Development of Thermal Displays for Haptic Interfaces

by

Anshul Singhal

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Author . . . .
Department of Mechanical Engineering
May 06, 2016

Certified by . . . .
Lynette A. Jones
Senior Research Scientist in Mechanical Engineering
Thesis Supervisor

Accepted by . . . .
Rohan Abeyaratne
Chairman, Department Committee on Graduate Students

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Abstract

This thesis studied the effect of different stimulus parameters on the thermal response of the skin. A set of thermal patterns, known as thermal icons, was presented to participants using a thermal display mounted on the hand. The thermal responses of the skin were studied to understand which features of the thermal stimuli were important and could be perceived by users. The effectiveness of these patterns was evaluated for applications involving hand-held and wearable thermal devices. In the first series of experiments, a set of six thermal icons was developed and presented on the thenar eminence and the fingertips. The second experiment was conducted on the wrist with a revised set of thermal icons which had a shorter duration and were presented relative to each participant's baseline skin temperature. The information transfer (IT) values for the thermal icons presented on the wrist-mounted thermal display demonstrated that the information processing capabilities of the thermal sensory system may rival those achieved with vibrotactile inputs. To date, thermal icon studies have only used the temporal properties of stimuli and not the spatial properties. A set of two experiments was conducted to examine how the spatial and temporal properties of thermal stimuli interact. The results showed that the temporal properties of thermal stimulation can influence the perceived location of a thermal stimulus. This space-time dependency for the thermal sensory system provides an extra dimension to use to present information in a thermal display and potentially could result in a display that functionally has a higher spatial resolution than the number of thermal elements would indicate.

Thesis Supervisor: Lynette A. Jones
Title: Senior Research Scientist in Mechanical Engineering

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Chapter 1

Introduction

The focus of the research presented in this thesis is to understand how different thermal stimulus parameters affect the response of the skin to thermal stimulation and whether these changes in skin temperature are perceived. Pre-defined sets of thermal patterns, known as thermal icons, when presented to the skin can be used to convey information. The basis for designing these thermal icons has not been well delineated. The thermal response of the skin to stimulation has to be studied in order to understand which features of thermal stimuli can potentially be encoded by thermoreceptors and perceived by the user. The effectiveness of these patterns has to be evaluated for the proposed applications in thermal displays that are part of hand-held or wearable devices. To date, studies of thermal icons have used only the temporal properties of thermal stimuli and not the spatial properties. The spatio-temporal interactions, which have been reported for other sensory modalities have to be studied for the thermal sensory system within the innocuous range of temperatures. If space-time interactions occur for the thermal sensory system, then the scope of parameters that can be used to create effective thermal patterns in thermal displays will be enhanced.

1.1. Haptic Interfaces

The haptic sensory system is based on inputs that arise from sensory and motor activity that involves sensors in the skin, muscle and joints. As illustrated in Figure 1.1, the haptics sense is a bi-communication channel, unlike the visual sense, which means that it can both sense and act on stimuli. The tactile or cutaneous senses are responsible for the ‘sense of touch’ and inputs to these arise through direct contact with the skin surface [1]. The tactile sense can detect four basic features of stimulation: mechanical, thermal, chemical and electrical. Kinesthetic or proprioceptive perception refers to sensations of position, velocity and forces that arise from receptors in muscles and tendons. Together, the tactile and kinesthetic senses play an important role in our interaction with the environment. The haptic sense gives us information essential to our daily lives, be it when pressing a button or holding a ball.

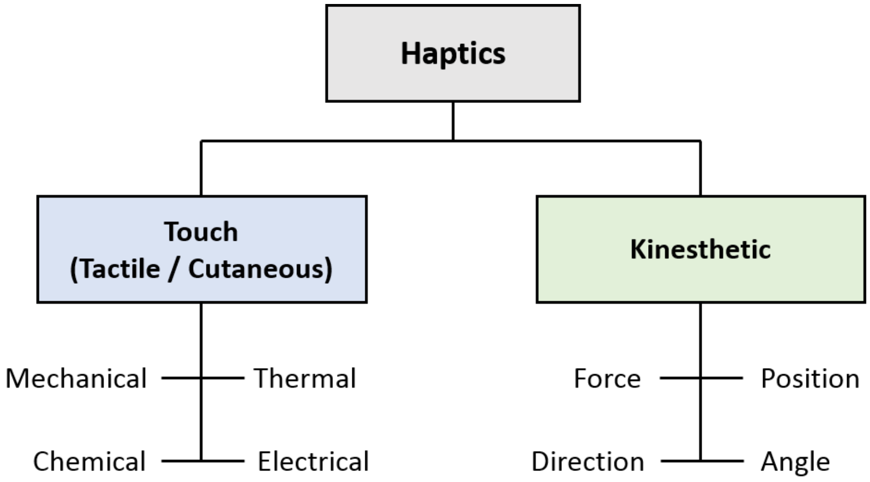


Figure 1.1 Haptic Sensory System

A device or interface that can provide haptic sensations, i.e. it is able to communicate with a user by providing tactile or/and kinesthetic perceptions, is known as a haptic interface. Haptic interfaces can provide useful feedback for perceiving physical surroundings. These interfaces have a wide range of applications, including in virtual environments and in teleoperation of robotic systems. Depending on the application, haptic interfaces can present tactile or force feedback to the user or take the user’s response to generate appropriate feedback.

Tactile displays convey detailed information about the interaction at a localized point of contact. One application of tactile displays is in sensory substitution, such as providing spatial information in the absence of visual cues. Refreshable Braille displays for people who are blind is an example of a tactile sensory substitution device [2]. Tactile displays can also be used to convey the shape, texture or contour of an object. This is achieved by deforming the skin or modulating the force distribution.

Force displays provide information about the forces involved during a virtual or a physical interaction. Force displays are usually developed as a desktop device or in the form of an exoskeleton, capable of generating kinesthetic feedback. The input to force displays can come from a virtual environment or in the form of closed loop feedback control by sensing limb position and movement [3].

A complete immersive picture of an interaction, either in a physical world or in a virtual environment, can be created using a combination of these displays. Such haptic displays which provide tactile, force, position and thermal feedback, are known as multi-modal haptic interfaces. The size, cost and effectiveness of any haptic display is largely dependent on its form factor which is governed by the actuators and sensors employed in it.

1.2. Thermal Sensory System

The thermal sensory system encodes information about the thermal interaction at the interface of the skin and an object. The skin is the largest organ in the body and has three main layers, as illustrated in Figure 1.2. The cutaneous sensory receptors are located in the two outermost layers. The outermost layer or the epidermis has a thickness of 65 to 115 µm. The second layer or dermis is approximately 0.3 to 3 mm thick, and contains nerve endings which respond to touch and pressure, temperature changes, and painful stimuli [4]. The third layer or hypodermis is located below the dermis layer and contains blood vessels and nerve fibers. It also attaches the skin tissues to the underlying bones and muscles.

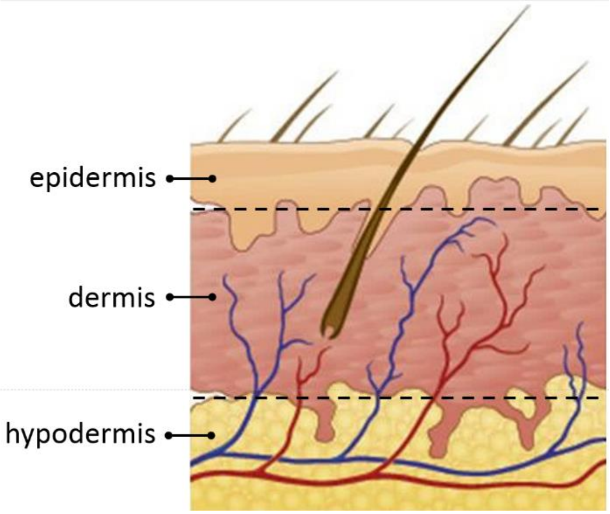


Figure 1.2 Three main layers of the skin: outermost layer or epidermis, middle layer or dermis and the innermost layer, the hypodermis. Figure adapted from [6].

The skin has numerous sensory receptors which are responsible for responding to particular types of stimuli. Mechanoreceptors sense mechanical stimulation, thermoreceptors sense increases or decreases in temperature and nociceptors sense pain. Across the body, the density of receptors varies and thus the sensitivity of the skin to stimulation also differs. The relative densities of these receptors varies at different locations, for example, the fingertips are highly sensitive to mechanical stimulation but they have lower thermal sensitivity as compared to other locations on the body such as the forearm [9].

A typical thermal interaction of the skin with an object is shown in Figure 1.3 (a). When the skin interacts with an object under normal conditions there is heat transfer due to differences in the temperatures of the skin and the object [5]. Due to heat flux at the contact interface of the skin and the object, the interface temperature changes as shown in Figure 1.3 (b). The thermoreceptors present in the epidermal and the dermal layers sense this change in the skin temperature and respond by varying their discharge rates. The encoded information of the thermal interaction is sent to the higher centers of the central nervous system (CNS), where the thermal sensation is perceived. The generation and transmission of thermal feedback is depicted in Figure 1.4.

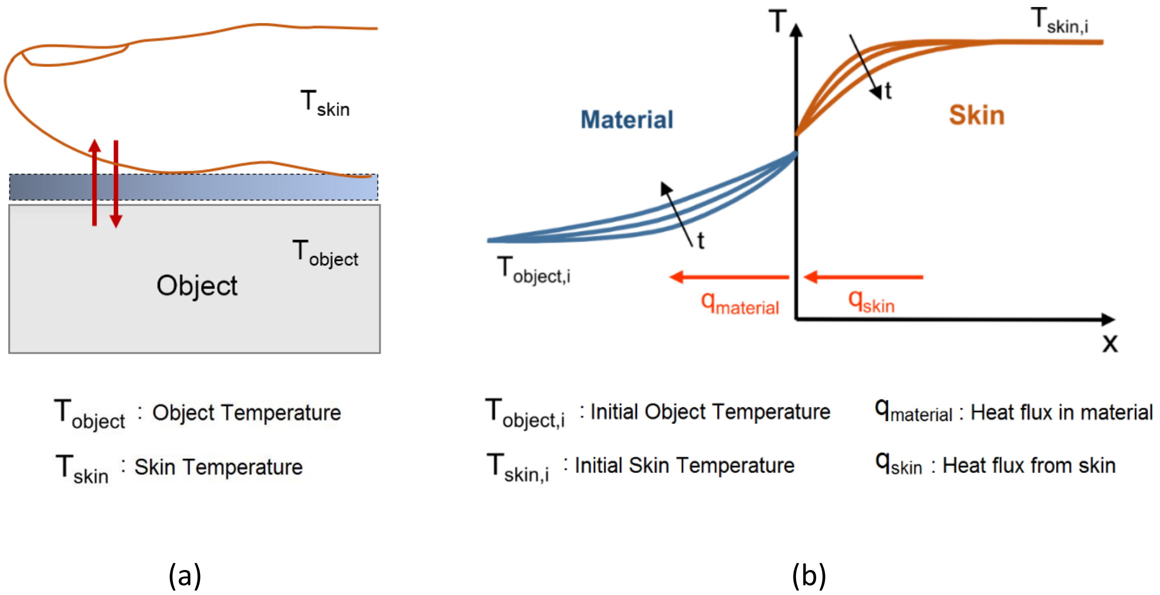


Figure 1.3 (a) Thermal Interaction due to the heat transfer between the skin and the object. (b) Heat flux at the contact interface of the skin and the object gives an interface temperature. Figure adapted from [5].

