MSc Thesis

The influence of user exploration on the perception of spatio-temporal thermal patterns

Luka Peters

Delft University of Technology

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The influence of user exploration on the perception of spatio-temporal thermal patterns

by

Luka Peters

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday June 8, 2022 at 2 PM.

Student number:	4211308	
Master:	Mechanical Engineering	
Track:	BioMechanical Design	Haptic Interfaces
Project duration:	March 1, 2021	June 8, 2022
Thesis committee:	Dr. ir. Y. Vardar	TU Delft, supervisor
	Prof. Dr. ir. D. A. Abbink,	TU Delft, chair
	Dr. Ir. D. M. Pool,	TU Delft, external member

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TU Delft

Preface

Dear reader, hereby I introduce my final master's thesis. Anyone who has seen the phones I have owned over the last 29 years of my existence, will laugh at the fact that I decided to graduated specializing in touchscreen interaction. However, the power of human thermal perception has made me realize the importance of including various feedback modalities in human-machine interaction, and has most definitely heightened my interest in how humans perceive.

It has been an eventful year, both within my research, as well as outside of this study, and I would have not been able to accomplish this result without the help of a lot of people. Firstly, Yasemin, for supervision, fruitful discussion, but also for allowing me the completely break down and show emotions, without ever holding this against me. David, thanks for constructive feedback leaving you empowered, rather than drained. Gökhan, thank you for your help with my finite element simulations. Members of the HITlab were very valuable in providing feedback during the early stages of this research. André and Jos have been indispensable in providing me with hardware and advice during my experiments. And a huge thanks goes to Valérie, who I could share my ups and downs with, without judgement, and who was always able to get my head straight again.

My friends have been irreplaceable and always provide me with a feeling of home, despite how much time has passed. Marah, Marije, Lucie, Anouk, Charlie, Laura and Rebecca, you are the best group of woman I have ever known in my life. Each one of you act as a rolemodel, and have accepted me, even when I am at my lowest. Gul, Emma and Demi, you've allowed for a perspective outside of my bubble, and show me there is more to life than academic success. And Mees, your are literally and figuratively my rock, and one day I will make it up to you.

Lastly, I would like to thank my family. My brother Raf, for showing interest and providing support, despite his preference to mainly talk about himself. My sister, Jazz, for being my best friend and venting partner, even when I am unreasonable. And my parents, Roland and Lianne, for embedding me with a Spartan work ethic, and valuing me based on my accomplishments as a person, rather than on my academic progress. I most definitely am forgetting people, but know that everything you have done for me over the past year will be stored in a warm place inside of my heart, no matter the method of exploration.

Luka Peters
Delft, May 2022

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Paper

The influence of user exploration on the perception of spatio-temporal thermal patterns

Luka Peters (4211308)

(for obtaining M.Sc. degree in BioMechanical Design Engineering)
Delft University of Technology
Delft, The Netherlands

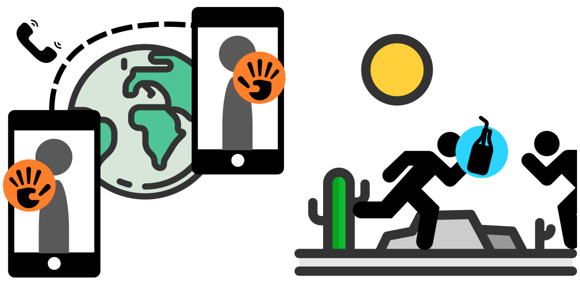
***Abstract*—Thermal feedback has been proven to enhance the user experience in human-machine interaction. However, state-of-the-art technology mainly focuses on static contact using either palm or fingertip, overlooking dynamic and multi-finger interactions. Underlying challenges include incompatible designs of the conventional interfaces for providing controllable salient thermal stimuli for such interactions and, thereby, lack of knowledge on human thermal perception for relevant conditions. Here we designed a new thermal display that can deliver distributed spatio-temporal thermal patterns and investigated the influence of user exploration on the perception of these patterns. Twenty-three human participants interacted with the device using three exploration conditions (static-single finger, dynamic-single finger, and static-multi finger) and evaluated 15 temperature differences ranging from +1.5°C to -7.5°C. Our results showed that humans are significantly more sensitive to thermal stimuli when exploring via static single-finger contact than other tested conditions. Moreover, in the case of static-single finger interaction, we found larger thermal discrimination thresholds compared to the literature. Our findings offer new perspectives on providing salient and consistent thermal feedback for future tactile interfaces.**

***Index Terms*—human thermal perception, thermal display, thermal feedback, human-machine interaction**

I. Introduction

Touch makes up a substantial part of humans' interaction with their surrounding objects and other people. However, humans also spend considerable time in the virtual environment interacting with smartphones, tablets, or computers. Yet, these interactions are far from natural, as these devices are not well equipped to emulate real-world tactile interactions.

Recent advances in the field of surface haptics have shown the possibility of enabling tactile cues of friction and vibration on touchscreens [1]. Although temperature is a key part of everyday tactile interactions, displaying thermal feedback on these displays has been overlooked. Thermal feedback can improve realistic rendering of material properties [2], [3], enhance user performance and comfort [4], [5], [6]; and it has a significant role in conveying emotions [7], [8]. Imagine if your smartphone could deliver realistic thermal feedback. During a long-distance call with a loved one, besides giving comfort with your words and facial expression, you could lay your hand on the screen, and the person on the other side could feel the warmth of your skin. Or, while playing a game in which you are running 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 (see Fig. 1). However, as human thermal perception is highly dependent on the individual, as well as contact conditions [9], [10], [11], implementing such feedback into our existing devices requires a large number of thermal sensors and actuators, and an extensive understanding of thermal hand-object interplay [12].



(a) (b)

Fig. 1: Example applications of thermal feedback for future interfaces. (a) Feeling the warmth of the hand of a loved one during a long distance call (b) Enjoying an immersive gaming environment.

State-of-the-art research on human thermal perception has mainly focused on static contact with a natural material or a thermal display using either finger or palm [12], [13], [4], [14]. However, real-life interactions with an object also include sliding and multi-finger contact, and our knowledge of how perception is affected by these conditions is limited. One reason for this knowledge gap is the challenge of designing thermal displays that can deliver controllable spatio-temporal thermal stimuli for such conditions. The available designs which allow spatial temperature distributions require either a large number of actuators or complex material manufacturing [15], [16].

Here we designed a new thermal display that is able to create spatio-temporal thermal patterns for various user interactions to overcome the indicated challenges, and we investigated how human thermal perception is affected by user exploration. Our minimalist design benefits from the thermal distribution generated by the heating/cooling of a stainless steel display, using only four commercially available peltier devices, which are positioned along the edges of the display (see Fig. 2a). Using this apparatus, we conducted human-participant experiments where 23 individuals evaluated 15 temperature differences ranging from +1.5°C to -7.5°C, while they explored the display using three different exploration conditions (static-single finger, dynamic-single finger, or static-multi finger).

This paper begins with an overview of previously developed thermal displays (Section II-A), and an evaluation of human thermal perception and the mechanisms underlying thermal information processing (Section II-B). Then, the methods used to perform our human subject studies are explained (Section III). Following these, we present our results (Section IV) and discuss them in Section V.

II. Background

A. Thermal Displays

Most thermal displays known from literature have been designed with the aim of investigating human thermal sensitivity. They mainly use peltier devices, which rely on electrical current to generate or remove heat [3]. These devices are generally closed-loop controlled, and their excessive heat can be dissipated through heat sinks [14], [13], [17] as well as active fluid cooling systems [18], [12]. On such thermal display designs, users either directly touch the surface of the peltier elements [14], [13], [17] or the material that is heated or cooled by the peltiers placed just below it [19]. These designs often only include a limited amount of heating devices, allowing for minimal options in displaying localized thermal cues.

On the other hand, the ThermoTouch is a thermal display which uses resistive wires and liquid cooling to distribute temperature over a flat surface. These wires are placed in a grid, such that they allow the formation of localized thermal patterns by applying current to only the specified grid points. However, the device is limited in terms of its cooling capacity [15]. A solution that allows for cooling would be using peltier elements in a similar fashion; yet it would require of a vast number of them and additional sensors, increasing the complexity of the device. A recent approach uses multi-layered anisotropic materials, in which each layer contains a single heat beam. By stacking multiple layers in various orientations, these combined beams are able to create various thermal patterns [16]. Still, the implementation of such a technique requires complex material manufacturing.

B. Human Thermal Perception

Cold and warm thermoreceptors, which are located in the epidermal and dermal skin layers, sense change 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 [20]. 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 [21]. However, these temperature thresholds can be different for each person; some people already feel pain in the margins above or below these limits [22].

