how thermal perception is affected by these conditions is limited. This lack of knowledge also restricts the effective design and implementation of thermal displays. For example, previous research on static contact [13] showed that human thermal sensation exhibits substantial spatial summation and poor spatial acuity (see Section II for a detailed overview of human thermal perception). Therefore, having a dense array of thermal stimulators [13] may not be necessary to develop a functional interface. Similarly, effective delivery of thermal stimuli may require significant adjustments for different touch interactions since contact variables such as pressure and finger contact area highly affect the human thermal perception [18], [19], [20], [21]. Therefore, a thorough investigation is necessary to understand how user exploration affects human thermal perception.

In this study, we designed the ThermoSurf, a new thermal display that can generate thermal patterns on a large interaction area. Our minimalist design relies on using only four commercially available Peltier heating/cooling devices positioned along the edges of a thermally conductive plate to generate a temperature distribution on the surface. Thanks to the careful selection of the plate material and dimensions, our compact thermal display can generate thermal patterns suitable for various user interactions without the need for high power. Although we used stainless steel for convenience, preliminary analyses showed that our methodology has potential to be applied on electronic screens if a transparent surface material with similar thermal properties (e.g., aluminum oxynitride, sapphire) is chosen. Using our thermal display, we conducted human experiments where 23 individuals explored the display with three different conditions (static-single finger, dynamic-single finger, or static-multi finger). During those interactions, the participants evaluated 15 temperature differences ranging from $-7.5\,°C$ to $+1.5\,°C$, where the initial temperature was set to $38\,°C$.

The paper begins with an overview of human thermal perception and the mechanisms underlying thermal information processing (Section II). Then, the details of the thermal display are explained together with the simulations supporting the design choices (Section III). After that, we present the results of the human subject studies following the methods used to perform the experiments (Section IV). Finally, we discuss our findings in Section VI.

II. BACKGROUND: HUMAN THERMAL PERCEPTION

Cold and warm thermoreceptors, which are located in the epidermal and dermal skin layers, sense changes in skin temperature. Cold receptors fire to the central nervous system in a temperature range of 5-43 °C with peak intensities at around 25 °C skin temperature. Warm receptors fire between the temperatures of 30 °C and 50 °C with a maximum sensitivity at 45 °C. In the neutral zone, between 30 °C and 36 °C, both receptors fire at an equal rate, and no thermal sensation is perceived [22]. When the temperature falls below 18 °C or above 45 °C, the activation of nociceptors (pain receptors) causes a sensation of pricking (too cold) or burning (too hot), respectively [23]. However, these temperature thresholds can be different for each person; some people already feel pain in the margins above or below these limits [24].

Since thermoreceptors sense changes in the skin temperature and not the temperature of the object, the perceived sensation depends on the amount and rate of the transferred thermal energy between the skin and the object. This energy depends on various variables, such as the heat capacity of the material and the initial skin temperature. A thermally conductive material alters skin temperature quicker, and therefore it is felt cooler or warmer than a thermally insulating material, even if they are both at the same temperature [22].

Human thermal perceptual sensitivity is affected by skin temperature and its rate of change as well as by stimulation area and location [21]. Skin thickness, however, does not influence the thresholds for cold and warm stimuli [25]. An earlier study by Stevens and Choo [18] found the just noticeable difference (JND) of the lips as about $-0.03\,°C$ at a temperature change rate of $-1.9\,°C/s$, and this value was about +0.03 °C at a rate of +2.1 °C/s. For the same rates of change, the temperature JNDs on the toe for cooling and warming were −1.8 °C and +5.6 °C, respectively. Under the same circumstances, the JNDs for the fingertips were reported as −0.6 °C for cooling and +0.9 °C for heating [18]. These values were determined for the participants aged from 40 to 60 and grew with increasing age. Changing the adapting skin temperature (the initial temperature with respect to which the difference is calculated) within the range of 25-40 °C also affects sensitivity [20]. Moreover, a decrease in sensitivity is observed when the temperature rate of change drops below 0.1 °C/s and the skin temperature stays within the neutral zone (30-36 °C). As a result, a temperature difference up to 5 °C can go unnoticed [21].

Another interesting aspect of human thermal perception is spatial summation, which leads to poor localization [22]. Upon temperature change, the intensity over the stimulated skin area is integrated [13], resulting in limited discrimination of two different thermal cues on the same finger [26]. This characteristic also gives rise to the 'synthetic heat illusion' shown by Green [24]. That illusive effect occurs when the outer two of three stimulators touching adjacent fingers are heated. In such a case, the middle finger also feels heated due to spatial summation.

Human thermal perception exhibits temporal features, distinctive from other senses. For instance, a time delay is present since the change of temperature within the skin is sensed, but not the temperature of the object. Hence, the time required to discriminate two materials based on temperature is longer than the discrimination duration based on hardness. Distinguishing a soft and a hard object takes about 400-500 ms, while the duration to differentiate two objects made of copper and wood based solely on their thermal properties averages at 900 ms [22].

Humans can identify various temporal thermal patterns [27]. For instance, a study conducted by Singhal and Jones [28] showed that six different patterns applied on the right index and middle finger can be recognized with a mean accuracy of 80%. That study also showed a square wave temperature input was discerned more successfully than a single step or a linearly varying input, implying that humans perceive faster changes in temperature more effectively than slower ones. Later, Ho and Jones [4] also found that humans are able to distinguish two different materials using their index fingers entirely based on thermal cues if the difference between thermal material properties is large enough. In another study, temperature-based identification of various synthetic and real materials is compared, and no significant difference was observed between the two types [5].

III. THERMAL DISPLAY DESIGN

In this study, we aimed to design a new tactile display that can deliver thermal patterns on a large interaction area suitable for dynamic and multi-finger interactions. We also targeted a system that is power efficient, compact, easy to integrate, and potentially transparent for multi-modal interactions.