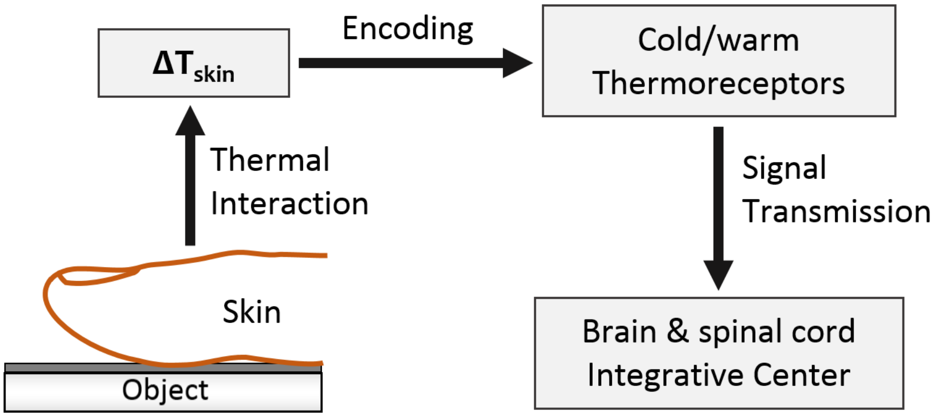


Figure 1.4 Generation of thermal feedback by the thermoreceptors and transmission by the brain and the spinal cord in the CNS.

The cold and warm thermoreceptors in the skin that signal changes in skin temperature vary with respect to the range of temperatures that they respond to, their innervation density across the body and the conduction velocity associated with transmitting information in the CNS.

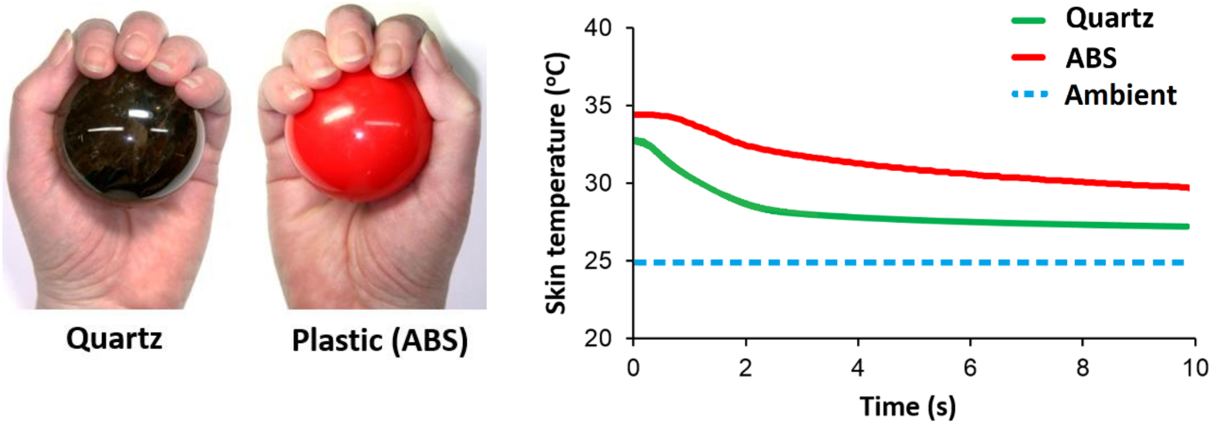
Cold thermoreceptors signal decreases in skin temperature from 43 to 5 °C and respond most vigorously around 25 °C, whereas warm thermoreceptors discharge with increasing skin temperature reaching a maximum at temperatures around 45 °C [7]. As the temperature of the skin falls below 15 °C or rises above 45 °C there is an abrupt change in sensation to one of pain [8].

The sensitivity of skin to thermal stimulation is variable. Across the body there is a 100-fold variation in thermal thresholds with the face being the most sensitive region and the feet being relatively insensitive [9]. For the upper extremity, cold and warm thresholds are lower (better sensitivity) on the thenar eminence at the base of the thumb as compared to the forearm and fingertips [9]. Thermal sensitivity maps are therefore quite different from homologous maps of spatial tactile acuity in which the exquisite sensitivity of the fingertips is predominant. In addition, all body regions are more sensitive to cold than to warm stimuli [9, 10], and although the rate of temperature change influences thermal thresholds, at rates above 0.1 °C/s it has little effect on the ability to detect thermal stimuli [11]. The difference in the conduction velocity of cold (10-20 m/s) and warm (1-2 m/s) afferent fibers does however affect reaction time. Cold stimuli are responded to more rapidly than warm stimuli [12]. These fundamental properties of the thermal sensory system provide a framework for defining the optimal characteristics of stimuli presented in a thermal display.

An understanding of how changes in skin temperature are encoded in the periphery and transmitted in the CNS is essential to the development of effective thermal displays. The sensitivity properties of the thermoreceptors demarcate the range of temperatures that should be presented in thermal displays to those between 18 and 40 °C so as not to elicit painful responses.

1.3. Development of Thermal Displays

Much of the research on thermal displays has focused on their use to simulate the thermal properties of objects encountered in the environment so as to facilitate identification and discrimination [13]. These displays attempt to reproduce the thermal sensations associated with making contact with a real object which vary as a function of the thermal properties of the object, such as its conductivity and heat capacity. An example is shown in Figure 1.5, where two different materials with the same shape and size can be identified from their different thermal properties. The objective of a thermal display is to assist in object recognition in situations in which visual information may be limited or absent, and to create a more realistic experience of the contact between the hand and the object in a virtual environment [14]. The three main components of a typical thermal display are shown in Figure 1.6.



(a) (b)

Figure 1.5 Example of object recognition using perception of thermal properties by the hand [5]. (a) Thermal interaction of the hand with different materials of the same shape and size. (b) Relative change in skin temperature due to the thermal interaction [5].

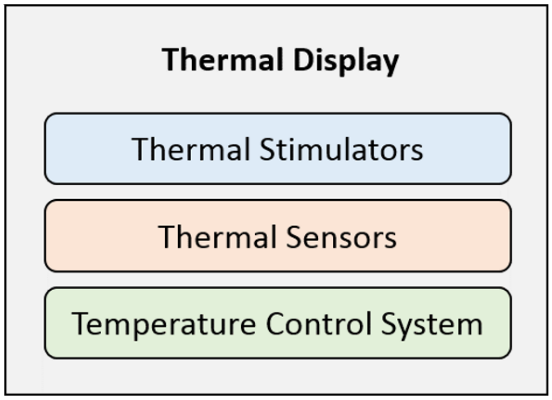


Figure 1.6 Main components of a thermal display.

These displays typically consist of thermal stimulators such as Peltier devices, thermal sensors, and a temperature control system that monitors and controls the surface temperature of the thermal display [13, 15, 16]. For applications of thermal interfaces in object simulation and identification, it has been shown that model-based displays are able to simulate thermal cues effectively such that participants can use these cues to identify and discriminate between materials with an accuracy that is similar to that attained with real materials [15, 17-20]. The particular model selected to characterize the hand-object thermal interaction depends on the objects and the contact conditions in the virtual environment. When the simulated objects are not distinct in terms of their thermal properties and precise identification is required the thermal model needs to be more complex and incorporate factors such as thermal contact resistance and object geometry. However, the simple “two semi-infinite bodies in contact” model works well when the simulated objects span a wide range of thermal properties and only identification or discrimination is required [13].

In addition to their use to simulate thermal properties of materials, thermal interfaces can be used to enhance user interactions with objects presented on digital media [21] or to present scalar information that is mapped onto temperature [22]. For example, the proximity of an object to a user could be encoded as an increase in temperature, or the increasing pressure during an undersea dive could be represented by decreases in temperature. Very few studies have examined the feasibility of using thermal cues to encode such abstract information and most of the devices that have been built to explore this possibility have not undergone rigorous human-use studies [e.g. 22, 23].

1.4. Thesis scope and Objectives

The objectives of the research conducted for this thesis were to study the effect of different thermal stimulus parameters on the thermal responses of the skin and the human user. Thermal stimuli, when presented in a set of defined patterns to the skin, can be used to convey information. Such thermal patterns are known as thermal icons, similar to tactons in the tactile modality. The basis for designing thermal icons has not been well delineated, and so the thermal responses of the skin to stimulation were measured to understand which features of a thermal stimulus can potentially be encoded by thermoreceptors and perceived by the user. Different locations on the body which varied with respect to the thermal sensitivity were used to present the thermal stimuli. Participants were required to identify the patterns presented. The thermal icons that were studied took advantage of only the temporal properties of thermal stimulation and not its spatial properties. By varying the spatio-temporal parameters of the thermal stimulation, it is possible that additional information may be conveyed. Spatio-temporal interactions have been reported for other sensory modalities, but not for the thermal sensory system within the innocuous range of temperatures. A set of experiments was therefore conducted to observe the effect of varying the temporal and spatial properties of thermal stimulation on the skin with cold and warm stimuli. Space-time interactions were found for the thermal sensory system which widens the scope of parameters that can be used to create effective thermal patterns.

This thesis is organized into the following chapters which describe the motivation, experimental design and results of the different studies. Chapter 2 details the development of a set of thermal icons which are based on the thermal sensory system's characteristics. Absolute identification experiments were conducted for the thermal patterns presented at two locations on the hand to evaluate the effectiveness of the thermal icons in conveying information. For these studies, a grounded thermal display using a Peltier module was developed.

Chapter 3 describes an absolute identification experiment with a revised set of thermal icons which have shorter durations and are presented relative to the participant's baseline skin temperature. In this study, the experiment was conducted using a wearable thermal display on the wrist. For the experiments presented in both Chapters 2 and 3, the effectiveness of the icons was evaluated both in terms of the percent correct responses and by calculating the Information Transfer (IT).

Chapter 4 describes the experiments which evaluated the spatio-temporal effects of thermal stimulation on the forearm. For these studies, a thermal display consisting of three Peltier modules capable of presenting short duration cold and warm thermal pulses on the forearm was developed. Two experiments were conducted to determine whether the perceived location of the thermal stimuli changed as a function of the temporal parameters of the stimulation, and to find out whether there were differences in thermal space-time interactions for cold and warm stimuli.

Chapter 5 provides a summary of this research as well as potential areas of future work.

Chapter 2

Thermal Pattern Identification on Hand

2.1 Motivation

The thermal sensory modality provides a novel dimension to present essential information to the users of a variety of hand- held devices provided the inputs are tailored to the properties of the sensory system. Much of the research on thermal displays has focused on their use to simulate the thermal properties of objects encountered in the environment so as to facilitate identification and discrimination [13]. Very few studies have examined the feasibility of using thermal cues to encode abstract information. One of the limitations in using thermal cues in this way is the relatively small number of sensations evoked by changes in skin temperature. Thermal stimulation results in perceptible warming or cooling and this is quantified in terms of the intensity and duration of the thermal stimulus. If changes in the magnitude of a variable are mapped onto variations in temperature, then the direction and rate of change are probably the most salient features to use.

Thermal displays can also be used to create thermal icons by analogy to tactile icons or tactons in the tactile domain or earcons in audition [24, 25]. Icons can be created using the four basic dimensions of stimuli namely quality, extension, intensity and duration. Quality refers to the various sensations evoked by different forms of stimulation, such as the warmth and cold induced by increasing and decreasing skin temperature, or the pain evoked at extreme temperatures. The attribute of extension characterizes the spatial aspects of a stimulus such as the location on the body stimulated and the size and separation between points of stimulation

[26]. There have been a few studies of thermal icons created by varying the direction, amplitude and rate at which the temperature of a thermal display changes [26-29]. In these studies, stimuli were created by varying the amplitude of each stimulus (±1, ±3 or ± 6 °C) and the rate of temperature change (1 °C/s or 3 °C/s). No measurements were made of the change in skin temperature in response to these thermal inputs although the thermal display was set at 32 °C so as to maintain skin temperature relatively constant between trials. The results from these experiments showed that the direction of change in temperature (i.e. warming or cooling) was the most salient feature of a thermal icon, that cooling was easier to detect than warming, and that the rates at which the thermal stimuli were presented affected the time to detect stimuli [28]. The reaction time to cold and warm stimuli are also different with cold stimuli being responded to more rapidly than warm stimuli [12]. Overall identification of small sets of thermal icons designed to convey information about the source and importance of a hypothetical text message has varied from 64% correct for four icons that differed with respect to quality and intensity [29], to 83% correct for a similar set of four icons [30]. The skin's thermal sensitivity varies as a function of location on the body. For the upper extremity, cold and warm thresholds are lower (better sensitivity) on the thenar eminence at the base of the thumb as compared to the forearm and fingertips [9].