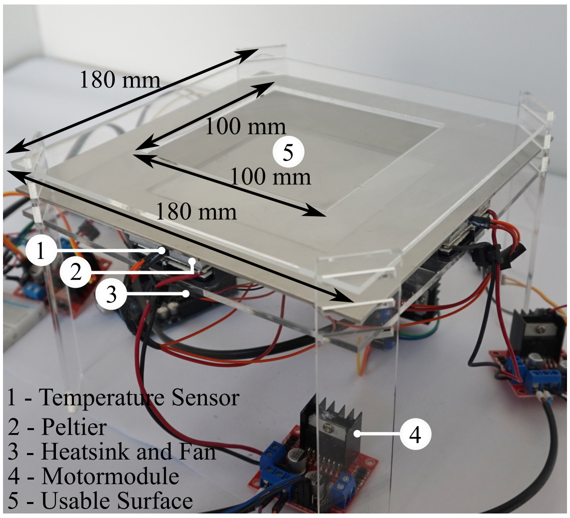
Since thermoreceptors sense change in the skin temperature and not the temperature of the object, the perceived sensation depends on the amount and rate of the transferred thermal energy between the skin and object. This energy depends on various aspects, such as the heat capacity of the material and the initial skin temperature. A thermally conductive material alters skin temperature quicker, and therefore it is perceived as colder or warmer than a thermally insulating material, even if they are both at the same temperature [20].

Skin temperature, rate of change of temperature, stimulation area, and location affect human thermal perceptual sensitivity [23]. Skin thickness, however, does not influence the thresholds for warm and cold stimuli [24]. Earlier study by Stevens & Choo [9] found the just noticeable difference (JND) of the lips 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. While, 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. For the fingertips, under the same circumstances, JNDs were reported as -0.6°C for cooling and +0.9°C for heating [9]. These values corresponded to participants aged 40-60 and climbed with increasing age. Moreover, changing the adapting skin temperature (the initial temperature from which a thermal difference is presented) within the scope of 25°C to 40°C, also affects sensitivity [11]. When the rate of change in temperature drops below 0.1°C/s and the skin temperature stays within the neutral zone (30-36°C), a decrease in sensitivity is observed. As a result, a temperature difference up to 5°C can go unnoticed [23].

Another interesting aspect of human thermal perception is spatial summation, which leads to poor localization [20]. Upon temperature change, the intensity over the stimulated skin area is integrated [12], resulting in limited discrimination of two different thermal cues on the same finger [25]. The 'synthetic heat illusion', as shown by Green [22], is also a result of this characteristic. This illusive effect occurs when out of three fingers the outer two are heated, but all three are tactically stimulated. In such a case, the middle finger also feels heated due to spatial summation.

Human thermal perception exhibits temporal features, distinctive from other senses. Since not the temperature of the object, but the change of temperature within the skin is sensed, some time delay is present. For example, the time required to discriminate between 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 differentiating two objects made of copper and wood, based solely on their thermal properties, averages at 900 ms [20].

Humans can identify various temporal thermal patterns [26]. For instance, a study conducted by Singhal & Jones [27] showed that six different patterns applied on the right index and middle finger can be recognized with mean accuracy of 80%. That study also showed a square wave temperature input was discerned more successfully than a step or a linearly varying input, implying that humans perceive faster changes in temperature more effectively than slower ones. Later, Ho & Jones [2] also found that, humans are able to distinguish two different materials



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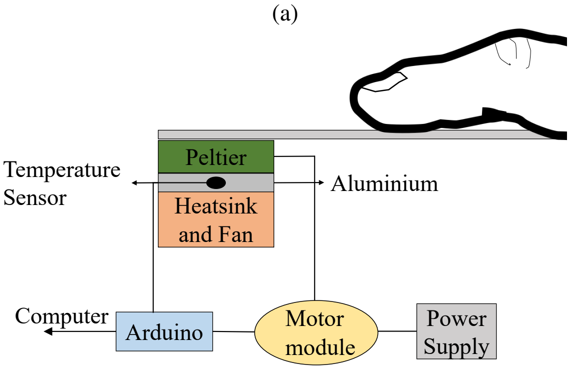


(b)

Fig. 2: (a) Custom-designed thermal display. (b) Schematic representation of a single peltier connection.

using their index fingers, based on solely thermal cues, if the difference between thermal material properties is large enough. In another study, temperature based identification of various synthetic and real materials are compared, and no significant difference was observed between the two types [3].

III. Methods

We conducted psychophysical experiments to investigate how user exploration affects human perception of spatio-temporal thermal patterns. The participants were asked to explore a thermal interface displaying various spatio-temporal thermal patterns with a specified exploration method (static-single finger (SS), dynamic-single finger (DS), static-multi finger (SM)) and report whether they felt a thermal difference between two specified locations.

A. Participants

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

B. Apparatus

A custom-designed thermal display was used for these experiments (see Fig. 2a). The display consisted of four 40×40×3.8mm peltier devices (QC-127-1.4-8.5AS, Quickcool) each connected to a motormodule (1573541, Joy-it), which allowed the peltiers to get enough current input. The motormodules were controlled via a microcontroller (Arduino Mega 2560, Arduino). The peltiers were 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 180×180×2mm stainless steel display. The dimensions and the surface material of the display were chosen by conducting finite element simulations that ensured the selected parameters enabled distinct thermal patterns and sufficient exploration space (see detailed simulation results in Appendix A). The output of these sensors was processed via another microcontroller (Arduino Uno, Arduino). Both microcontrollers were controlled by a laptop (Elitebook 2560p, HP). The bottom side of each peltier was placed on a heatsink and fan combination (CEBF0140401605-00, Malico), using thermal tape. A schematic representation of a single peltier connection is given in Fig. 2b. Moreover, extra fans were used to cool the whole experimental setup (TA350DC, Nidec Beta V and OD6025-24HSS, RSPro).

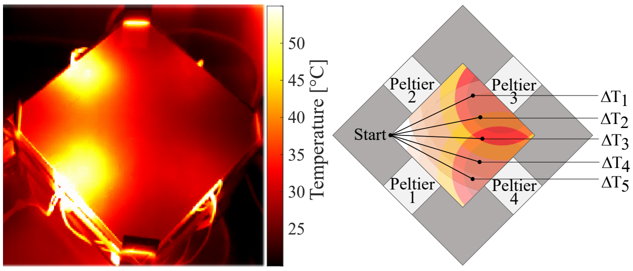
Before the experiments, the participants were trained to keep a constant exploration force of 1.5 N using a scale (80810018, HEMA). During the experiments, the participants wore headphones (HA-RX500, JVC); and they entered their answers using a keyboard (SK140, HAMA). A thermal camera (FLIR E75, InfraTec)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

The thermal display was controlled via open-source Arduino IDE software. A closed-loop PID control ensured precise and accurate temperature control of the peltier devices. A graphical user interface (GUI) designed via Processing (Version 4.0), allowed for the temperature control of each individual peltier. The parameters for the PID controller can be found in Appendix B. This device has been approved by the Health, Security and Environment advisor of the faculty of 3mE at TU Delft.

C. Stimuli

The stimulus was the perceived temperature difference between two locations (standard and comparison) of the thermal display surface. These stimuli were obtained by steady-state thermal patterns displayed on the surface by controlling the temperature of each peltier. Fig. 3a visualizes a tested thermal pattern in the experiments. The thermal camera measurements showed that the thermal display reached the steady-state in approximately 10 min.

As the adapting temperature influences how humans perceive temperature [11], the standard temperature was kept constant throughout a set of trials (∼38°C). The spatial distance between the standard stimulus and comparison stimulus was set at 10 cm. By measuring the surface temperature using a thermal camera, 15 stimuli ranging from ΔT = 0°C to ΔT= 7°C were selected for



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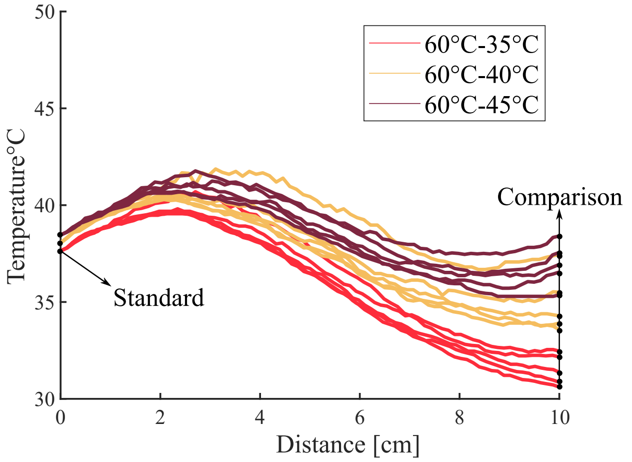
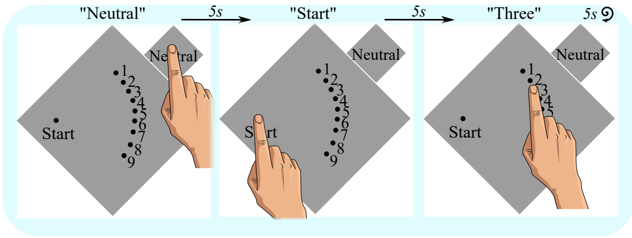
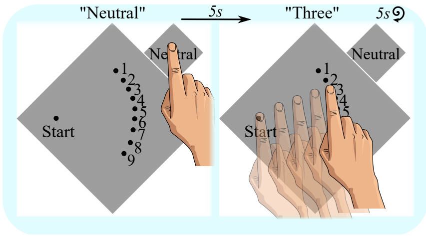


(b)

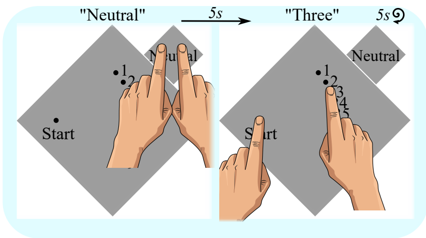
Fig. 3: (a) Example thermal camera measurement when input temperatures for Peltier 1&2 = 60°C and Peltier 3&4 = 35°C. (b) Temperature slopes for all tested stimuli; the legend corresponds to the input temperature of Peltier 1&2, and Peltier 3&4 respectively.