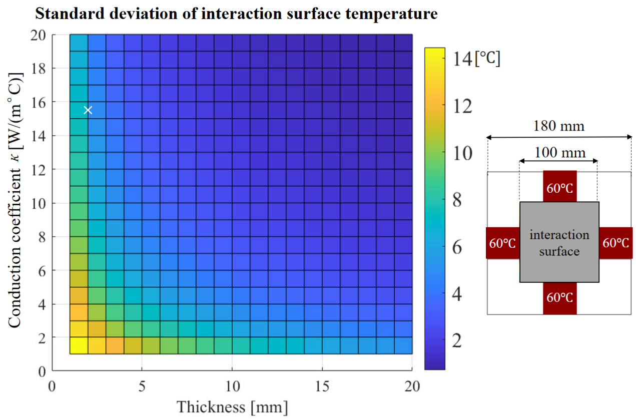


FIGURE 1. Standard deviation of interaction surface temperature as a result of a parametric sweep using stationary multiphysics FE simulations. The input temperature of each four Peltiers placed along the edges of the display surface was set to 60 °C. The selected material thickness and conduction coefficient for the final design are indicated with a white marker '×'.

Based on these design goals, we decided on a 100 mm×100 mm interaction surface, on which users can explore thermal patterns created by four Peltier devices placed along the edges of the display surface (see the small illustration on the right in Fig. 1). This configuration allows enough space for various user interactions and creates perceivable thermal patterns by activating different Peltiers. For this design, four commercially available 40×40 × 3.8 mm Peltiers (QC-127-1.4-8.5AS, Quickcool) with high bandwidth temperature generation capability were selected; therefore, a minimum of 180 mm×180 mm display area was required for sufficient interaction space.

The thickness and surface material of the display were chosen by conducting finite element (FE) analyses using the COMSOL Multiphysics® software. These simulations justified the parameter values selected to attain distinct steady-state thermal patterns. The transient thermal response of the display was not considered. For the simulations, the ambient temperature (T_a) was set as 20 °C. The heat flux from the surface to the surrounding air was simulated using a convective heat flux over a horizontal plate. The convection coefficient was assigned by COMSOL based on natural convection for the external air pressure of 1 bar. Radiation was assumed to be negligible.

The two most important variables governing the steady-state heat diffusion through the material are the thickness and the conduction coefficient (κ). Hence, we systematically varied the values of these two variables to test their combined effects on the temperature distributions at the interaction surface while keeping the other variables constant. We selected the standard deviation of the average surface temperature as the metric indicating the temperature variability. The mean surface temperature was calculated by averaging temperature values at 81 nodes evenly distributed over the entire surface. We considered the condition where all four Peltiers were set to 60 °C, the maximum stable

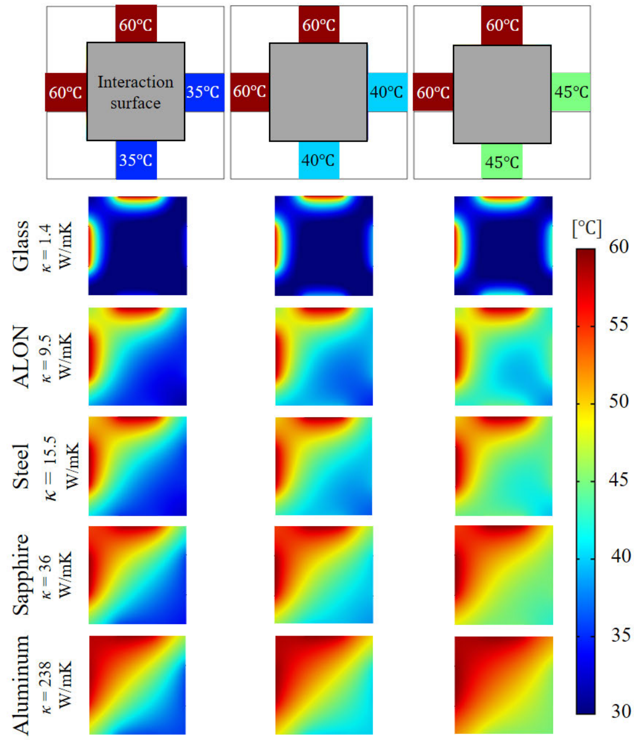


FIGURE 2. **Sample steady-state thermal distributions obtained by multiphysics FE simulations by using glass, ALON, stainless steel, sapphire, and aluminum surfaces with the same thickness (2 mm) and setting different input temperatures for Peltiers. Note that, glass, ALON, and sapphire are transparent materials.**

temperature that can be obtained with these devices. The readers can refer to [29] for more details on the FEM simulations.

Figure 1 shows the result of the parametric sweep simulations. A very low standard deviation signifies a uniform temperature distribution, implying that the entire interaction surface has almost the same temperature. On the other hand, a very high standard deviation indicates that there is not enough heat distribution to create perceivable thermal patterns on the overall interaction surface. Therefore, a thickness-conductivity combination resulting in a mid-standard deviation value is necessary for our application. Hence, as the display structure, we selected a 2 mm-thick stainless steel (κ = 15.5 W/mK) plate that was available in our lab.

Although we used stainless steel for convenience, our simulations demonstrate that this methodology can also be applied to electronic visual displays by selecting a transparent surface material with optimal conductivity and thickness. To highlight this opportunity, we conducted another set of FE simulations for the same display surface dimensions, three different input temperature combinations of Peltier elements, three transparent materials (glass, ALON, sapphire), and two non-transparent materials (stainless steel and aluminum). The results presented in Fig. 2 indicate that thermal distributions similar to the ones generated with stainless steel can be attained with sapphire or ALON. The three temperature