The development of thermal icons for use in interacting with digital media should be based on our knowledge of human thermal sensory processing and on understanding the sources of errors that occur when identifying icons. Development of a set of thermal icons which are based on the thermal sensory system's characteristics is presented in this chapter. A set of experiments using these thermal icons was conducted with a thermal display. The development of the thermal display along with the experimental design and results are described. The experiments were designed to evaluate the effectiveness of the set of thermal icons in providing information. As a measure of the effectiveness of the icons, Information Transfer (IT) was calculated for the thermal icon set presented on the thenar eminence and the fingertips. These locations vary with respect to their thermal sensitivity and are candidates in a number of the proposed applications of thermal icons involving hand-held devices.

The objectives of the present experiments were (1) to determine which dimensions of thermal icons could be accurately identified and (2) to estimate the information transfer (IT) associated with these icons. IT values have often been measured for tactile icons and as they are dimensionless and independent of task conditions they can be directly compared across experiments and modalities [25]. The basis for designing thermal icons has not been well delineated, and so the thermal responses of the skin to stimulation were measured in the present experiment so as to understand which features of a thermal stimulus can potentially be encoded by thermoreceptors and perceived by the user. Preliminary experiments were conducted to evaluate how skin temperature changed in response to different types of thermal stimulation. These pilot studies were particularly focused on determining how rapidly skin temperature changed with the different thermal inputs and whether features of the thermal stimulus that may be used to create icons (e.g. a sinusoidal or square waveforms) were captured in the responses of the skin.

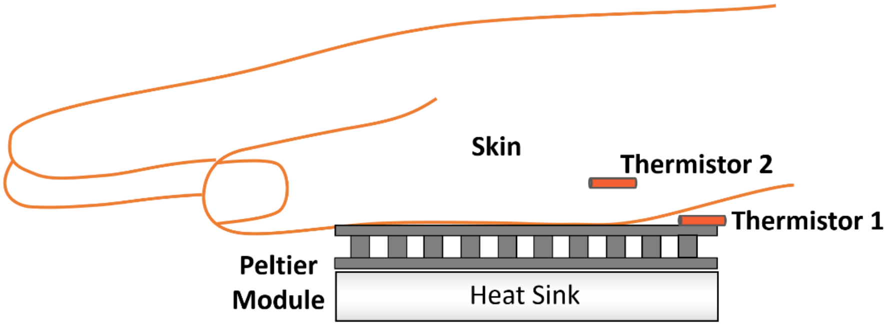


Figure 2.1 Concept of the thermal display with the thermoelectric module mounted on a heat sink and the thenar eminence placed over the thermoelectric module. Thermistors 1 and 2 measure the temperature of the display and the skin respectively.

2.2 Thermal Icons on Thenar Eminence

In the first experiment, the thenar eminence at base of the thumb was selected as the site to present stimuli as it is the most thermally sensitive region on the glabrous surface of the hand [9]. In addition to this, the base of the thumb was chosen as the site of stimulation as a number of the proposed applications of thermal icons involve the hand holding a device such as a mobile phone or computer mouse [e.g. 31, 32]. The concept of the thermal display on the thenar eminence is shown in Figure 2.1.

2.2.1 Experimental Design

The experiment was an absolute identification study in which participants had to identify which of six thermal stimuli that varied with respect to intensity and the rate and direction of change in temperature had been presented.

Participants

Ten normal healthy individuals, 8 males and 2 females, ranging in age from 20 to 28 years old (mean: 25 years) participated in the experiments. They were all right-handed. They had no known abnormalities of the skin or peripheral sensory or vascular systems. None of the participants had any significant experience in thermal stimuli pattern recognition. They all signed an informed consent form that was approved by the MIT Committee on the Use of Humans as Experimental Subjects.

Apparatus

A thermal display was developed using a thermoelectric module (Model TE-127-1.0-2.5, TE Technology, Inc.) mounted on a heat sink and fan. The thermoelectric module was a Peltier device, 30-mm in length and width, with a thickness of 4.8 mm as shown in Figure 2.3. The module’s temperature was controlled using a portable controller unit (Model TC-720, TE Technology, Inc.) run by a dual-mode power supply. Two thermistors, 457 µm in diameter and

3.18 mm in length (Model 56A1002-C8, Alpha Technics), were used in the experiment. One thermistor was mounted on the surface of the thermal display for feedback control of the device's temperature. The second thermistor measured the temperature of the skin in contact with the display. Two fixtures were fabricated using 3-D printing, one of which held the assembly of the thermoelectric module, heat sink and fan, and the other provided support for the subject's wrist and hand (see Figure 2.3). The input to the feedback control was the temperature of the display rather than skin temperature so that the same stimulus was delivered to all participants and the temperature of the skin was essentially the same at the start of each trial.

A LabVIEW-based (National Instruments) graphical user interface (GUI) was used to send commands to the controller for the thermal display and to record skin temperature continuously at 20 Hz. A second computer was used to run a GUI in LabVIEW on which the participants' responses were recorded.

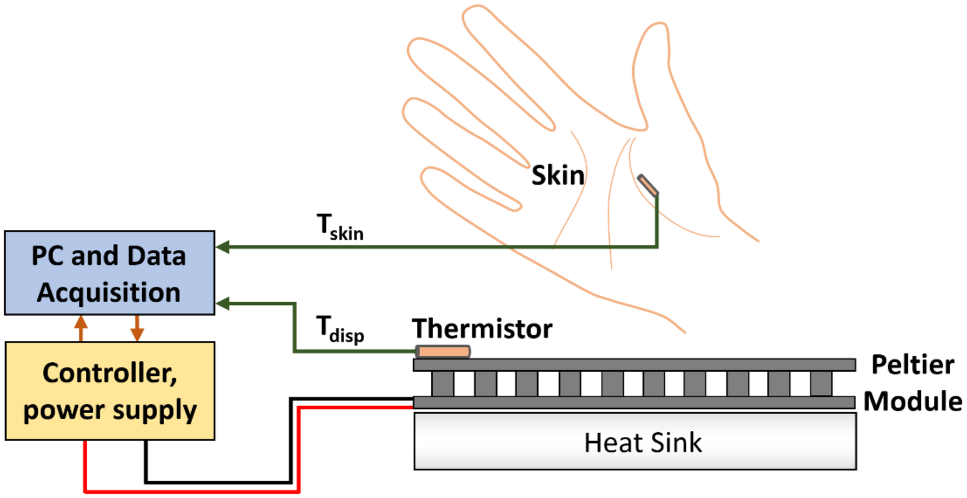


Figure 2.2 Schematic illustration of the thermal display with the Peltier module mounted on a heat sink, and thermistors measuring the temperature of the module and of the skin at the base of the thumb

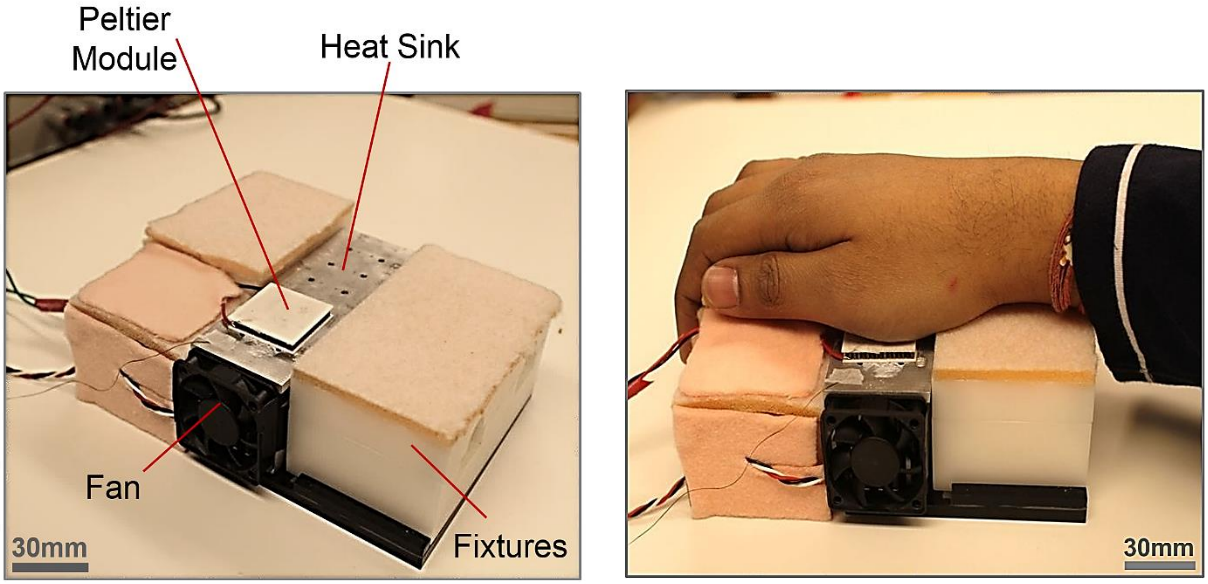


Figure 2.3 Thermal display with thermoelectric module mounted on a heat sink and fan (left) and with the thenar eminence over the thermoelectric module during stimulus presentation (right)

Thermal Stimuli

The thermal stimulus patterns were designed by varying two stimulus dimensions, the amplitude and rate of change in temperature. In terms of the stimulus dimensions described in the Introduction, the quality (i.e. warming or cooling the skin), intensity and duration (rate of change) were used to create these thermal icons (see Figure 2.4). Three basic thermal profiles (square wave, step and ramp) were used, each of which had two values to give a total of six patterns.

The duration of all six patterns was 30 seconds. Figure 2.5 provides a schematic illustration of the patterns that participants used to indicate their responses. The waveforms depicted were not intended to be precise in terms of the actual rate and intensity of the stimuli delivered but served to emphasize the differences among the patterns. The time and temperature axes did not have numeric values on them when viewed by participants. They were informed that the dotted red line represented the baseline skin temperature of 32 °C. Patterns A and F were based on a square wave input, B and D were linearly decreasing and increasing ramps, respectively, and C and E were based on a step input. The average rate of change of temperature was 3 °C/s for A and F, 0.7 °C/s for B and D, and 2 °C/s for C and E. The direction and intensity of the changes in temperature differed in the above pairs to make them more distinguishable. The temperature ranged between 24 and 38 °C for A and C, and 18 and 32 °C for E and F. The direction of the 18 °C change in temperature for B and D was reversed. The rate of temperature change and intensity values were chosen based on pilot studies which revealed the time course of changes in skin temperature in response to various thermal inputs (See Figure 2.6).