(a) Static-SingleFinger Exploration (SS)



(b) Dynamic-Single Finger Exploration (DS)



(c) Static-Multi Finger Exploration (SM)

Fig. 4: Visualization of experimental procedure for a single experimental trial per condition.

the experiments (check Fig. 3). All stimuli were chosen such that their slopes had similar trends to minimize the influence of the rate of temperature change during dynamic exploration. The chosen thermal patterns did not exceed the non-painful temperature range (18-45°C) within the touched area of the display [21]. Research has shown that a rate of change ($v_{\Delta T}$) falling below 0.1°C/s will decrease the ability to perceive a temperature change [12]. Hence, based on the smallest tested temperature difference (ΔT = 0.5°C), the minimal exploration time was calculated as follows:

$$t = \frac{\Delta T}{v_{\Delta T}} = \frac{0.5\ °C}{0.1\ °C/s} = 5\ s. \quad (1)$$

Each contact with the thermal display lasted 5 s for all exploration conditions. As humans can distinguish between materials based on thermal properties within 900 ms [20], 5 s was also sufficient during static exploration. The applied force of the participant was set at 1.5 N, based on previous research stating this amount to be optimal when thermally exploring a texture [28]. This amount of force is found to maximize the change in temperature as a function of contact area and force, without unnecessarily fatiguing the hand [10]. The initial skin temperature was kept constant prior to touching the thermal display during the experiment, by touching a stainless steel slab at room temperature for 5 s, represented by "Neutral" in Fig. 4. This duration was selected based on a preliminary test.

D. Procedure

Before the experiments, each participant 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 which they familiarized themselves with the experimental procedures and practiced keeping their applied force at 1.5 N.

During the experiments, a participant's 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. 4). After each trial, the participant answered "yes" if they perceived a thermal difference, and "no" otherwise.

An audio sequence played on headphones guided the participant during the experiment. The beginning of each trial was indicated by a sound cue. The participant was instructed to place their index finger on a piece of steel at room temperature to neutralize their skin temperature when they heard this sound. Afterward, depending on the condition, the participant proceeded as follows:

- For the SS condition, the participant was instructed to put 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 and put it to 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 at 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 place their left index finger at 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. 4.

The experiment was conducted in three sessions. In each session, the participant explored a single steady-state thermal pattern using all three exploration conditions, after which a 15 min break allowed the participant to relax and the thermal display to reach a new thermal equilibrium. Each steady-state thermal pattern contained five stimuli (temperature differences), repeated five times per participant in random order, resulting in a set of trials of 25 comparisons. During these 25 trials, the participant applied only one single 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 total experiment consisted of 225 trials (5 stimuli $\times$ 5 repetitions $\times$ 3 exploration conditions $\times$ 3 different steady-state patterns). Including two breaks, as well as a training session and instruction, the total experiment time was about 125 minutes.

Due to the external factors, such as outside temperature differences, humidity and airflow, the generated thermal patterns varied slightly on different days. 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 determine the exact temperature differences felt per participant. The emissivity of the thermal display was calibrated using a thermocouple (ϵ = 0.18) and all measurements were conducted in a darkroom, to minimize the effect of external light. The collected thermal images were analyzed using the embedded software of the camera. The actual stimuli set can be found in Appendix C.

IV. Results

The percentages of correctly perceived temperature differences were analyzed for both intended and measured temperature differences; see Fig. 5 and Fig. 6, respectively.

The results for the intended temperature differences (ΔT) were calculated for each participant and then averaged among all 23 participants. In case of static single-finger (SS) exploration, the mean percentage correct score of a total of 12 stimuli were above chance level ($> 50\%$). In case of dynamic single-finger exploration (DS), this amounted to 4 stimuli. Static multi-finger exploration (SM) totaled at 3 temperature differences correctly perceived above chance level, based on the mean percentage correct. A generalized linear mixed model (GLMM) was created to test the effect of the exploration conditions and the amount of 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 failed the normality assumption. Both exploration condition ($F_{2,22} = 17.999, p < 0.001$) and amount of temperature difference ($F_{14,22} = 2.523, p = 0.002$) significantly affected the perceived temperature difference. A Fisher's LSD post-hoc test showed a significantly higher performance when statically exploring the surface using a single finger, as opposed to dynamically exploring using a single finger ($p < 0.001$) or using both fingers in static exploration ($p < 0.001$). The pairwise comparisons between temperature differences for each exploration condition can be found in Fig. 5.

As the measured ΔTs varied among participants, the results were grouped into bands corresponding to twice the measured just noticeable differences for human thermal perception (-0.3°C) in an earlier study [9]. All bands which were not present for all conditions were removed from the analysis. Moreover, the data of the participants that were present in a single band more than once were averaged; all participants not represented in a band were treated as missing data. More information on the restructuring can be found in Appendix D. SS condition resulted in the mean percentage correct score of a total of 12 stimuli to be above chance level ($> 50\%$). In case of DS condition, this amounted to 6 stimuli, while for SM condition 4 temperature differences were correctly perceived above the chance level, based on the mean percentage correct scores. A GLMM analysis showed that user exploration significantly affected perceived temperature differences ($F_{2,22} = 8.484$, $p < 0.001$). The average bandwidth temperature difference amounted to no significant effect on the percentage correctly perceived ($F_{14,22} = 1.303$, $p = 0.200$). A Fisher's LSD corrected post-hoc analysis showed that SS condition was different than DS and SM conditions ($p < 0.001$ and $p = 0.004$ respectively). The significantly different temperature difference pairs are depicted in Fig. 6.

V. Discussion

In this study we investigated the influence of user exploration on the human perception of spatio-temporal thermal patterns. We first designed a thermal display specifically for this aim and performed human participant 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)).

A. *Influence of Surface Exploration Method*

Our results show that the sensitivity of perceiving spatio-temporal thermal patterns is significantly higher for a static exploration than for a dynamic one. This outcome is agreement with the findings of a recent study by Choi et al. [29]. There, they showed that perceived friction during dynamic exploration of a glass surface

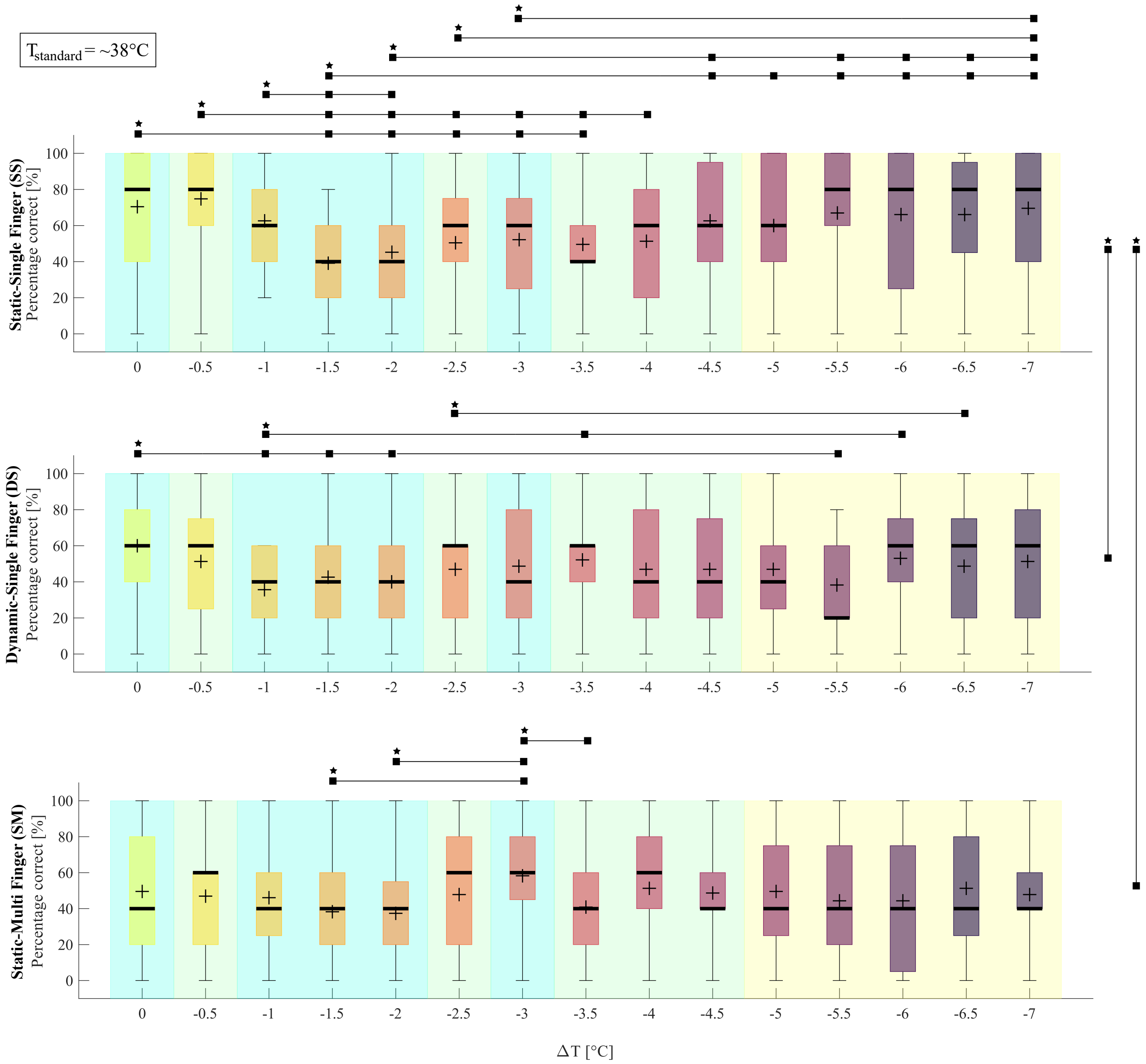


Fig. 5: The percentage of correctly perceived per *intended* temperature difference. The stimuli presented in a single steady-state distribution are indicated with color-coded background rectangles. The significant pairs are indicated with ⋆, where as the means are depicted with +.