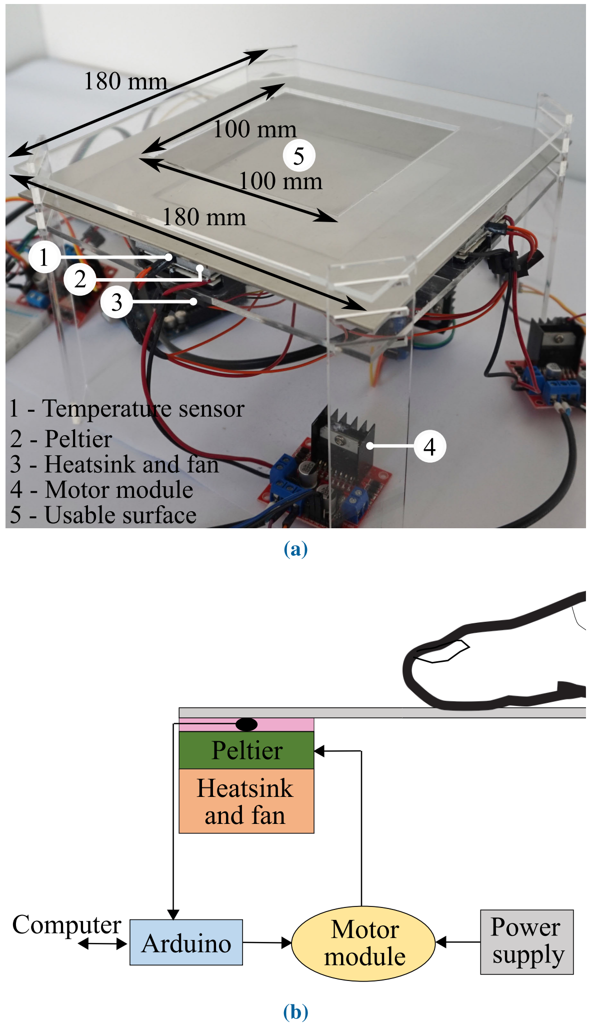


FIGURE 3. **(a) The custom-designed thermal display. (b) A schematic representation of a single Peltier connection. The temperature sensor (represented as a black ellipse) is placed between stainless-steel surface and Peltier via thermal paste.**

distributions obtained for the stainless steel surface were also used for the psychophysical experiments; see Section IV for more details.

Our final display (see Fig. 3a) consists of four 40×40 × 3.8 mm Peltier devices (QC-127-1.4-8.5AS, Quickcool) each connected to a motor module (1573541, Joy-it), which allows the Peltiers to get enough current input. The motor modules are controlled via a microcontroller (Arduino Mega 2560, Arduino). The Peltiers are powered by two external power supplies (ES 030-05, Delta Elektronika). Four temperature sensors (MCP9701A-E/TO, Microchip), one per Peltier, were placed between the Peltiers and a 180 × 180×2 mm stainless steel plate. The output of the sensors is processed via another microcontroller (Arduino Uno, Arduino). Both microcontrollers were controlled by a laptop (Elitebook 2560p, HP). The bottom side of each Peltier was attached onto a heatsink and fan combination (CEBF0140401605-00, Malico) using thermal tape. A schematic representation of a single Peltier connection is given in Fig. 3b. Moreover, extra fans (TA350DC, Nidec Beta V, OD6025-24HSS, RSPro) were used to cool the whole experimental setup.

The thermal display is controlled via open-source Arduino IDE software. A closed-loop PID control ensures precise and accurate temperature control of the Peltier devices. A graphical user interface (GUI) designed via Processing (Version 4.0) permits controlling the temperature of each individual Peltier. This device has been approved by the Health, Security, and Environment advisor of TU Delft.

IV. PSYCHOPHYSICAL EXPERIMENTS

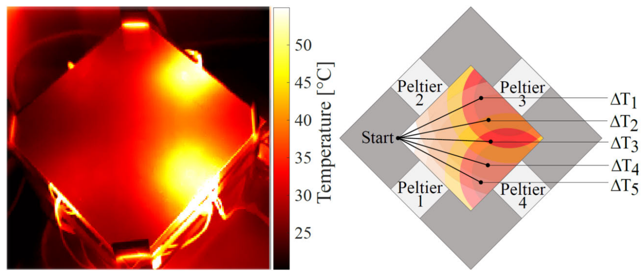
We conducted psychophysical experiments to investigate the perception of thermal patterns generated via ThermoSurf. The participants were asked to employ a specified interaction (static-single finger (SS), dynamic-single finger (DS), static-multi finger (SM)) and explore our custom-designed thermal interface. Then, they reported whether they felt a thermal difference between the two specified locations.

Eleven women and twelve men within the age interval of 20-31 participated in the study. All participants were right-handed. The experiments were conducted based on the Declaration of Helsinki, and all participants gave informed consent. This study was approved by the Human Research Ethics Committee of TU Delft with case number 1988.

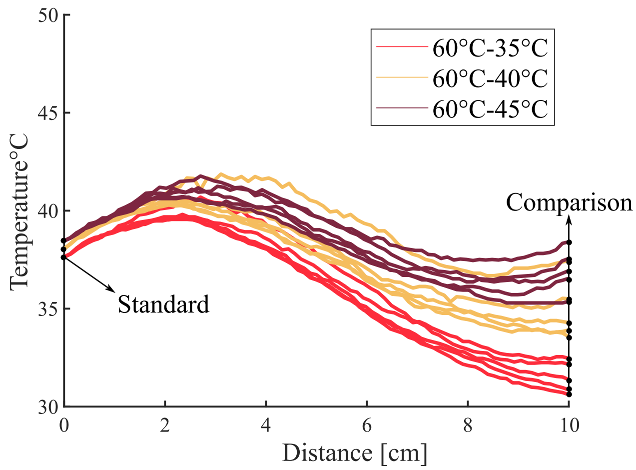
In these experiments, we used our custom-designed thermal display explained in Section III. Before the experiments, the participants were trained using a scale (80810018, HEMA) to keep a constant exploration force of 1.5 N. During the experiments, the participants wore headphones (HA-RX500, JVC); and they entered their answers using a keyboard (SK140, HAMA). A thermal camera (FLIR E75, InfraTec) and its embedded software (ResearchIR 4, FLIR) were used to measure the temperature of the generated thermal patterns.

The stimulus was the temperature difference between two locations (standard and comparison) of the thermal display surface. The users perceived these temperature differences, ΔT, by exploring different paths over the steady-state thermal distributions generated on the display surface. Figure 4a exemplifies thermal camera measurement over the display surface for one tested distribution (left) and visualizes five corresponding stimuli considered in the psychophysical experiments (right). In total, we used three steady-state thermal distributions in our experiments; see Fig. 2 for the input temperatures of each Peltier and simulated thermal distributions corresponding to the stainless steel surface. The thermal camera measurements showed that the display reached a steady state in approximately 10 min.