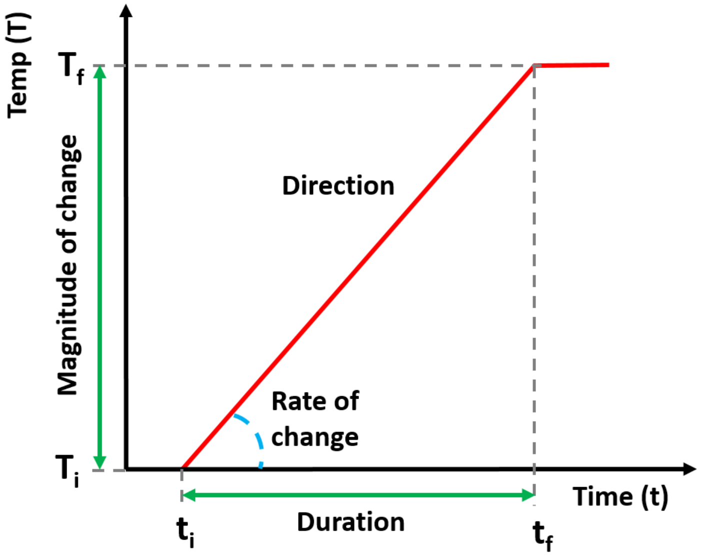


Figure 2.4 Visual depiction of the stimulus dimensions which were used to create a set of six thermal stimuli.

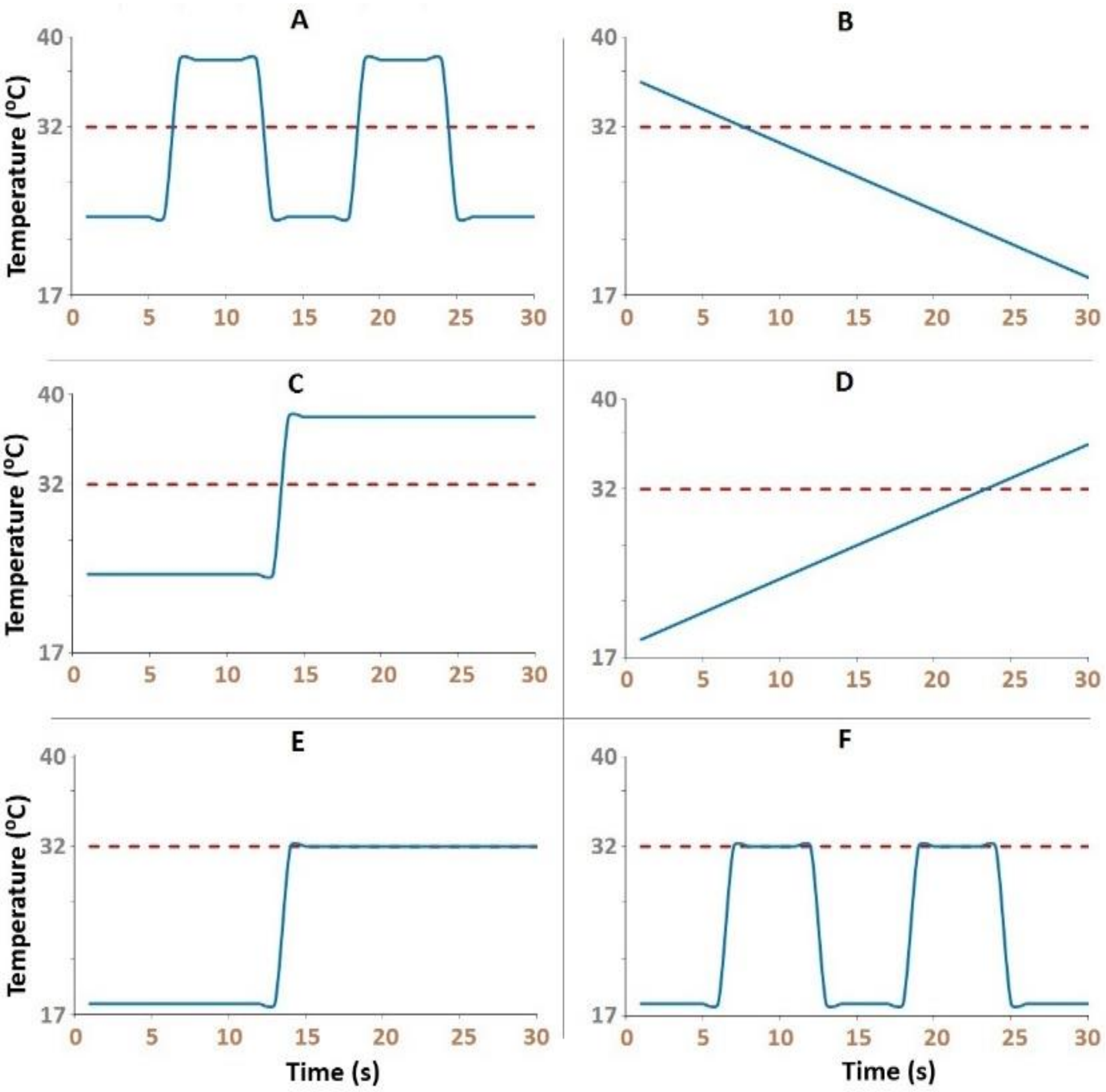
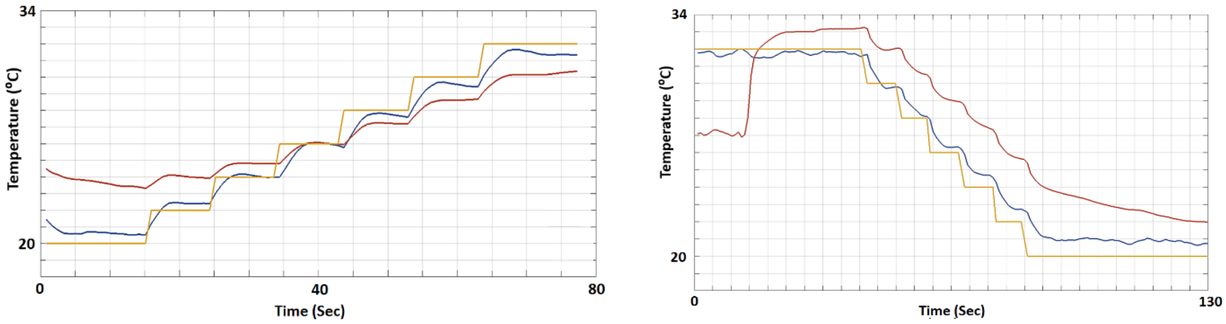
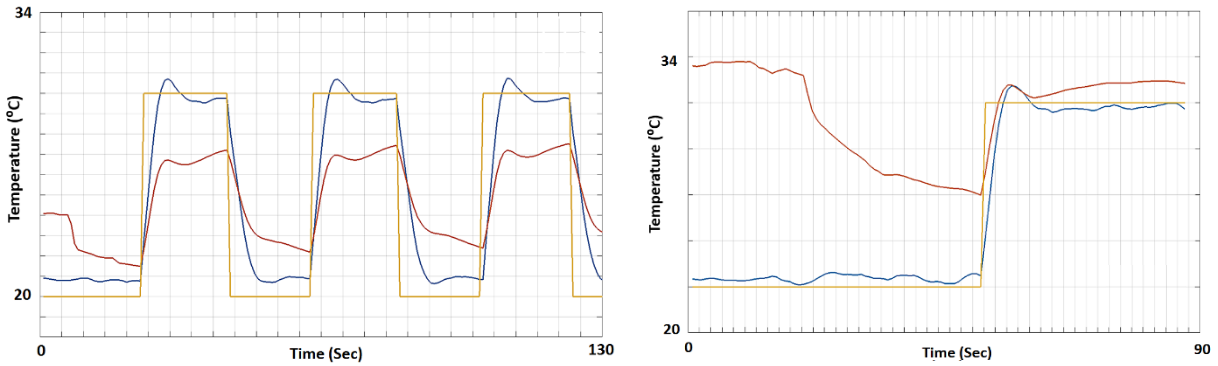


Figure 2.5 Visual depiction of the six thermal patterns that varied with respect to the intensity and rate of change in temperature. The dashed line indicates the baseline skin temperature. In the template that participants viewed there were no numeric values on the axes.



Heating Ramp

Cooling Ramp



Square Waveform with ΔT=10 ^{0}C

Heating Step

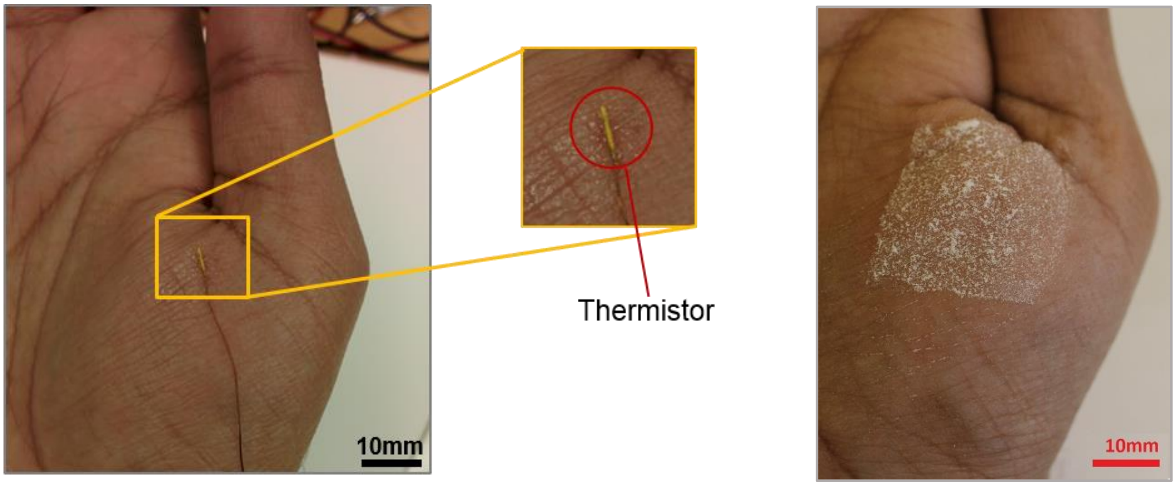
🟦 **Display** 🟥 **Skin** 🟨 **Set**

Figure 2.6 Pilot studies' data illustrating the response of the skin to different thermal stimuli

Procedure

Participants washed their hands prior to starting the experiment. A thermistor was then glued to the thenar eminence (at the base of the thumb) on the right hand using biocompatible cyanoacrylate (Liquid Bandage^{TM}, Johnson & Johnson) (see Figure 2.7). The thermistor was chosen on the basis of its small dimensions and low thermal mass. Initial skin temperatures of the participants ranged from 30 to 34 °C with a mean of 32 °C. The ambient temperature in the room was maintained at 24 °C, as measured with a thermocouple in free air. Participants placed their wrist and hand on the supporting fixture, and brought their thenar eminence in contact with the thermoelectric module's surface as illustrated in Figure 2.3 (a). The contact area between the hand and the Peltier device ranged from 600-750 mm^2 across participants (see Figure 2.7).

A visual depiction of the stimuli was presented on the computer screen in front of the participant (see Figure 2.5). In the familiarization period participants selected each stimulus in turn using a computer mouse and the stimulus was then presented on the hand while they looked at the visual display. After this, there was a series of practice trials in which stimuli were presented and participants had to indicate which pattern they felt. Feedback was provided after each response. After the practice session which typically lasted 5 minutes, the experiment began. To ensure that the skin temperature of the hand returned to a baseline temperature before each stimulus was presented, the thermal display was maintained at 30 °C for 20 seconds between trials.



(a) (b)

Figure 2.7 (a) Placement of thermistor on the skin for recording the skin temperature. In (b) baking soda was used to mark the contact area of the skin on thenar eminence with the thermal display

Each stimulus lasted 30 seconds and was presented eight times in a randomized order to give a total of 48 trials. Two different auditory cues were provided to signal the start and finish of each stimulus presentation. After the second auditory cue, participants indicated their responses by selecting the letter (A-F) associated with the visual pattern on the GUI on the screen. Responses had to be made within 10 seconds and on most trials participants made their responses within a couple of seconds. A rest break was provided when requested. No feedback regarding the correctness of the responses was provided during the main experiment.