can be modulated by increasing the surface temperature without creating noticeable thermal cues. They reported that during their experiments a temperature difference of 18°C could go completely unnoticed. One possible reason for this phenomenon could be that thermal perception gets masked by the perceived frictional cues during dynamic exploration [14], [30]. Earlier works also show supporting evidence for this argument. For example, Singhal & Jones [14] found the recognition of certain thermal cues did not reach above 50% when vibrotactile pulses were simultaneously applied to the thenar eminence. Lui et al. [30] showed friction forces about 5 N, depending on the pressure, which could mask thermal cues in a similar fashion. Another reason could be the relatively smaller contact area during dynamic sliding, showed by Delhaye et al. [31]. Kenshalo [23] previously proved that stimulating a larger skin area will increase the amount of stimulated thermoreceptors, increasing sensitivity to temperature.

During static exploration, using a single finger results in a significantly better discrimination performance, in comparison to using multiple fingers. This behaviour could be explained by spatial summation that occurs when multiple body sites are stimulated simultaneously. For example, Yang et al. [25] investigated the spatial resolution of the fingertip by applying two thermal stimuli with a large temperature difference to two locations at once and found that participants were unsuccessful at identifying where the original thermal stimulation was located. The extent of this effect depends on body location, as well as on the distance between the cues. Ho et al. [32] found thermal cues applied to different fingers separated by 20 mm were correctly perceived more often than when the fingers were adjacent. Interestingly, this effect was also present if both fingers were on opposite hands. Rózsa & Kenshalo [33] proved that if both forearms were simultaneously pressed against a surface, but only a single arm was thermally

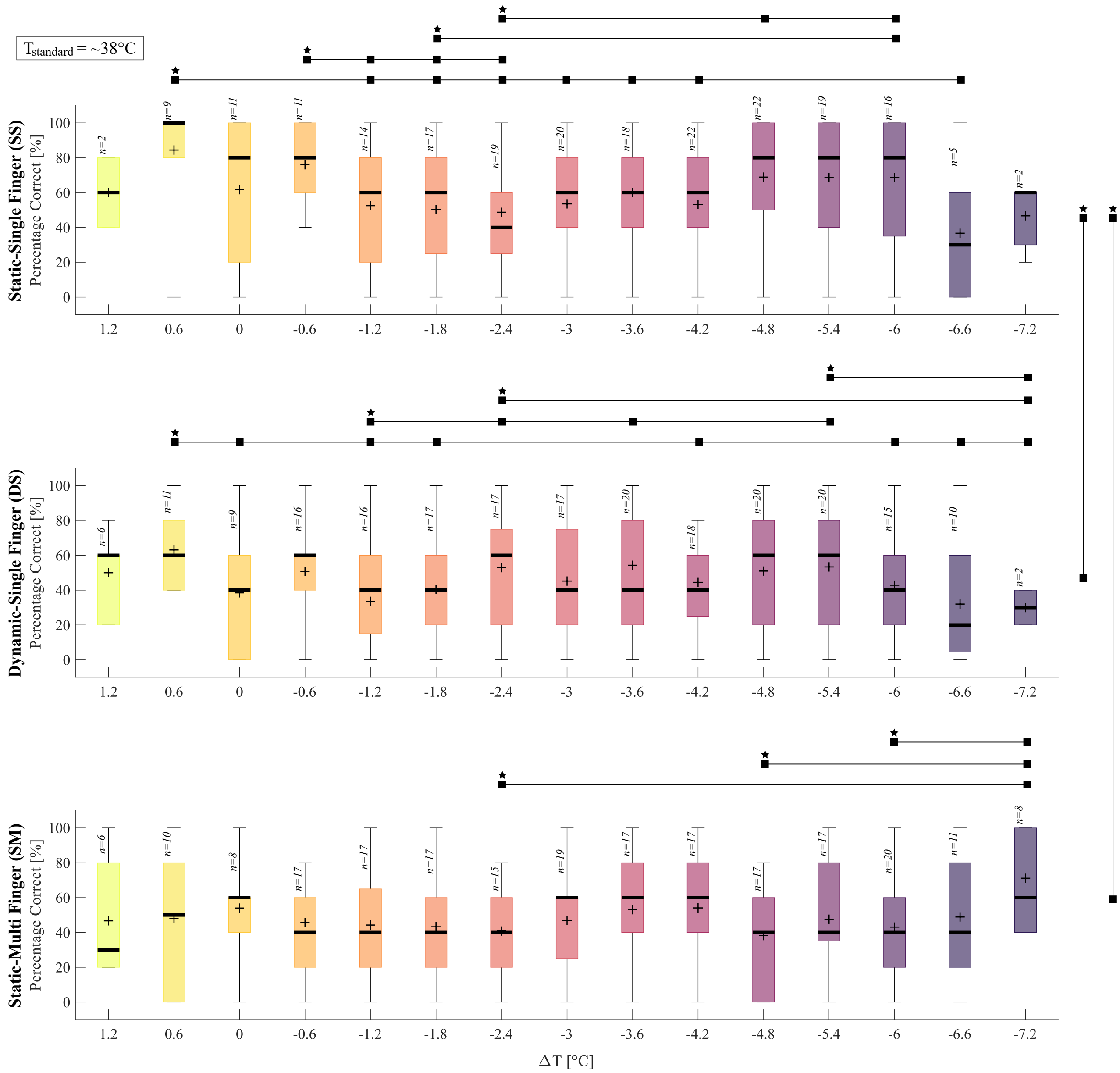


Fig. 6: The percentage of correctly perceived per *measured* temperature difference. The results were grouped per temperature bandwidth corresponding to twice the human perception JND for a cooling temperature difference, measured by Stevens & Choo (width=0.6°C [9]). The significantly different pairs are indicated with ⋆, whereas the means are depicted via +. The corresponding sample sizes n are shown above each boxplot.

stimulated, spatial summation resulted in a warm sensation of both locations. Both results imply spatial summation to be present even over the body mid-line. Therefore, spatial summation could also have influenced the ability to reliably distinguish between two temperatures, when applied simultaneously to both hands.

B. Effect of Temperature Difference

The selected thermal differences did not significantly affect the discrimination performance; this result contradicts previous research into 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°C to -6°C in SS exploration, indicating these temperatures are reliably felt (check Fig. 6). However, this value diverges from the previously found discrimination threshold (JND) by Stevens & Choo [9]. Their JND for cooling temperatures was measured at -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 substantially between two studies. Stevens & Choo [9] used a thermal stimulator displaying a constant rate of temperature change, while continuously in contact with the body part. The participant's task was indicating when a thermal change was felt, after which the direction of change was reversed. As a result, the temperature changes follow a linear slope, which is felt by the participants, whereas our method results in an instantaneous change in temperature. Research by Gerr & Letz [34] used a similar methodology to our experimental design: the participants were asked to indicate if a difference was felt between two locations using a single index finger, in which the adaptation cue was always at 25°C, and the second varied in temperature. Similarly, these locations were heated while the participant was not in direct contact. The warming JND for the index finger found via this method differed only slightly from the warming JND for the same age group found by Stevens & Choo (+0.82°C vs. +0.9°C). They did not evaluate a cooling JND, but based on this comparison it is not expected that the cooling JND in our case is much larger than the one found by Stevens & Choo.

An underlying reason for the mentioned differences in the discrimination performance between our study and earlier ones could be the perceptual adaptation (38°C vs. 25°C). Due to thermal adaptation, which can also be affected by the duration and amount of performed experimental trials, a temperature difference felt initially can eventually go unnoticed [35]. These results support that adaptation on thermal sensitivity is an important factor in designing future tactile interfaces displaying salient thermal feedback for long-term use. Also, our findings suggest that for observing better discrimination performance, a stimulus set with larger temperature differences should be selected even for the static single finger condition.

Interestingly, for SS condition, the mean percentage of correct discrimination are also above the chance level for temperature differences ranging from ΔT = +0.6°C to -0.6°C (Fig. 6). This abrupt increase in the thermal sensitivity could be explained by perceiving contrasting stimuli (both warming and cooling) in a short period of time. As can be seen in Fig.5, the intended low temperature differences (+0.6°C, 0°C, and -0.6°C) were present in the same tested spatio-temporal pattern. In an earlier work, Sato & Maeno [13] were able to increase sensitivity to both hot and cold cues, by presenting carefully designed spatially divided hot and cold stimuli to the index finger simultaneously. Via this method they created the sensation of a more rapid change in temperature. This heightened sensitivity by alternating hot and cold signals aligns with the outcome of this study, in which we found the presence of a single positive temperature to increase perceptibility of the remaining stimuli contained in the same thermal pattern. Further research could provide valuable insights in how this heightened sensitivity could be utilized in future display designs containing thermal feedback.