As the adapting temperature influences how humans perceive temperature [20], the standard temperature was kept constant at ∼38 °C throughout a set of trials. The spatial distance between the standard stimulus and comparison stimulus was set as 10 cm. By measuring the surface temperature using a thermal camera, 15 stimuli ranging from $\Delta T = -7\,°C$ to $\Delta T = 0\,°C$ were selected for the experiments (check Fig. 4b). To minimize the influence of the rate of temperature change during dynamic exploration, all stimuli were chosen such that their temperature variations had similar trends. The temperatures across the chosen thermal patterns were within the non-painful range (18-45 °C) inside the interaction area of the display [23].



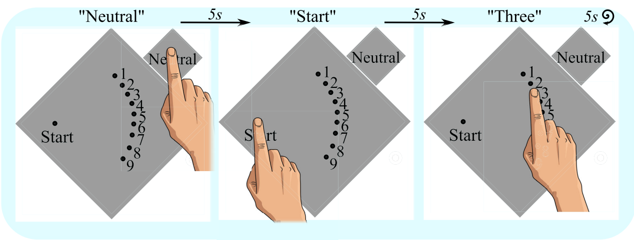
(a)



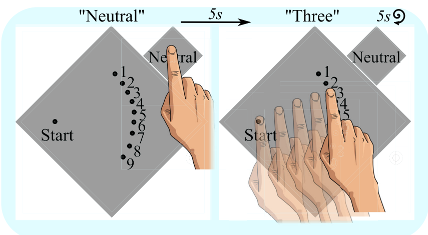
(b)

FIGURE 4. (a) Example thermal camera measurement for one tested steady-state thermal distribution (the input temperatures for the Peltier pairs 1-2 and 3-4 are 60 °C and 35 °C, respectively) and visualization of five corresponding stimuli (temperature differences, ΔT). (b) Temperature variation across all tested stimuli; the left and right legend entities correspond to the input temperatures of the Peltiers 1-2 and 3-4, respectively.

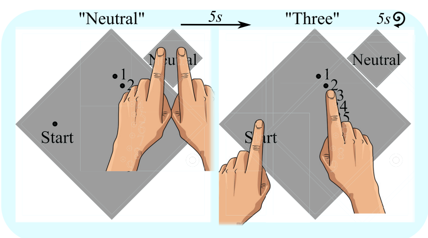
Research has shown that a rate of change below 0.1 °C/s decreases the thermal perception sensitivity [13]. Hence, based on the smallest tested temperature difference ($\Delta T = 0.5\,°C$), the minimal exploration time was calculated as 5 s. Therefore, each contact with the thermal display lasted 5 s for all exploration conditions. This duration was also sufficient for static exploration since humans can distinguish between materials based on thermal properties within 900 ms [22]. The force applied by the participants was maintained at 1.5 N based on previous research stating this amount to be optimal for the thermal exploration of a texture [30]. This force magnitude was found to maximize the change in temperature as a function of contact area and force, without unnecessarily fatiguing the hand [19]. To control the initial skin temperature, the participants touched a stainless steel



(a) Static-Single finger exploration (SS)



(b) Dynamic-Single finger exploration (DS)



(c) Static-Multi finger exploration (SM)

FIGURE 5. Visualization of experimental procedure for a single experimental trial per condition. In this example, the comparison stimulus is at location "three".

slab at room temperature for 5 s before the experiment. This duration was selected based on a preliminary test.

Prior to the experiments, the participants washed their hands (with water and soap) and dried them at room temperature. Then, they watched an instruction video and completed a training session. During the practice, the participants familiarized themselves with the experimental procedures and exercised keeping the pressing force at 1.5 N.

In the experiments, the task was to compare the perceived temperature of a standard stimulus marked as 'start', to a comparison stimulus, which was indicated on the thermal display by a number ranging from 1 to 9 (see Fig. 5). After each trial, the participant answered 'yes' if they perceived a thermal difference and 'no' otherwise.

An audio sequence played on headphones provided guidance during the experiment. The beginning of each trial was indicated by a audio cue. Upon hearing this sound, the participants were instructed to place their index finger on a piece of steel at room temperature to neutralize their skin temperature. Afterward, depending on the condition, the procedure continued as follows:

- For the SS condition, the participant was instructed to place their index finger first on the 'start' position and keep it there for 5 s until they heard another sound cue. Then, they were asked to raise their finger, put it on a specified location, and keep it there for 5 s until the next sound cue.
- For the DS condition, the participant was instructed to put their index finger on the 'start' position and immediately start to move it to a specified location while continuously touching the display, aiming for a total exploration time of 5 s.
- For the SM condition, the participant was asked to maintain their left index finger on the 'start' location and the right one on a specified location for a total of 5 s.

After 25 trials, another beep indicated the end of the set. A visual representation of the procedure is given in Fig. 5.

The experiment was conducted in three sessions. In each session, the participant explored a single steady-state thermal distribution using all three exploration conditions, which were separated by 15 min breaks that allowed the participant to relax and the display to reach a new thermal equilibrium. Each steady-state thermal distribution contained five stimuli (temperature differences) repeated five times per participant in random order, resulting in a set of 25 comparisons. During these 25 trials, the participant followed only one exploration condition. Before each set, the experimenter instructed the participant about the exploration to be performed. This process was repeated for all three steady-state distributions in arbitrary order. The entire procedure consisted of 225 trials (5 stimuli $\times$ 5 repetitions $\times$ 3 exploration conditions $\times$ 3 steady-state distributions). The total experiment time was about 125 minutes including instructions, training, and two breaks.

The generated thermal patterns varied slightly on different days due to external factors such as outside temperature differences, humidity, and airflow. Hence, we also measured the display surface temperature during the experiments using the thermal camera. This measurement allowed us to monitor the heat distribution and time frame until reaching the steady state and to determine the exact temperature differences explored by each participant. The emissivity of the thermal display was calibrated using a thermocouple ($\epsilon = 0.18$), and all measurements were conducted in a dark room to minimize the effect of external light. The collected thermal images were analyzed using the embedded software of the camera.

V. RESULTS

The percentages of correctly perceived temperature differences were analyzed for both intended and measured cases; see Figs. 6 and 7, respectively.