2.2.2 Results

The group mean temperature measured on the hand and the thermal display during the experiment are shown in Figure 2.8. The initial data in each plot indicate that the display temperature remained constant at 30 °C and that the skin temperature was generally within 1 °C of the display temperature. At the onset of each stimulus the skin temperature tracks that of the display but does not reach the minimum and maximum intensities of the display temperature within the presentation time. As expected, the skin temperature changed more slowly than that of the display due to the thermal dynamics of the skin.

The participants' responses to the thermal stimuli were analyzed initially in terms of the percentage of correct responses for each stimulus. There was some variability across participants with individual mean scores averaged across all stimuli ranging from 89% to 98% correct and an overall mean of 91% correct. Figure 2.9 shows the mean percentage of correct responses for each of the six stimuli. Pattern B, which involved a linear decrease in temperature was the easiest stimulus to identify with 100% correct responses across participants, whereas pattern C which was a step change from cold to warm had the lowest percent of correct responses at 84%. Surprisingly, pattern D which was the opposite to pattern B with a linear increase in temperature from cold to warm was also one of the more difficult patterns to identify with 85% correct. Due to the inhomogeneity of the variance in the percent correct responses for each thermal stimulus, a non-parametric ANOVA (Friedman's test) was conducted on these data. The results indicated that there was a significant main effect of thermal stimuli (p=0.005). Post hoc analyses revealed that pattern B had a significantly higher number of correct responses than pattern C.

The confusion matrix of the participants' responses (Table 2.1) indicates which of the six stimuli were most frequently confused and provides cues as to the dimensions of thermal patterns that may have been difficult to encode. In general, participants made very few errors, and the patterns that were confused usually had similar properties. For example, patterns A and F were both square waves with different magnitudes and C and E were both step responses that differed with respect to the final temperature of the step input.

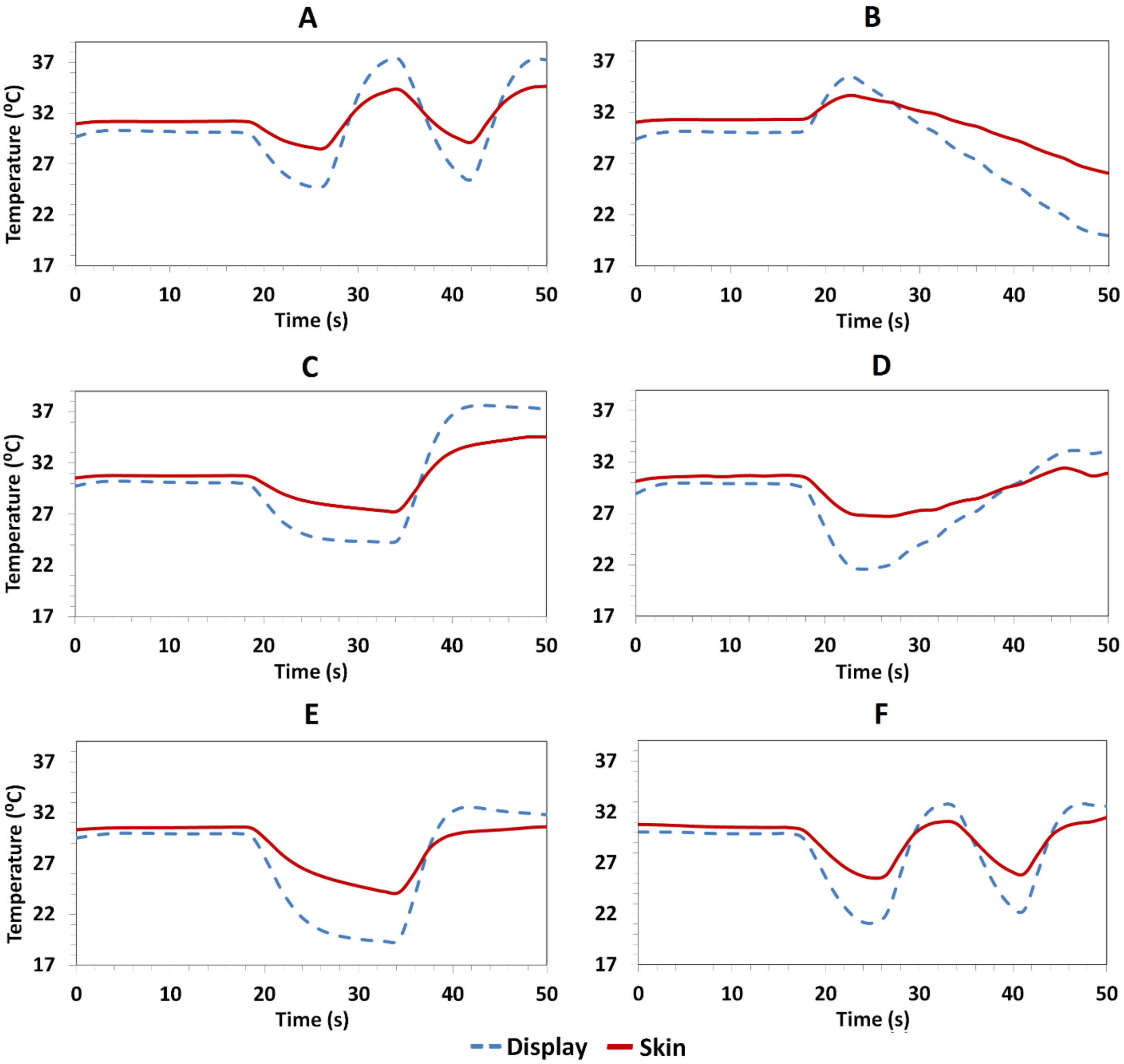


Figure 2.8 Temperatures measured on the skin and the display averaged across trials and subjects for each of the six thermal stimuli. The first 20 s of data prior to each stimulus presentation are also shown.

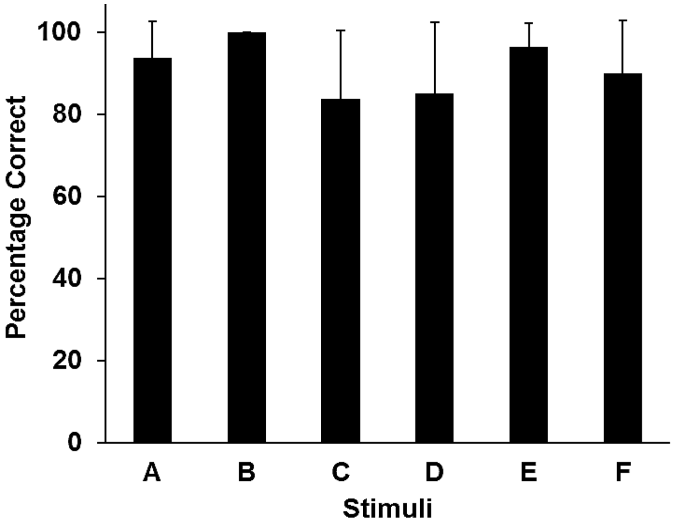


Figure 2.9 Group mean percent of correct responses for each thermal pattern. The standard deviations are shown.

Table 2.1 Confusion matrix of the group responses with scores out of the total of the 80 trials presented for each stimulus. The highlighted diagonal represents correct responses.

Stimuli	A	B	C	D	E	F
A	75	0	2	0	0	3
B	0	80	0	0	0	0
C	0	0	67	3	10	0
D	0	0	4	68	7	1
E	0	0	1	1	77	1
F	5	0	0	2	1	72

The information transfer (IT) was calculated from the confusion matrix from each participant using the relevant equations in Tan et al. [33]. IT values specify how many "bits" of information participants can distinguish from the set of patterns presented and indicate the maximum number of stimuli that can be identified without error. For each stimulus-response pair (S_i, R_j) the IT was calculated by:

$$\boldsymbol{IT\left(S_i, R_j\right) = \log_2\left(\frac{P(S_i/R_j)}{P(S_i)}\right)},$$

where $P(S_i/R_j)$ is the proportion of correct responses R_j for S_i, and $P(S_i)$ is the probability of stimulus S_i. The average IT value for each skin site and spacing was calculated using the equation:

$$\boldsymbol{IT} = \sum_{j=1}^{K}\sum_{i=1}^{K} \boldsymbol{P}(\boldsymbol{S}_i, \boldsymbol{R}_j) \log_2\left(\frac{\boldsymbol{P}(\boldsymbol{S}_i/\boldsymbol{R}_j)}{\boldsymbol{P}(\boldsymbol{S}_i)}\right) = \sum_{j=1}^{K}\sum_{i=1}^{K} \boldsymbol{P}(\boldsymbol{S}_i, \boldsymbol{R}_j) \log_2\left(\frac{\boldsymbol{P}(\boldsymbol{S}_i, \boldsymbol{R}_j)}{\boldsymbol{P}(\boldsymbol{S}_i)\boldsymbol{P}(\boldsymbol{R}_j)}\right),$$

where $P(S_i, R_j)$ is the probability of response R_j given S_i, and $P(R_j)$ is the probability of R_j. The maximum IT is called the Information in Stimulus (IS) which is the total number of bits contained in the stimuli or the IT value for 100% accuracy, and can be calculated more simply using the equation:

$$\boldsymbol{IS} = -\sum_{i=1}^{K} \boldsymbol{P}(\boldsymbol{S}_i) \log_2 \boldsymbol{P}(\boldsymbol{S}_i)$$

The IS, or maximum IT for 6 stimuli is 2.6 bits, meaning that there are 2.6 total possible bits of information to be transferred from the six stimuli that have to be identified. The calculation 2^{IT} gives the maximum number of stimuli that can be correctly identified, although it is not generally an integer [33]. The IT values ranged from 1.76 to 2.49 bits across participants and the group mean value was 2.11 bits. This is interpreted as indicating that for this set of six stimuli 4.3 patterns can be correctly identified.

2.3 Thermal Icons on Fingertips

The fingertips of our hands are not as sensitive to thermal stimuli as the base of the thumb or several other locations such as the wrist or forearm. The objective of this experiment was to present the same set of thermal icons, as that used in the first experiment, to the fingertips of the first two fingers of the right hand and compare the results with those obtained on the thenar eminence. In this experiment apart from the location of the presentation of the thermal stimuli, all other parameters were the same as those used in the first experiment.

2.3.1 Experimental Design

Participants

Eight normal healthy individuals, 6 males and 2 females, ranging in age from 20 to 27 years old (mean: 25 years) participated in the experiments. They were all right-handed. They had no known abnormalities of the skin or peripheral sensory or vascular systems. None of the participants had any significant experience in thermal stimuli pattern recognition. They all signed an informed consent form that was approved by the MIT Committee on the Use of Humans as Experimental Subjects.

Apparatus

The second experiment used the same apparatus as was used in the first experiment where the thermal icons were presented on the thenar eminence. The thermal display based on a Peltier device provided the thermal stimuli to the skin on the fingertips (see Figure 2.10).

Procedure

Participants washed their hands prior to starting the experiment. A thermistor was then glued to the edge of the index finger on the right hand using biocompatible cyanoacrylate (Liquid Bandage^{TM}, Johnson & Johnson). Initial skin temperatures of the participants ranged from 29 to

33 °C with a mean of 30 °C. The ambient temperature in the room was maintained at 24 °C, as measured with a thermocouple in free air. Participants placed their palm and the wrist on the supporting fixture, and brought their fingertips in contact with the thermoelectric module's surface.