As can be seen in Fig. 5 and 6, a large variance among performance per stimuli is present. This is also visible in the raw data, shown in Appendix E. Individual sensitivity to temperature could be underlying the variance per bandwidth, as we know temperature perception to be dependent on multiple factors, such as age, environment and contact conditions [9], [10], [11]. Secondly, the environmental conditions had a large effect on the generated thermal patterns, introducing variability in stimuli given. This effect became apparent using thermal measurements, which allowed us to monitor the differences in steady-state temperature distributions per participant. As a result, the continuity of stimuli between participants was jeopardized. Also, due to restructuring of the measured data, some bands in Fig. 6 only contained a limited amount of data points. As a result, these bands might not give an accurate representation of the overall percentage correct scores.

C. Limitations and Future Extensions

Although the experimental conditions were kept similar for each participant, a large variance in temperature difference per participant was experienced. This situation might be caused by environmental factors, such as ambient temperature, humidity, and airflow. Closer monitoring of these factors could reduce this variance. Moreover, real-time control of the actual surface temperature, instead of the peltier temperature, can reduce this variability. This would require the addition of multiple sensors on the bottom side of the usable surface, to allow for closed loop control, without compromising the smoothness of the surface. For such a design, one may also choose a different display material for a faster thermal response.

Another limitation was the inability to create larger temperature differences with the chosen cooling system. Using water cooling could result in better heat dissipation. Conducting similar experiments with larger temperature differences or investigating the effect of cooler initial temperature can be exciting future research directions.

D. Significance and Potential Applications

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. Our findings can benefit industries interested in including salient and consistent thermal feedback to their tactile interfaces. Moreover, as far as we know, this is the first thermal display generating distributed thermal patterns by heating solely from the sides. Modification of this design using a transparent display material having similar thermal properties to stainless steel would allow for concurrent visual feedback. Our preliminary finite element simulations (Appendix A) already showed that ALON™ can be a viable transparent ceramic, which allows for clearly defined thermal patterns. This would allow for novel applications of combined visual and thermal feedback.

Acknowledgements

A special thanks goes to Dr. Yasemin Vardar, for supervision and constructive debate on the subject. Secondly, my appreciation goes to Gökhan Serhat, for the help with multi-physics, finite element simulations. André van der Kraan and Jos van Driel were a great help in supplying an experimental environment and equipment. Also, thanks to the members of the HITLab at the CoR Department at TU Delft, for providing valuable feedback. Lastly, we would like to provide gratitude to all participants, who took time to be a part of this research.

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A

Simulation Results

Figure A.1, A.2, A.3 & A.4 show results of steady-state finite element simulations. Note that these do not take into account the heat distribution over time and use calibrated environmental parameters. Therefore the temperatures may differ from real life temperatures. These simulations are mainly to show the material behaviours for certain circumstances compared to each other, as well as comparing the influence of certain design parameters.

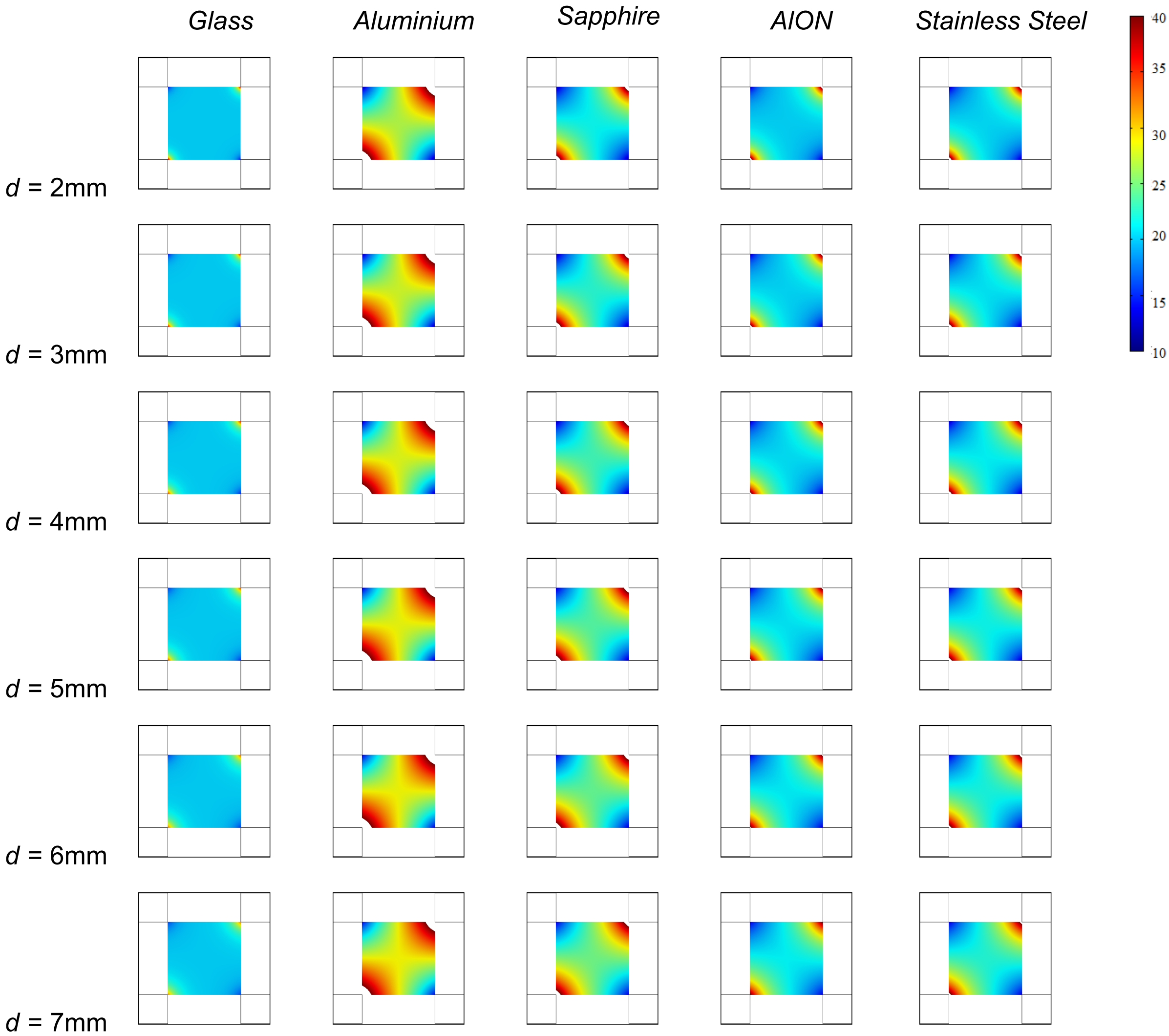

Figure A.1: Results of steady-state FE multi-physics simulations of a 18 mm $\times$ 18 mm square slab with varying thicknesses and materials. The area shown is within the 10 mm $\times$ 10 mm of the usable surface. The ambient temperature was set at 20 °C and a convection coefficient of $h = 86.37\frac{W}{m^2 \cdot K}$, obtained from calibration experiments, was used. Input temperature of each hot Peltier was set at 50 °C and the cold Peltiers were set at 10°C. The colorbar is given in °C. Temperatures which are within the usable area of the surface, but outside the given temperature range, are not shown.