The results for the intended temperature differences (ΔT) were calculated for each participant and then averaged over all 23 participants (see [29] for the breakdown of individual results). The number of ΔT values with mean correct discrimination percentage above 50% was 12, 4, and 3 for SS, DS, and SM conditions, respectively. A generalized

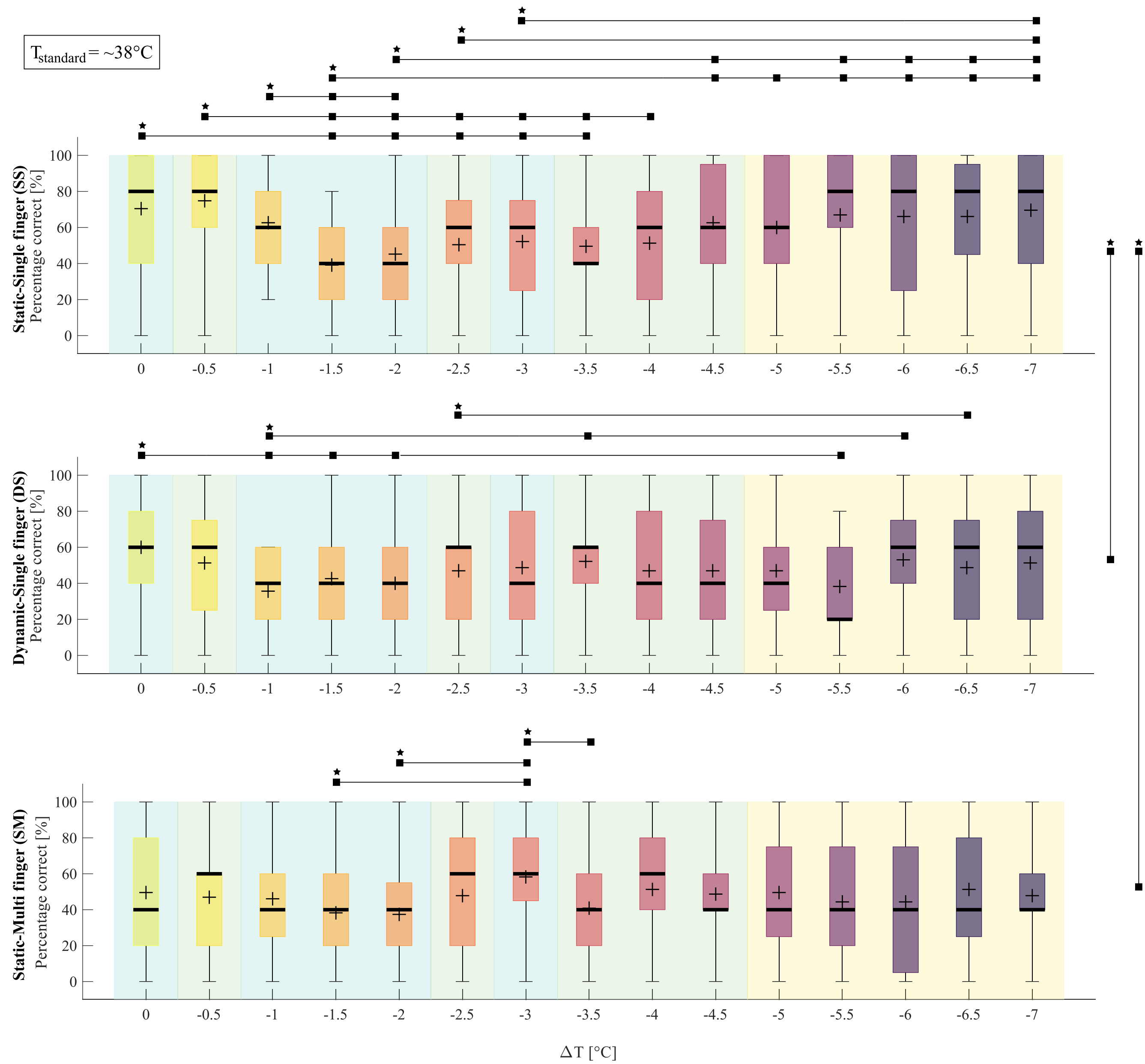


FIGURE 6. The percentage of correct answers for each *intended* temperature difference. The stimuli applied in a single steady-state distribution are indicated with color-coded background. The statistically significant *($p < 0.05$)* pairwise differences are marked with ⋆, whereas the means are depicted with +.

linear mixed model (GLMM) was created to test the effect of the exploration condition and temperature difference on the thermal perceptibility of the stimuli set. This method was selected because each condition was repeated for each participant and the data violated the normality assumption. Both exploration condition ($F_{2,22} = 17.999, p < 0.001$) and ΔT ($F_{14,22} = 2.523, p = 0.002$) significantly affected the perceived temperature difference. A Fisher's LSD post-hoc test revealed the significantly higher performance attained with a single static finger, compared to using a single finger in dynamic exploration ($p < 0.001$) or using both fingers in static state ($p < 0.001$). The pairwise comparisons between temperature differences for each exploration condition can be found in Fig. 6.

As the measured ΔT's varied among participants, the results were grouped into bands corresponding to twice the JNDs for human thermal perception ($-0.3\,°C$) determined in an earlier study [18]. The bands that did not include all conditions were removed from the analysis. Moreover, the data of the participants represented in a single band more than once were averaged, and the data were treated as missing for the bands in which all participants were not present. The number of ΔT values with mean correct discrimination score percentage above the chance level ($> 50\%$) was 12, 6, and