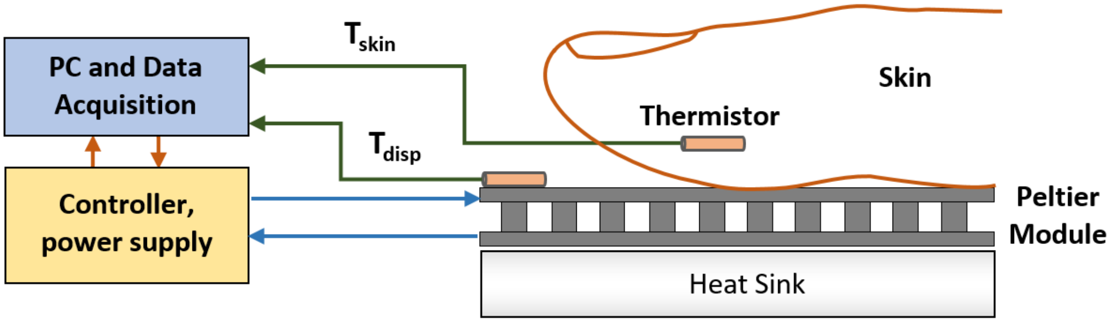


Figure 2.10 Thermal display with thermoelectric module mounted on a heat sink and fan (left) and with the fingertips over the thermoelectric module during stimulus presentation (right)

The contact area between the fingers and the Peltier device was 600-700 mm^2 across participants, which was similar in range to the first experiment (see Figure 2.11). A visual depiction of the stimuli was presented on the computer screen in front of the participant (see Figure 2.5). In the familiarization period participants selected each stimulus in turn using a computer mouse and the stimulus was then presented on the hand while they looked at the visual display. After this, there was a series of practice trials in which stimuli were presented and participants had to indicate which pattern they felt. Feedback was provided after each response. After the practice session which typically lasted 5 minutes, the experiment began. To ensure that the skin temperature of the hand returned to a baseline temperature before each stimulus was presented, the thermal display was maintained at 30 °C for 20 seconds between trials.

Each stimulus lasted 30 seconds and was presented eight times in a randomized order to give a total of 48 trials. Two different auditory cues were provided to signal the start and finish of each stimulus presentation. After the second auditory cue, participants indicated their responses by selecting the letter (A-F) associated with the visual pattern on the GUI on the screen. Responses had to be made within 10 seconds and on most trials participants made their responses within a couple of seconds. A rest break was provided when requested. No feedback regarding the correctness of the responses was provided during the main experiment.

Figure 2.11 Baking soda was used to mark the contact area of the skin on the fingertips with the thermal display.

2.3.2 Results

The group mean temperature measured on the hand and the thermal display during the experiment are shown in Figure 2.12. The initial data in each plot indicate that the display temperature remained constant at 30 °C and that the skin temperature was generally within 1 °C of the display temperature. It is evident from the plots that skin temperature changed more slowly than that of the display due to the thermal dynamics of the skin.

The percentage of correct responses for each stimulus among participants averaged across all stimuli ranged from 75% to 85% correct with an overall mean of 80% correct. Figure 2.13 shows the mean percentage of correct responses for each of the six stimuli. Pattern B, which involved a linear decrease in temperature was the easiest stimulus to identify with 100% correct responses across participants, whereas pattern D which was the opposite to pattern B with a linear increase in temperature from cold to warm had the lowest percent of correct responses at 64%. Pattern C which was a step change from cold to warm was also one of the more difficult patterns to identify with 75% correct. The results of a non-parametric ANOVA (Friedman's test) indicated that there was a significant main effect of thermal stimuli (p=0.005). Post hoc analyses revealed that pattern B had a significantly higher number of correct responses than pattern D.

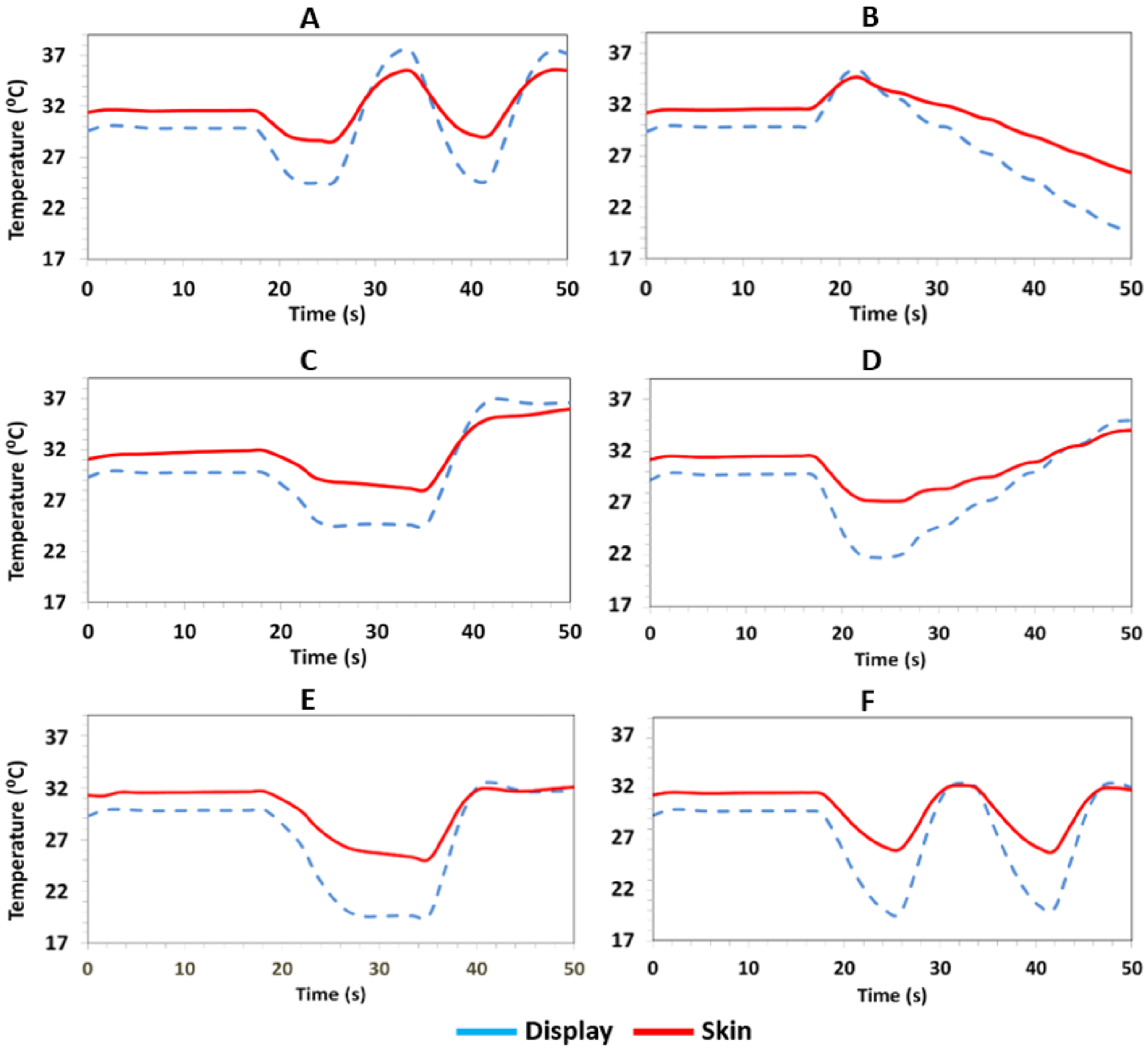


Figure 2.12 Temperatures measured on the skin and the display averaged across trials and subjects for each of the six thermal stimuli. The first 20 s of data prior to each stimulus presentation are also shown.

The confusion matrix of the participants' responses (Table 2.2) indicates that participants confused patterns A and F which were both square waves with different magnitudes. Surprisingly, participants confused pattern C with pattern D, which differed in respect to the rate at which temperature changed. Pattern D was confused most often with pattern E, which can be attributed to the similarity in their ranges of temperature.

The IT values, calculated from the confusion matrix from each participant, ranged from 1.66 to 2.02 bits across participants and the group mean value was 1.83 bits. This is interpreted as indicating that for this set of six stimuli 3.6 patterns can be correctly identified.

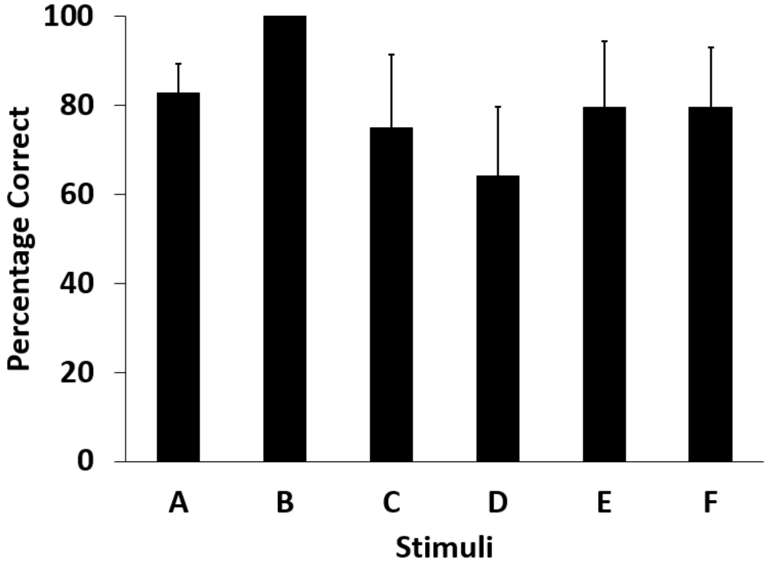


Figure 2.13 Group mean percent correct responses for each thermal pattern. The standard deviations are shown.

Table 2.2 Confusion matrix of the group responses with scores out of the total of the 64 trials presented for each stimulus. The highlighted diagonal represents correct responses.

Stimuli	A	B	C	D	E	F
A	53	0	0	0	0	11
B	0	64	0	0	0	0
C	0	0	48	13	3	0
D	0	0	6	41	17	0
E	0	0	4	9	51	0
F	13	0	0	0	0	51

2.4 Discussion

The results from the present experiments indicate that small sets of thermal icons created by varying the direction, magnitude and rate of temperature change can be readily identified with little training. The overall performance of participants in the first experiment was 91% correct which is better than the 83% correct reported by Wilson et al. [30] for a smaller set of four thermal icons. In the second experiment in which the thermal stimuli were presented on the fingertips, the participants achieved 80% correct responses. However, in the experiment by Wilson et al. each stimulus was presented for 10 s as compared to 30 s in the present study, which no doubt contributed to the better performance reported here. It is also possible that auditory cuing of the stimulus onset and offset facilitated performance. This was implemented so that participants would attend to the stimuli and know when to make a response. In contrast to other types of stimulation involving the skin, such as vibration, the temperature of the skin is continually changing, particularly on the hands and feet, and so even when the thermal stimulus has finished, the skin continues to change temperature.

The decision to use a relatively long presentation time was based on pilot studies on the changes in skin temperature with different thermal inputs. Pilot data indicated that skin temperature changed slowly over the temperature range of interest and that for stimuli such as square-wave inputs a longer presentation time was required in order for the stimuli to be represented on the skin. These preliminary experiments also revealed that different input waveforms such as sinusoids, square waves and triangular waves would not be perceptually distinguishable as the changes in skin temperature with each of these input signals were very similar when presented over 30 s intervals. One of the objectives of the experiment was to identify stimulus features that were accurately identified that could then be used to create shorter, highly salient, thermal icons.