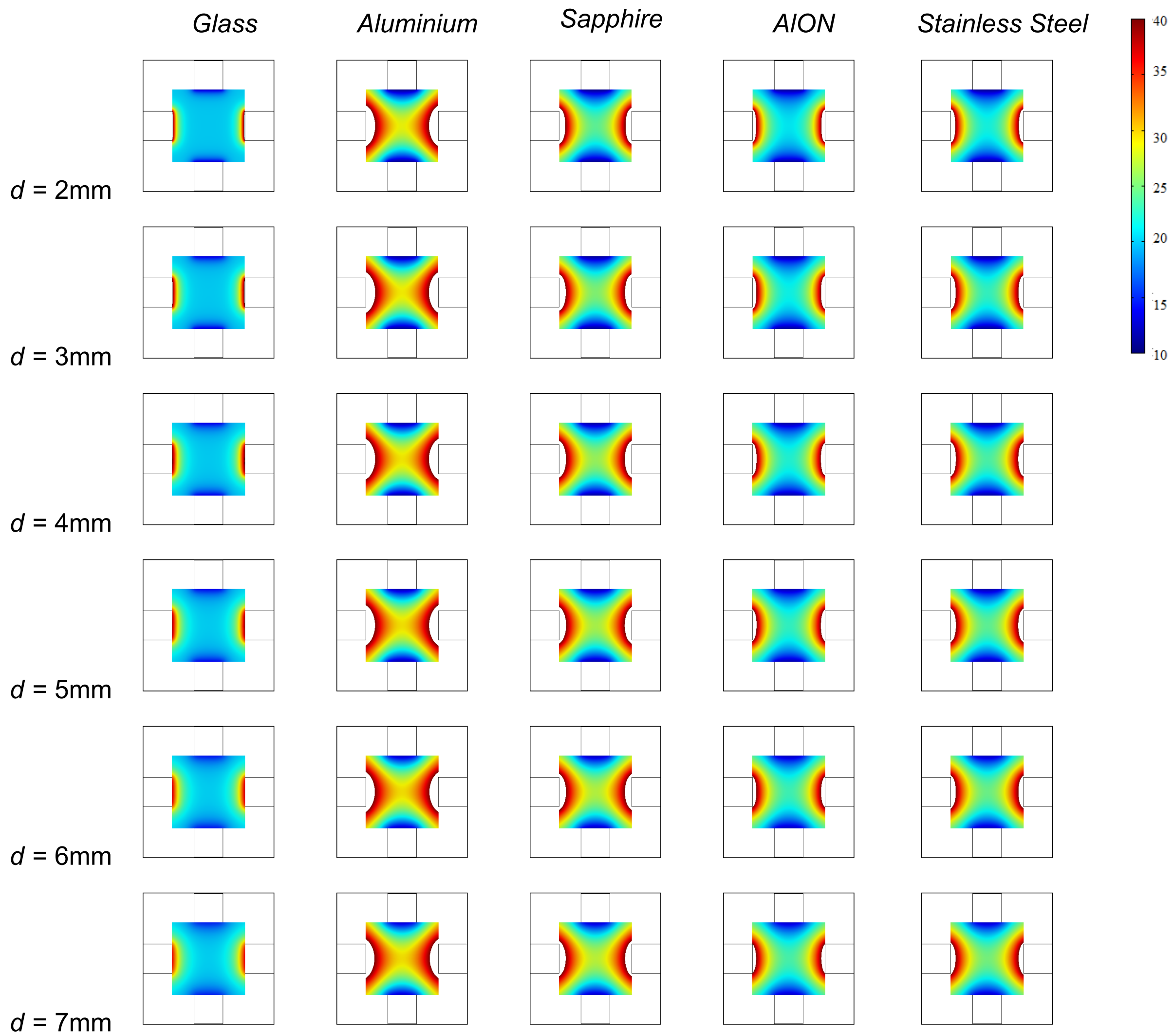

Figure A.2: Results of steady-state FE multi-physics simulations of a 18 mm $\times$ 18 mm square slab with varying thicknesses and materials. The area shown is within the 10 mm $\times$ 10 mm of the usable surface. The ambient temperature was set at 20 °C and a convection coefficient of $h = 86.37\frac{W}{m^2.K}$, obtained from calibration experiments, was used. Input temperature of each hot Peltier was set at 50 °C and the cold Peltiers were set at 10°C. The colorbar is given in °C.Temperatures which are within the usable area of the surface, but outside the given temperature range, are not shown.

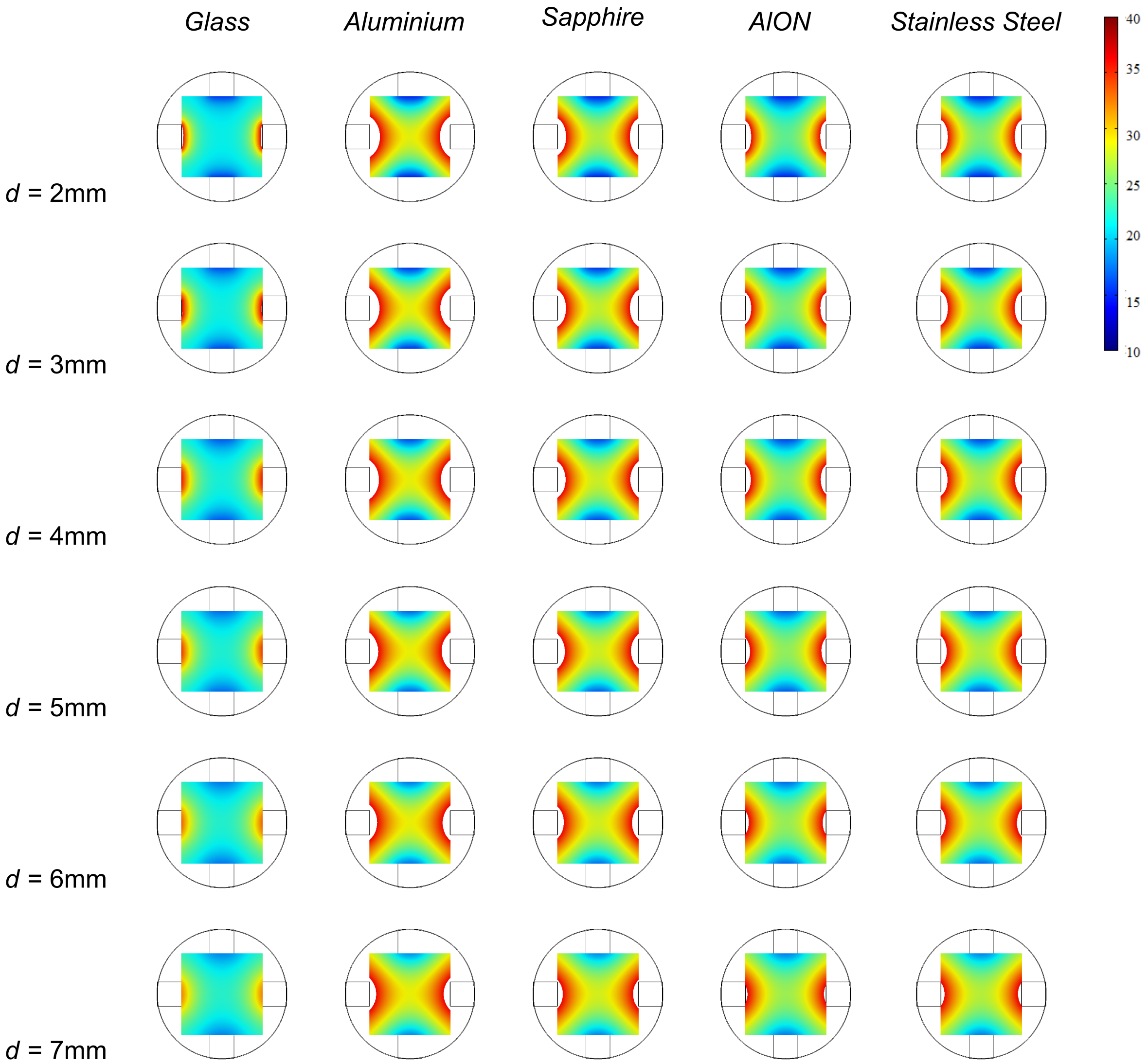

Figure A.3: Results of steady-state FE multiphysics simulations of a ∅ 8 mm round slab with varying thicknesses and materials.The area shown is within the 5 mm × 5 mm of the usable surface. The ambient temperature was set at 20 °C and a convection coefficient of $h = 86.37 \frac{W}{m^2 \cdot K}$, obtained from calibration experiments, was used. Input temperature of each hot Peltier was set at 50 °C and the cold Peltiers were set at 10°C. The colorbar is given in °C. Data which is within the usable area, but outside the given color range is not shown.