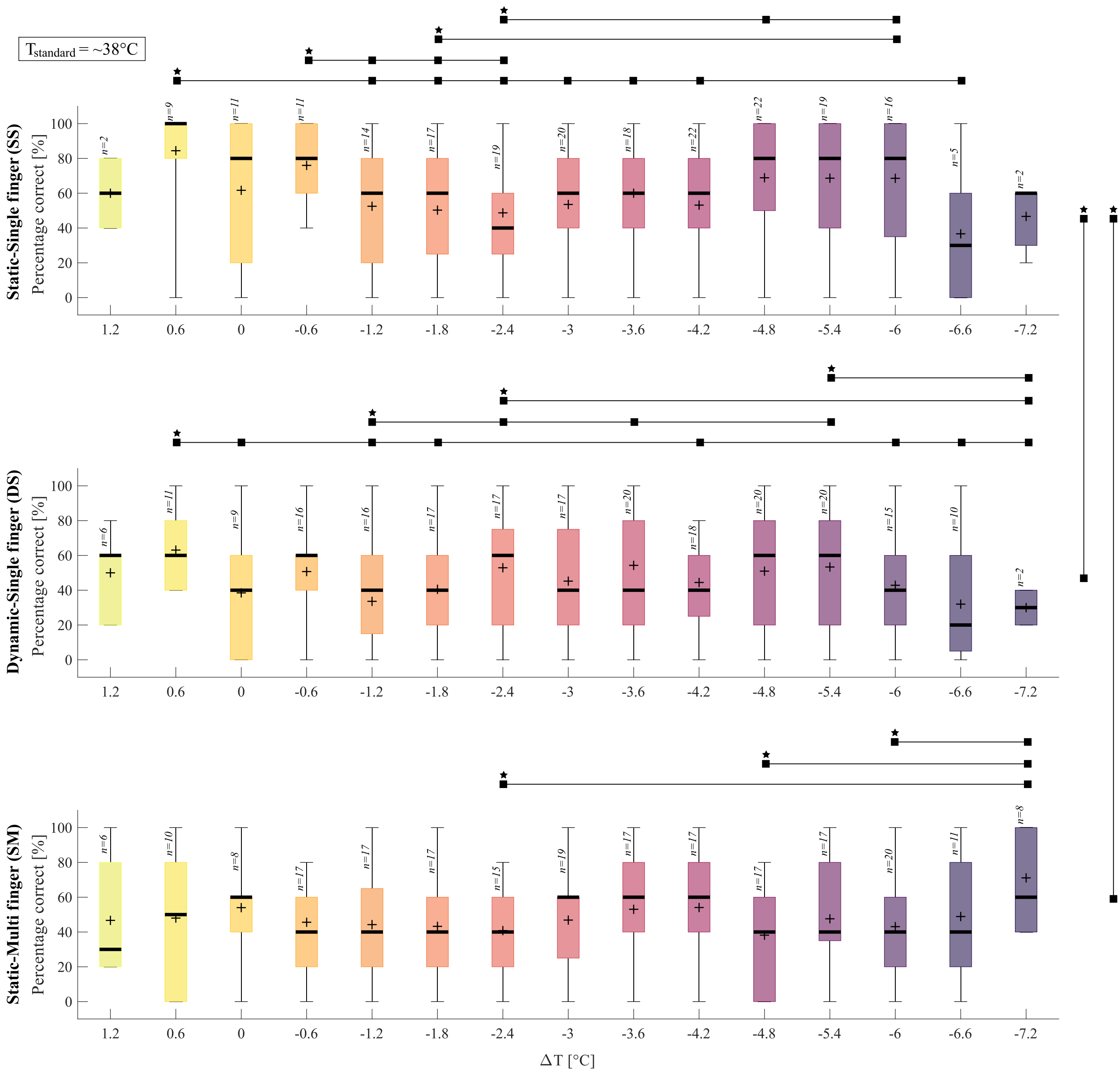


FIGURE 7. The percentage of correct answers for each ***measured*** temperature difference. The results were grouped per temperature interval corresponding to twice the human perception JND for cooling measured by Stevens & Choo (width=0.6°C [18]). The statistically significant ***(p < 0.05)*** pairwise differences are marked with ⋆, whereas the means are depicted via +. The corresponding sample sizes ***n*** are shown above each box plot.

4 for SS, DS, and SM conditions, respectively. A GLMM analysis showed that user exploration significantly affected the perceived temperature differences ($F_{2,22} = 8.484$, $p < 0.001$), whereas ΔT had no significant effect ($F_{14,22} = 1.303$, $p = 0.200$). A Fisher's LSD corrected post-hoc analysis showed that SS condition was different than DS ($p < 0.001$) and SM ($p = 0.004$). The pairwise comparisons of temperature differences are depicted in Fig. 7.

VI. DISCUSSION

In this study, we presented ThermoSurf, a new thermal display technology for dynamic and multi-finger interactions. Using our device, we investigated the influence of user exploration on the human perception of thermal patterns. We performed human experiments in which the participants were asked to report whether they felt a perceptual difference between two thermal stimuli. Each participant performed this task using three different types of exploration: static-single finger (SS), dynamic-single finger (DS), and static-multi finger (SM).

Our results show that the sensitivity of perceiving thermal patterns is significantly higher for static exploration than for dynamic ones. This outcome is aligned with the findings of a recent work, which showed that the friction perceived during dynamic exploration of a glass surface can be modulated by increasing the surface temperature without causing noticeable thermal cues [31]. That study reported that even a temperature difference of as large as 18°C could be unnoticed. One possible explanation for this phenomenon could be the reduced fingertip contact area during sliding [32] since stimulating a smaller skin area also decreases thermal sensitivity [21]. Another reason could be that thermal perception is masked by the perceived frictional cues during dynamic exploration. For example, Singhal and Jones [9] found that recognition accuracy of certain thermal cues decreased when vibrotactile pulses were simultaneously applied to the thenar eminence.

During static exploration, using a single finger results in a significantly better discrimination performance compared to multi-finger interactions. This behavior could be explained by spatial summation that occurs when multiple body sites are stimulated simultaneously. For example, Rózsa and Kenshalo [33] simulated either one forearm or both forearms simultaneously with a cooling stimulus and showed that detectability was superior for the latter, indicating spatial summation. Later, Yang et al. [26] applied two thermal stimuli with a large temperature difference to two skin spots at once and found that participants failed to identify their actual locations. The extent of this effect depends on body sites as well as the distance between the cues.

The selected thermal differences did not significantly affect the discrimination performance. This result contradicts previous research regarding human thermal thresholds for static-single-finger exploration. Nonetheless, there is a visible increasing trend in the correct percentage scores above the chance level from -4.8 to -6 °C in SS exploration, indicating that these temperatures are reliably felt (check Fig. 7). However, this value diverges from the previously found discrimination threshold (JND) reported by Stevens and Choo [18]. Their JND for cooling was measured as -0.3 °C in case of static temperature perception for participants aged 18 to 28. This difference could be explained by the methodological factors that differ between the two studies. Stevens and Choo [18] measured the thresholds for warming and cooling stimuli having a constant rate of change from an initial temperature of 33°C. During their experiments, the participants kept their fingers on the thermal stimulator. In our case, the participants felt an instant temperature difference compared to the standard stimulus (38°C). However, research by Gerr and Letz [34] used a methodology similar to our experimental design; the participants were asked to explore two thermal plates using their index fingers and indicate if a temperature difference was felt. The first plate was maintained at 25°C, and the other one's temperature was altered while the participant was not making contact. The warming JND for the index finger found via this method (+0.82 °C) differed only slightly from the warming JND found by Stevens and Choo (+0.9 °C) for the same age group. Unfortunately, we cannot directly compare their results with ours as they did not test for cooling stimuli.