The present experiment also revealed the importance of recording changes in skin temperature during stimulus presentation as these measurements provide insight into the responses made by participants. Pattern B had the highest accuracy in terms of identification and was the only stimulus that involved a slight increase in temperature followed by a steady decrease. In future experiments it will be important to determine whether this result reflects the uniqueness of the stimulus or the superior ability to detect cold as compared to warmth [8, 9]. The two icons that were the most difficult to identify were patterns C (a step input) and D (a ramp). The skin temperature measurements made while these were presented indicate that the change in temperature was very similar for these two icons (see Figure 2.8 and Figure 2.12). In addition, they were both most likely to be misidentified as pattern E (see Table 2.1 and Table 2.2), which also resulted in a similar temperature profile. If a larger set of thermal icons were to be created and evaluated these transient thermal responses of the skin would need to be taken into account to maximize the distinctiveness of the icons. Clearly, the presentation time for thermal icons will need to be reduced if they are to be implemented in hand-held displays. For this to occur the initial transient thermal responses on the skin will need to be made as distinct as possible. It is known that the time taken to process thermal information is slower than that for other aspects of cutaneous stimulation [34] and so it is unlikely that a high throughput rate will ever be feasible for thermal icons.

One challenge in implementing thermal icons in a display will be thermal adaptation, which refers to the decrease in neural responsiveness to stimulation with continuous exposure to the stimulus [10]. The skin adapts to both warm and cold stimulation, and the rate at which adaptation occurs is very rapid for temperatures close to that of the skin, and much slower for more extreme temperatures [35]. Much of the research on the temporal aspects of thermal stimulation such as adaptation has focused on its effect on thermal thresholds [36], rather than supra-threshold stimuli of the type used in the present study. Future research will need to address this shortcoming and determine which rates of stimulus presentation are optimal for identification and how changes in the baseline temperature of the skin influence identification. For the group of participants in the present experiment, baseline skin temperatures ranged between 30 and 34 °C. However, under normal conditions the resting temperature of the skin of the hand can vary between 25 and 36 °C across individuals [37, 38]. This means that thermal stimuli such as those used in the present experiment can evoke very different perceptual responses across individuals because the same stimulus may warm or cool the skin depending on its initial temperature.

The response required of participants was to match the thermal sensation on the hand to a schematic visual representation of the thermal input (Figure 2.5). As the responses depicted in Figure 2.7 and Figure 2.11 illustrate the change in skin temperature did not precisely match these representations and there was always an initial transient response as the skin cooled or warmed. A more realistic representation of the change in skin temperature should be adopted in future work using this experimental paradigm. Alternative strategies such as training participants initially to associate each thermal stimulus with an abstract concept could also have been implemented, as this has been successfully employed previously [29].

The mean IT of 2.11 bits for the stimulus presentation on the thenar eminence was surprisingly high given previous findings on thermal icon identification [29, 30]; it is important to note that in the latter studies the participants were mobile and outdoors and so the thermal conditions were much more dynamic. With six stimuli, the IT value is interpreted as indicating that between four and five thermal patterns can be identified. For the tactile modality, IT values of around 2.4 bits have been reported for sets of nine vibrotactile tactons presented at a single site on the hand [25]. Similar to the present experiment, these studies also required that participants match the tactile pattern to a visual representation. Higher IT rates have been found when spatial signals have been used to create vibrotactile tactons [39]. Spatially distributing stimulation across the hand would probably be much less effective for the thermal modality because of the pervasive spatial summation that occurs. Yang et al. [40] found that participants were unable to discriminate between two thermal inputs presented on the fingertip and that thermal stimuli displayed on one finger influenced the perception of stimuli presented to other fingers on the same hand. One possible dimension of thermal stimulation that should be further explored in this context is creating the perception of moisture or wetness by delivering particular patterns of cold and pressure stimulation [41].

2.5 Conclusion

The results from this experiment indicate that small sets of thermal icons created by varying the direction, magnitude and rate of temperature change can be readily identified with little training. The temperature of the skin tracked that of the thermal display but did not reach the minimum and maximum intensities of the display within the presentation time. Preliminary experiments on the response of the skin to various types of thermal inputs indicated that waveforms such as square waves, sinusoids and triangular waves resulted in very similar changes in skin temperature and so were unlikely to be perceptually distinguishable. The three profiles selected did produce distinct changes in temperature as reflected in the participants' performance. The individual mean scores associated with the six thermal stimuli ranged from 80% to 98% on the thenar eminence and from 81% to 88% on the index finger with overall means of 91% and 84% respectively. The information transfer values for the thenar eminence averaged 2.11 bits and for the finger 1.83 bits. These findings demonstrate that with sufficiently long presentation times, the information processing capabilities of the thermal sensory system may rival those achieved with vibrotactile inputs. Finally, the results provide support for the use of thermal displays in applications in which the device or interface is grasped in the palm of the hand.

Chapter 3

Thermal Pattern Identification with Revised Thermal Icons

3.1 Motivation and Concept

The previous experiments on absolute identification of thermal patterns on the thenar eminence and the fingertips showed that a set of unique thermal icons can be created with effective stimulus dimensions. The thermal icons were more accurately identified on the thenar eminence as compared to the fingertips which indicated the importance of considering the variable thermal sensitivity across the human body.

The set of six thermal icons presented on the thenar eminence were identified accurately and when performance was evaluated in terms of Information Transfer (IT) the IT values were comparable to those of other tactile modalities such as vibrotactile inputs. This supports the use of thermal displays in applications in which the device or interface is grasped in the palm of the hand. However, the long duration of 30 seconds for each thermal icon limits the application of these icons in displays. The earlier studies which proposed the concept of thermal icons [29, 30] used a stimulus duration of 10 seconds followed by an adaptation period of 20 seconds.

In the earlier experiment the same absolute change in temperature was presented to all the participants. The skin temperature was recorded at the periphery of the contact area only to monitor the change in temperature of the skin in contact with the display, and was not used as an input to the thermal display. In order to present the same change in temperature to all users, the thermal stimuli should be presented relative to the user's skin temperature. Such a set of thermal icons should induce similar thermal sensations by presenting the same temperatures to all users.

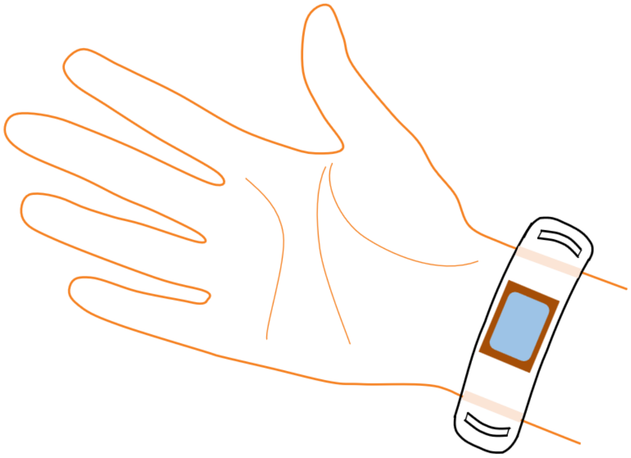


Figure 3.1 Concept of the thermal display mounted on a user's wrist with a strap.

Improvements in the design of the thermal icons are required if they are to be used effectively in a thermal display. A set of revised thermal icons were created that had a shorter duration and a profile that was determined by the user's skin temperature. The location of the thermal display on the body is important due to large variations in thermal sensitivity. It is reported that the thenar eminence at the base of the thumb and the wrist have better sensitivity as compared to the forearm and fingertips [9]. The wrist is one of the most thermally sensitive regions in the upper extremity and a wearable thermal display on the wrist is also convenient for user-based applications. The concept of the thermal display is shown in Figure 3.1.

In this chapter the development of a wearable thermal display is described together with the results from an absolute identification experiment in which a revised set of thermal icons was presented. The objectives of the present experiment were (1) to develop a revised set of thermal icons that are presented relative to the participant's baseline skin temperature and that have a shorter duration of 10 seconds, and (2) to estimate the information transfer (IT) associated with these thermal icons.

3.2 Experimental Design

Participants

Ten normal healthy individuals, 10 males, ranging in age from 20 to 28 years old (mean: 25 years) participated in the experiments. They were all right-handed. They had no known abnormalities of the skin or peripheral sensory or vascular systems. None of the participants had any significant experience in thermal stimuli pattern recognition. They all signed an informed consent form that was approved by the MIT Committee on the Use of Humans as Experimental Subjects.

Apparatus

A wrist strap based thermal display was developed using a thermoelectric module (Model TE-83-1.0-1.5, TE Technology, Inc.) mounted on a water cooled copper heat sink. The thermoelectric module was a 22 mm long and 19 mm wide Peltier device, with a thickness of 3.8 mm, giving a contact area of 418 mm^2. The water cooled heat sink was a CNC milled copper water block (Model WBA-1.00-0.49-CU-01, Custom Thermoelectric) with a cross-section of 25 mm x 25 mm and a thickness of 12 mm. The water block was connected to a 200 ml capacity water tank (80 mm x 60 mm x 60 mm) made from laser cut acrylic sheets; a continuous flow of water in the assembly was maintained by a DC brushless submersible water pump (Model DC30A-1230, ZKSJ) with dimensions of 40 mm x 40 mm x 30 mm. The water-based cooling system was chosen in preference to a fan based system as it provided more rapid cooling and did not result in any vibration sensations on the wrist.

Three thermistors, 457 µm in diameter and 3.18 mm in length (Model 56A1002-C8, Alpha Technics) were used in the experiment. The thermistor was chosen on the basis of its small dimensions and low thermal mass. One thermistor was mounted on the surface of the thermal display for feedback control of the device’s temperature. Two other thermistors measured the temperature at two locations on the skin. A schematic of the thermal display with thermistors and the control setup is shown in Figure 3.2.