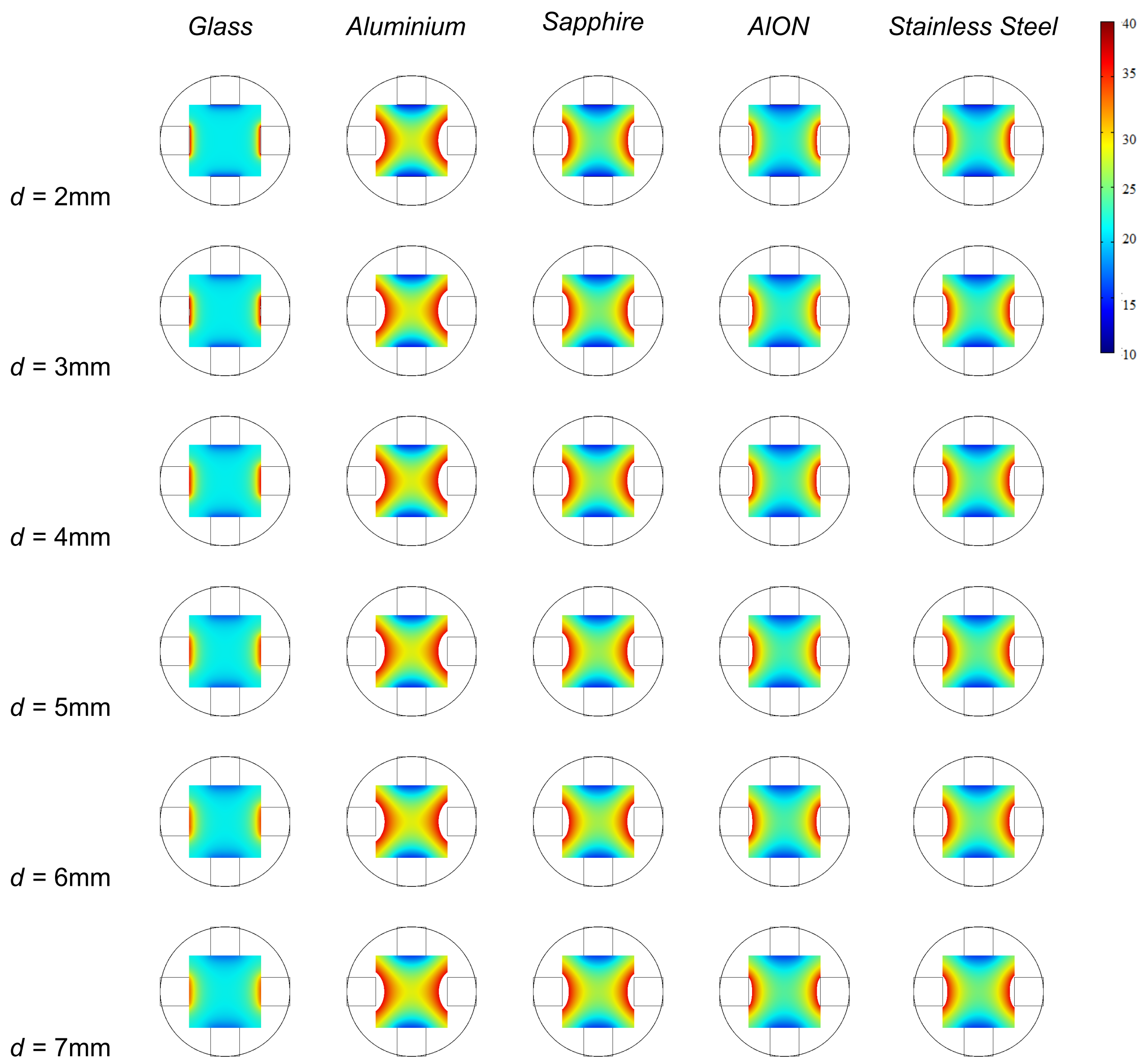

Figure A.4: Results of steady-state FE multiphysics simulations of a ⌀ 18 mm round slab with varying thicknesses and materials. The area shown is within the 10 mm × 10 mm of the usable surface. The ambient temperature was set at 20 °C and a convection coefficient of $h = 86.37 \frac{W}{m^2 \cdot K}$, obtained from calibration experiments, was used. Input temperature of each hot Peltier was set at 50 °C and the cold Peltiers were set at 10°C. The colorbar is given in °C. Temperatures which are within the usable area of the surface, but outside the given temperature range, are not shown.

B

PID Parameters

Table B.1 contains the calibrated PID parameters per Peltier

	K_P		K_I		K_D	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
Peltier 1	100	210	4	5	2	0.8
Peltier 2	100	210	3	2	2	0.8
Peltier 3	100	210	3	10	0.5	0.5
Peltier 4	100	210	3	5	1	0.9

Table B.1: Proportional (K_P), Integral (K_I) and Derivative (K_D) constants as calibrated per Peltier, for both cooling and warming.

C

Stimuli Set

Since the temperature distribution varied from day-to-day, the temperature distribution on the surface during each set of trials was measured. The actual stimuli and their variance, are shown in Table C.1.

Stim.	Static		Dynamic		Multi	
	$\mu[°C]$	SD$[°C]$	$\mu[°C]$	SD$[°C]$	$\mu[°C]$	SD$[°C]$
1	0.32	0.78	0.97	0.79	0.70	0.61
2	-1.08	0.64	-0.58	0.66	-0.73	0.51
3	-1.19	0.63	-0.68	0.70	-0.82	0.53
4	-2.15	0.68	-1.69	0.67	-1.79	0.54
5	-2.28	0.55	-1.82	0.65	-1.91	0.55
6	-2.23	0.64	-1.87	0.90	-2.02	0.76
7	-2.94	0.62	-2.45	0.94	-2.72	0.74
8	-3.14	0.56	-2.67	0.96	-2.87	0.67
9	-4.00	0.61	-3.52	0.94	-3.74	0.66
10	-4.18	0.82	-3.92	0.87	-4.18	0.71
11	-4.46	0.60	-4.23	0.72	-4.68	0.85
12	-4.93	0.78	-4.97	0.70	-5.42	0.82
13	-5.45	0.76	-5.47	0.67	-6.11	0.80
14	-5.65	0.79	-5.66	0.68	-5.95	0.82
15	-6.03	0.75	-6.03	0.71	-6.51	0.76

Table C.1: Mean temperature differences (μ) with their corresponding standard deviation (SD) given to participants per condition (static-single finger; dynamic-single finger and static-multi finger).

D

Bandwidth Structure

Table D.1 contains information on the restructuring of the data into bandwidths. All bandwidths which did not contain datapoints for all three conditions were removed. If a participant was present more than once within a bandwidth, their percentage correct scores were averaged over the amount of times present.

Band	Temperatures $[°C]$			Datapoints					
				Single		Dynamic		Multi	
	From:	To:	Average:	Before:	After:	Before:	After:	Before:	After:
1	1.5	0.9	1.2	2	2	6	6	6	6
2	0.9	0.3	0.6	9	9	13	11	10	10
3	0.3	-0.3	0	12	11	13	9	10	8
4	-0.3	-0.9	-0.6	15	11	28	16	25	17
5	-0.9	-1.5	-1.2	24	14	25	16	33	17
6	-1.5	-2.1	-1.8	35	17	39	17	37	17
7	-2.1	-2.7	-2.4	39	19	31	17	25	15
8	-2.7	-3.3	-3.0	34	20	23	17	35	19
9	-3.3	-3.9	-3.6	30	18	35	20	23	17
10	-3.9	-4.5	-4.2	38	22	27	18	27	17
11	-4.5	-5.1	-4.8	36	22	31	20	22	17
12	-5.1	-5.7	-5.4	37	19	30	20	29	17
13	-5.7	-6.3	-6.0	21	16	21	15	26	20
14	-6.3	-6.9	-6.6	6	5	15	10	18	11
15	-6.9	-7.5	-7.2	3	2	2	2	9	8

Table D.1: Data points per bandwidth. “Static” represents the static-single finger exploration. “Dynamic” the dynamic-single finger exploration. And “Multi” represents the static-multi finger exploration. The first column per condition represents the amount of data points without averaging over a participant reoccurring in a bandwidth. The second column represents the amount of data points in a bandwidth after averaging.

E

Extensive Results

Figures E.1, E.2 and E.3 show all datapoints seperated per stimulus.

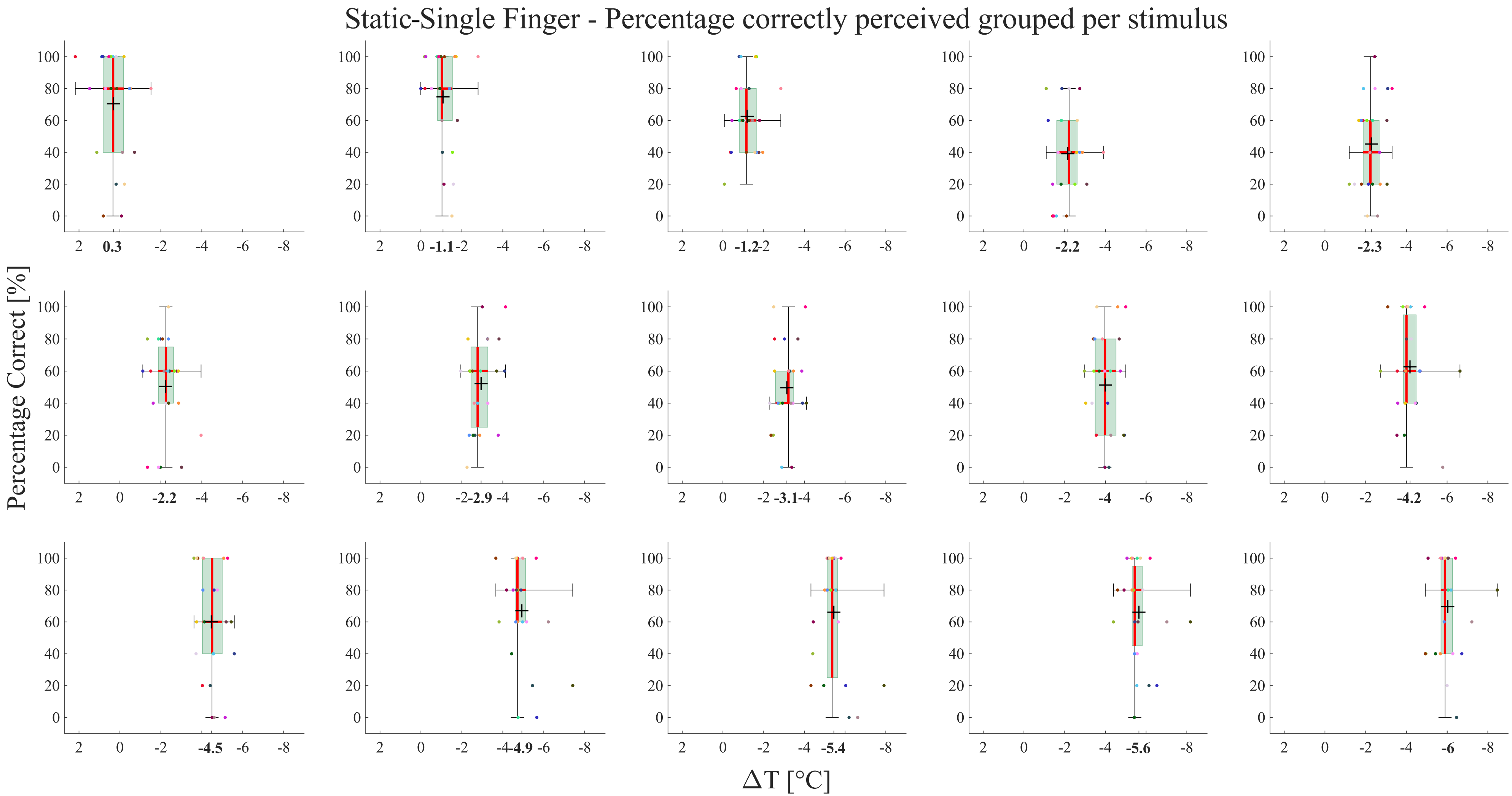

Figure E.1: Results per stimulus, with stimulus variance shown, together with the correctly perceived answers in a dual boxplot. Red lines depict the median of both the temperature difference, as well as percentage correctly perceived. Overall mean is depicted as $\mu = +$. Individual answers are represented as dots, in which each participant is color coded.