Another reason underlying the differences in the discrimination performance between our study and earlier ones could be the perceptual adaptation (38 °C vs. 25 °C and 33 °C). Due to thermal adaptation, which can also be affected by the duration and number of experimental trials, a temperature difference felt initially can eventually become unnoticed [35]. These results support that thermal adaptation is an important factor in designing future tactile interfaces for continued use. It is also important to note that some temperature bands in Fig. 7 only contained a limited amount of data points due to the restructuring of the measured data. Hence, these particular bands might not accurately represent the overall percentage of correct scores.

As seen in Figs. 6 and 7, the discrimination performances exhibit broad variances. Individual thermal sensitivities [18], [19], [20]) and factors that affect contact conditions (e.g., hydration or finger mechanical properties [36]) could have played a role in this variability. Moreover, environmental conditions (e.g., humidity, airflow, and ambient temperature) could have affected the generated thermal patterns, introducing variability in the presented stimuli. This effect became apparent using thermal measurements, which allowed us to monitor the differences in steady-state temperature distributions per participant. More meticulous monitoring of these variables or real-time control of the actual surface temperature instead of the Peltier temperature could lessen this variance. The latter would require a closed-loop controlled system by adding multiple sensors to the bottom side of the usable surface.

One limitation of the current design of ThermoSurf is the inability to generate larger temperature differences with the chosen cooling system. Using liquid cooling could result in better heat dissipation. Conducting similar experiments with broader temperature differences or investigating the effect of lower initial temperatures can be interesting future research directions.

In our design, we used stainless steel as the display material due to availability reasons. However, using a transparent material having thermal properties similar to steel (e.g., ALON or sapphire) would allow providing thermal cues concurrently with visual feedback and create new application opportunities. One may also choose a different display material for such a design to attain a faster thermal response.

Moreover, this study focused on steady-state effects. In the future, response time and transient dynamics can be included in the design process. This can open new possibilities such as creating active local patterns as a function of finger speed and location.

To the best of our knowledge, this is the first study investigating the effect of user exploration (static, dynamic, and multi-finger) on human thermal perception. Moreover, as far as we know, ThermoSurf is the first display that can generate thermal patterns via heat input solely coming from the sides. This design consequently enables transparency if a transparent display material with the optimal thermal parameters is selected. Our findings can benefit user interface designers and engineers in developing tactile interfaces with salient and consistent thermal feedback. Our display design and experimental results can be used for navigation devices, immersive gaming, communication, online shopping, aid for the limited vision, or health applications.

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DATA AND CODE AVAILABILITY

The relevant data and code of the article can be found in the 4TU ResearchData repository with the identifier https://doi.org/10.4121/21988757.

AUTHOR CONTRIBUTIONS

Luka Peters and Yasemin Vardar: conceptualization. Luka Peters: formal analysis, investigation, and software. Luka Peters, Gokhan Serhat, and Yasemin Vardar: methodology. Yasemin Vardar: supervision. Luka Peters and Yasemin Vardar: visualization. Luka Peters and Yasemin Vardar: writing–original draft. Gokhan Serhat and Yasemin Vardar: writing–review and editing.

REFERENCES

[1] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, "A review of surface haptics: Enabling tactile effects on touch surfaces," *IEEE Trans. Haptics*, vol. 13, no. 3, pp. 450–470, Sep. 2020.

[2] A. El Ali, X. Yang, S. Ananthanarayan, T. Röggla, J. Jansen, J. Hartcher-O'Brien, K. Jansen, and P. Cesar, "ThermalWear: Exploring wearable on-chest thermal displays to augment voice messages with affect," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2020, pp. 1–14.

[3] S. Akiyama, K. Sato, Y. Makino, and T. Maeno, "ThermOn: Thermo-musical interface for an enhanced emotional experience," in *Proc. Int. Symp. Wearable Comput.*, New York, NY, USA, Sep. 2013, pp. 45–52.

[4] H.-N. Ho and L. A. Jones, "Contribution of thermal cues to material discrimination and localization," *Perception Psychophys.*, vol. 68, no. 1, pp. 118–128, Jan. 2006.

[5] H.-N. Ho and L. A. Jones, "Development and evaluation of a thermal display for material identification and discrimination," *ACM Trans. Appl. Perception*, vol. 4, no. 2, p. 13, Jul. 2007.

[6] S.-W. Kim, S. H. Kim, C. S. Kim, K. Yi, J.-S. Kim, B. J. Cho, and Y. Cha, "Thermal display glove for interacting with virtual reality," *Sci. Rep.*, vol. 10, no. 1, pp. 1–12, Jul. 2020.

[7] R. L. Peiris, W. Peng, Z. Chen, L. Chan, and K. Minamizawa, "ThermoVR: Exploring integrated thermal haptic feedback with head mounted displays," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Denver, CO, USA, May 2017, pp. 5452–5456.

[8] Z. Wang, K. Warren, M. Luo, X. He, H. Zhang, E. Arens, W. Chen, Y. He, Y. Hu, L. Jin, S. Liu, D. Cohen-Tanugi, and M. J. Smith, "Evaluating the comfort of thermally dynamic wearable devices," *Building Environ.*, vol. 167, Jan. 2020, Art. no. 106443.

[9] A. Singhal and L. A. Jones, "Perceptual interactions in thermo-tactile displays," in *Proc. IEEE World Haptics Conf. (WHC)*, Jun. 2017, pp. 90–95.

[10] K. Sato and T. Maeno, "Presentation of rapid temperature change using spatially divided hot and cold stimuli," *J. Robot. Mechtron.*, vol. 25, no. 3, pp. 497–505, Jun. 2013.

[11] A. Manasrah, N. Crane, R. Guldiken, and K. B. Reed, "Perceived cooling using asymmetrically-applied hot and cold stimuli," *IEEE Trans. Haptics*, vol. 10, no. 1, pp. 75–83, Mar. 2017.