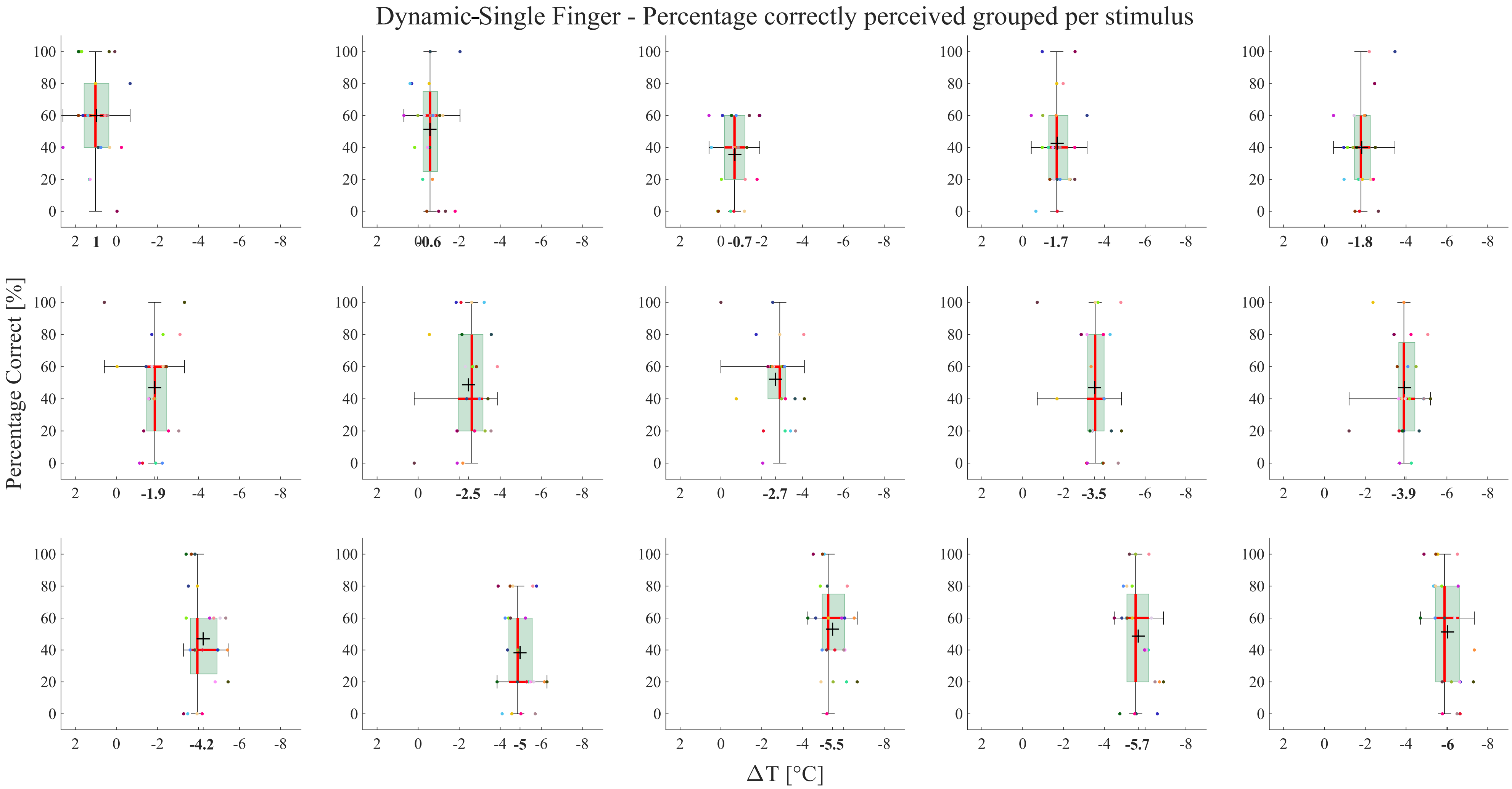

Figure E.2: Results per stimulus, with stimulus variance shown, together with the correctly perceived answers in a dual boxplot. Red lines depict the median of both the temperature difference, as well as percentage correctly perceived. Overall mean is depicted as $\mu = +$. Individual answers are represented as dots, in which each participant is color coded.

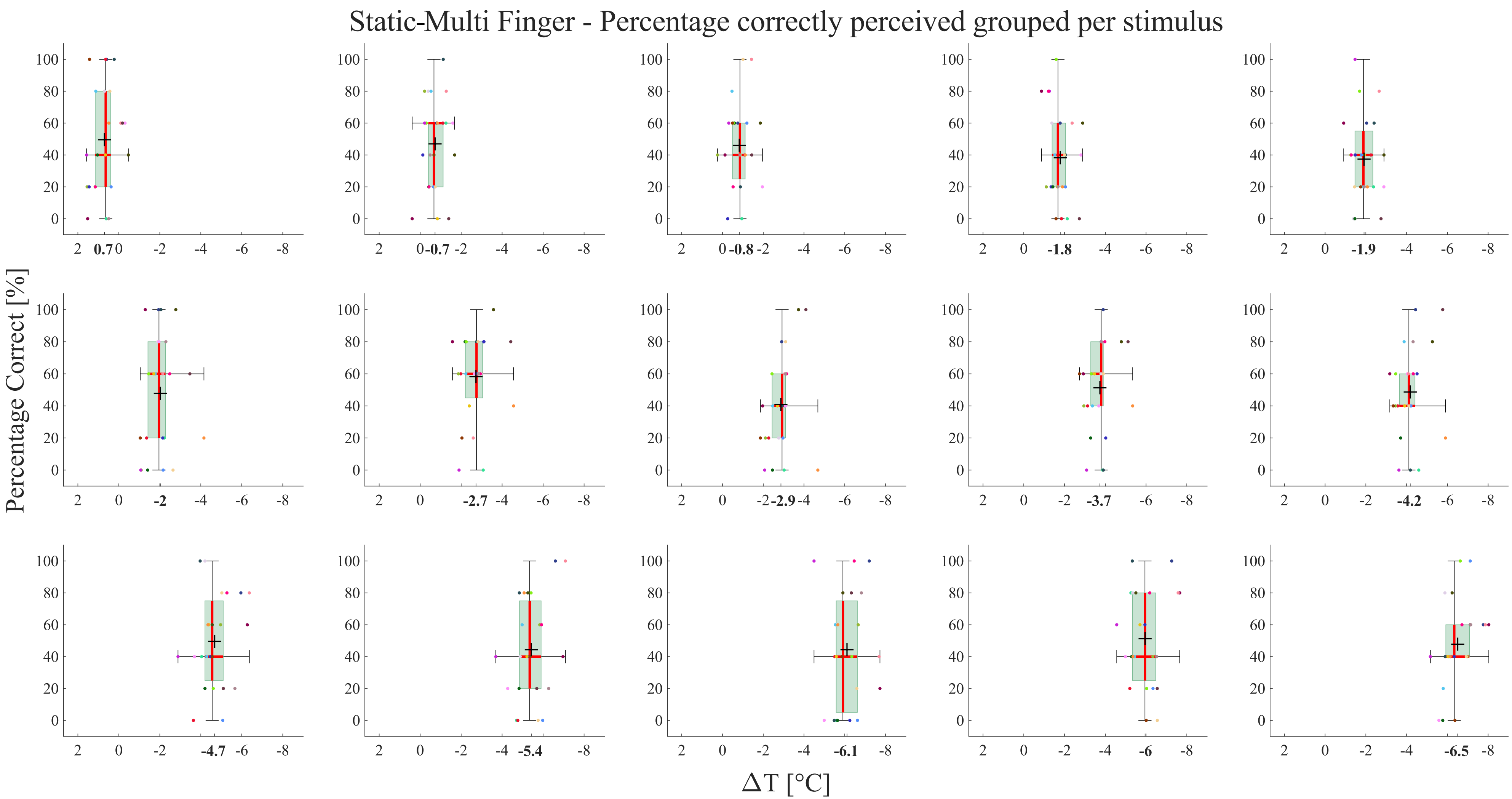

Figure E.3: Results per stimulus, with stimulus variance shown, together with the correctly perceived answers in a dual boxplot. Red lines depict the median of both the temperature difference, as well as percentage correctly perceived. Overall mean is depicted as $\mu = +$. Individual answers are represented as dots, in which each participant is color coded.