[12] G.-H. Yang, K.-U. Kyung, M. A. Srinivasan, and D.-S. Kwon, "Development of quantitative tactile display device to provide both pin—Array-type tactile feedback and thermal feedback," in *Proc. 2nd Joint EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst. (WHC)*, Mar. 2007, pp. 578–579.

[13] L. A. Jones and H.-N. Ho, "Warm or cool, large or small? The challenge of thermal displays," *IEEE Trans. Haptics*, vol. 1, no. 1, pp. 53–70, Jun. 2008.

[14] S. Patwardhan, A. Kawazoe, D. Kerr, M. Nakatani, and Y. Visell, "Dynamics and perception in the thermal grill illusion," *IEEE Trans. Haptics*, vol. 12, no. 4, pp. 604–614, Dec. 2019.

[15] S. Kratz and T. Dunnigan, "ThermoTouch: A new scalable hardware design for thermal displays," in *Proc. ACM Int. Conf. Interact. Surf. Spaces*, Oct. 2017, pp. 132–141.

[16] S. Liu, Y. Li, Q. Liu, K. Xu, J. Zhou, Y. Shen, Z. Yang, and X. Hao, "Thermal manipulation in multi-layered anisotropic materials via computed thermal patterning," *Adv. Funct. Mater.*, vol. 32, no. 13, Mar. 2022, Art. no. 2109674.

[17] Y. Vardar and K. J. Kuchenbecker, "Finger motion and contact by a second finger influence the tactile perception of electrovibration," *J. Roy. Soc. Interface*, vol. 18, no. 176, Mar. 2021, Art. no. 20200783, doi: 10.1098/rsif.2020.0783.

[18] J. C. Stevens and K. K. Choo, "Temperature sensitivity of the body surface over the life span," *Somatosensory Motor Res.*, vol. 15, no. 1, pp. 13–28, Jan. 1998.

[19] J. Galie and L. A. Jones, "Thermal cues and the perception of force," *Exp. Brain Res.*, vol. 200, no. 1, pp. 81–90, Jan. 2010.

[20] H. Molinari, J. Greenspan, and D. Kenshalo, "The effects of rate of temperature change and adapting temperature on thermal sensitivity," *Sensory Processes*, vol. 1, pp. 354–362, Aug. 1977.

[21] R. Kenshalo, "Correlations of temperature sensation and neural activity: A second approximation," in *Thermoreception and Temperature Regulation*, J. Bligh, K. Voigt, H. Braun, K. Bruck, and G. Heldmaier, Eds. Berlin, Heidelberg: Springer, 1990, pp. 67–88.

[22] S. Okamoto, H. Nagano, and H.-N. Ho, "Psychophysical dimensions of material perception and methods to specify textural space," in *Pervasive Haptics*. Berlin, Germany: Springer, 2016, pp. 3–20.

[23] I. Darian-Smith and K. O. Johnson, "Thermal sensibility and thermoreceptors," *J. Investigative Dermatology*, vol. 69, no. 1, pp. 146–153, Jul. 1977.

[24] B. G. Green, "Synthetic heat at mild temperatures," *Somatosensory Motor Res.*, vol. 19, no. 2, pp. 130–138, Jan. 2002.

[25] R. Lundström, H. Dahlqvist, M. Hagberg, and T. Nilsson, "Vibrotactile and thermal perception and its relation to finger skin thickness," *Clin. Neurophysiol. Pract.*, vol. 3, pp. 33–39, Jan. 2018.

[26] G.-H. Yang, D.-S. Kwon, and L. A. Jones, "Spatial acuity and summation on the hand: The role of thermal cues in material discrimination," *Perception Psychophys.*, vol. 71, no. 1, pp. 156–163, Jan. 2009.

[27] G. Wilson, S. Brewster, M. Halvey, and S. Hughes, "Thermal icons: Evaluating structured thermal feedback for mobile interaction," in *Proc. 14th Int. Conf. Human-Comput. Interact. Mobile Devices Services*, Sep. 2012, pp. 309–312.

[28] A. Singhal and L. A. Jones, "Creating thermal icons—A model-based approach," *ACM Trans. Appl. Perception*, vol. 15, no. 2, pp. 1–22, Apr. 2018.

[29] L. Peters, "The influence of user exploration on the perception of spatio-temporal thermal patterns," M.S. thesis, Dept. Cogn. Robot., Delft Univ. Technol., Delft, The Netherlands, 2021.

[30] L. A. Jones and M. Berris, "Material discrimination and thermal perception," in *Proc. 11th Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, Mar. 2003, pp. 171–178.

[31] C. Choi, Y. Ma, X. Li, S. Chatterjee, S. Sequeira, R. F. Friesen, J. R. Felts, and M. C. Hipwell, "Surface haptic rendering of virtual shapes through change in surface temperature," *Sci. Robot.*, vol. 7, no. 63, Feb. 2022, Art. no. eabl4543.

[32] B. Delhaye, P. Lefèvre, and J.-L. Thonnard, "Dynamics of fingertip contact during the onset of tangential slip," *J. Roy. Soc. Interface*, vol. 11, no. 100, Nov. 2014, Art. no. 20140698.

[33] A. J. Rózsa and D. R. Kenshalo, "Bilateral spatial summation of cooling of symmetrical sites," *Perception Psychophys.*, vol. 21, no. 5, pp. 455–462, Sep. 1977.

[34] F. Gerr and R. Letz, "Covariates of human peripheral nerve function: II. Vibrotactile and thermal thresholds," *Neurotoxicology Teratology*, vol. 16, no. 1, pp. 105–112, Jan. 1994.

[35] E. Eliav and R. Gracely, "Chapter 3—Measuring and assessing pain," in *Orofacial Pain and Headache*, Y. Sharav and R. Benoliel, Eds. IL, USA: Mosby, 2008, pp. 45–56. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780723434122100033

[36] G. Serhat, Y. Vardar, and K. J. Kuchenbecker, "Contact evolution of dry and hydrated fingertips at initial touch," *PLoS ONE*, vol. 17, no. 7, Jul. 2022, Art. no. e0269722, doi: 10.1371/journal.pone.0269722.

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