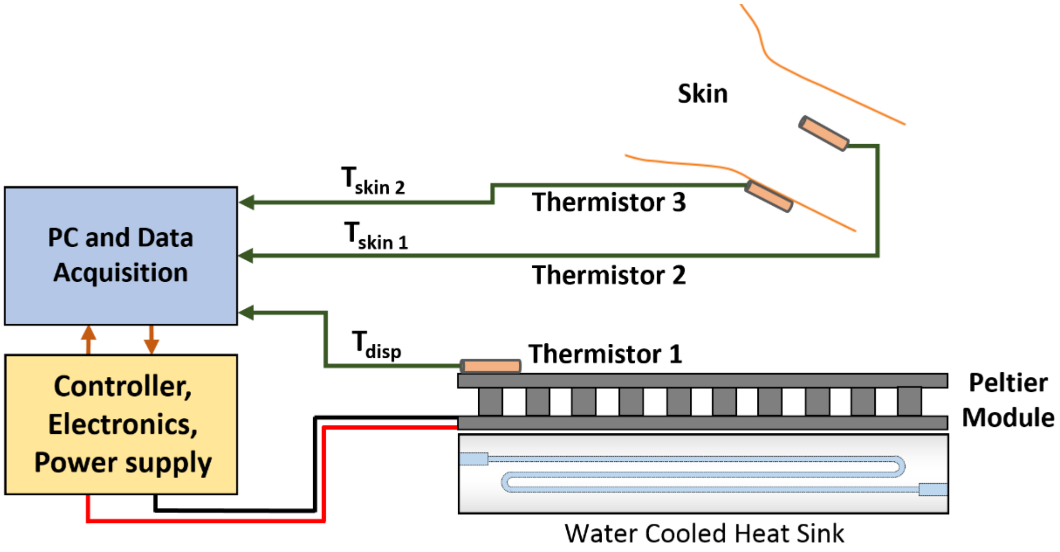
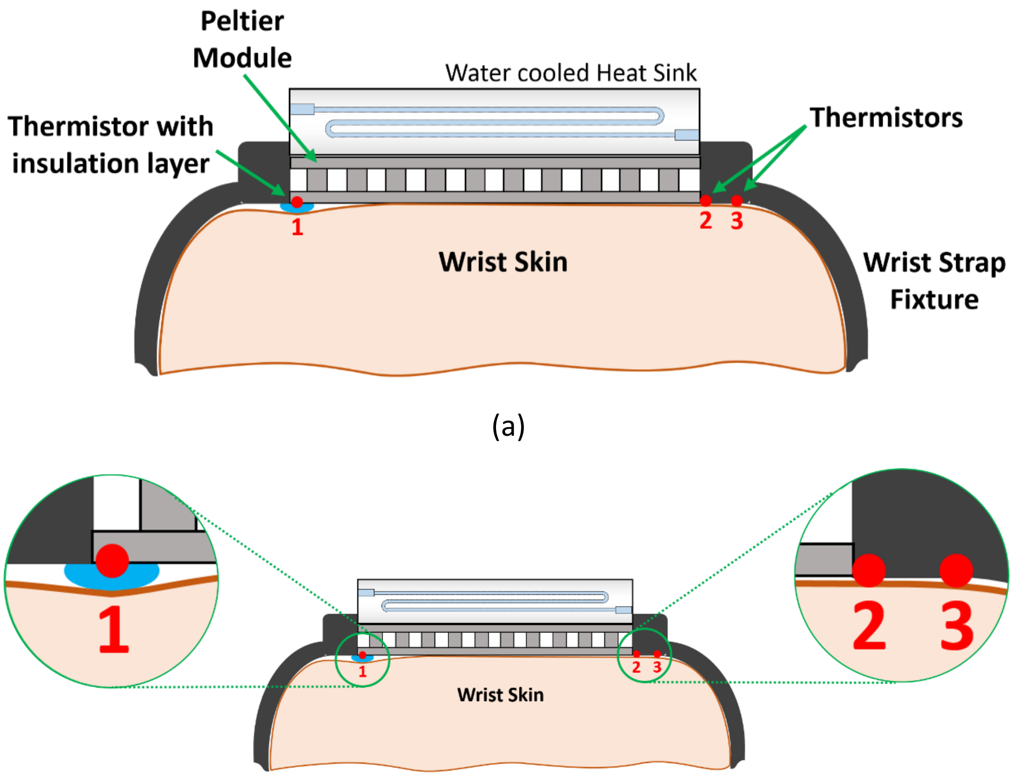


Figure 3.2 Schematic illustration of the thermal display with the Peltier module mounted on a water cooled heat sink, and thermistors measuring the temperature of the module and of the skin on the wrist

Figure 3.3 depicts the cross-sectional view of the setup mounted on the wrist with the three thermistors. The thermistor at location 1 measured the temperature of the Peltier module's surface as shown in Figure 3.3 (b). There was an insulation layer on one side of it to prevent thermal contact with the skin and thus reduce the error in measuring the display temperature. The thermistor at location 2 measured the skin temperature at the edge of the contact area of the skin with the Peltier module (see Figure 3.3 (b)). This measurement indicated the change in skin temperature due to the thermal stimulus presented on the thermal display. A baseline temperature measurement on the wrist was given by the thermistor at location 3 (see Figure 3.3 (b)). This baseline skin temperature measurement was different for each participant and was unaffected by the thermal stimuli due to the measurement location. The wrist mounted fixture for holding the Peltier module and the heatsink was fabricated using a rapid prototyping system (Viper Laser Stereolithography Forming Center, 3D Systems) (see Figure 3.4). The fixture was designed such that it could comfortably fit on the wrist and then can be fastened so that it could not move (see Figure 3.5 (a)). The surfaces of the Peltier module and thermistors were made flush with the surface of the fixture in contact with the skin.



(a)

(b)

Figure 3.3 (a) Cross-sectional view of the setup showing the thermal display mounted on the wrist using a strap. A water cooled heat sink mounted on the thermoelectric module is also shown. (b) Magnified view of the position of three thermistors as indicated by numbers 1, 2 and 3. Thermistor 1 has an insulation layer on one side to avoid thermal contact with the skin. Thermistor 2 measures the skin temperature at the periphery of the contact area of the skin and the display. Thermistor 3 measures the baseline skin temperature which is unaffected by the display temperature.

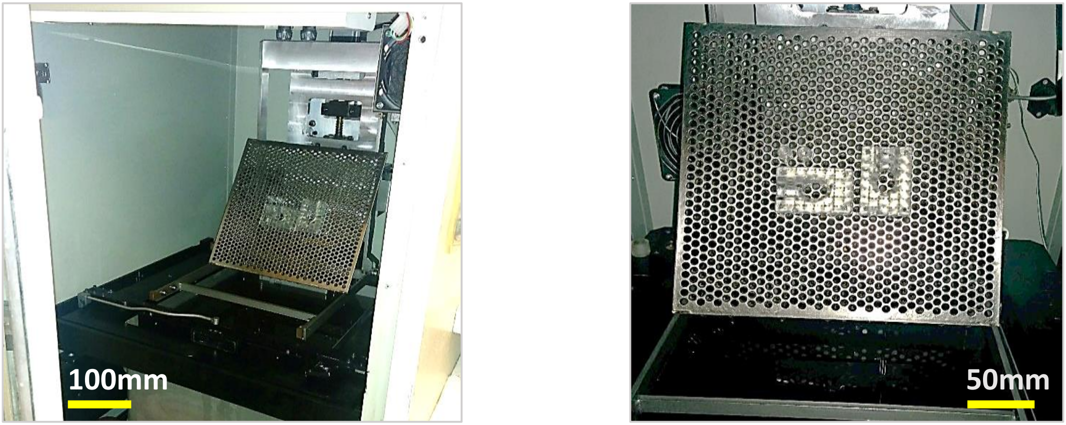
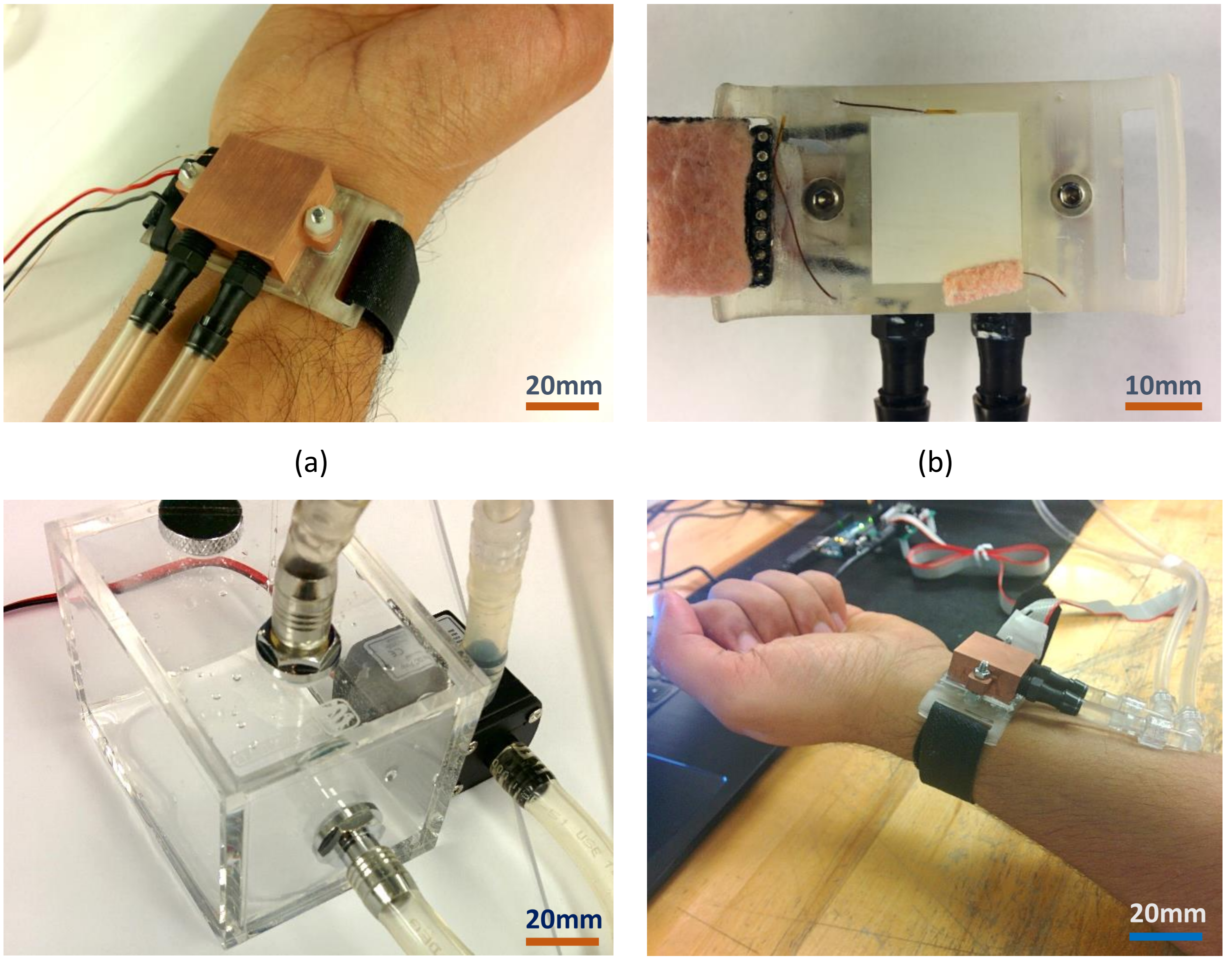


Figure 3.4 Fabrication of fixture in Viper Laser Stereolithography Forming Center.

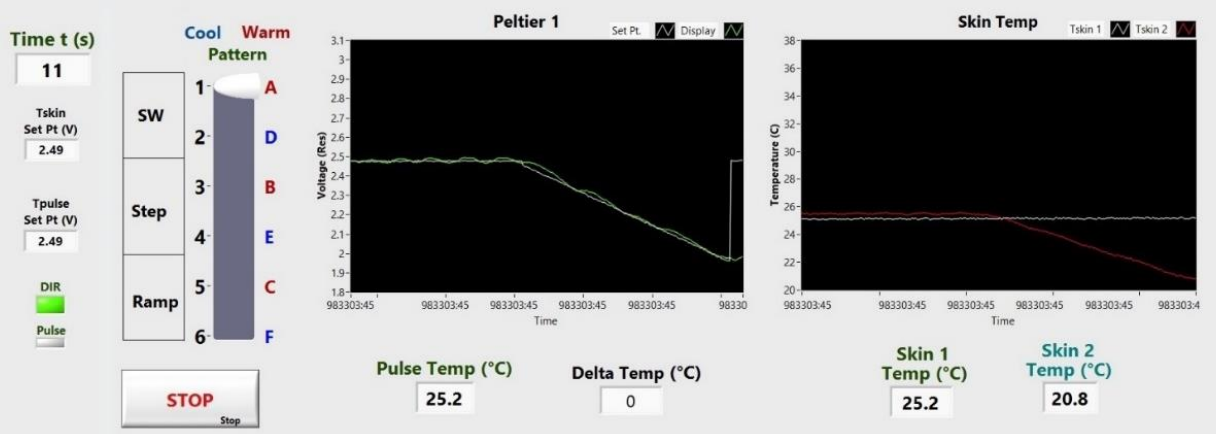


(a) (b)

(c) (d)

Figure 3.5 (a) Water block mounted over the fixture and the assembly fastened onto the wrist of the user. (b) The inner side of the display showing the Peltier module surface and thermistors 1 (under the insulation layer), 2 and 3. (c) Assembly of water cooling system showing the water tank and submersible pump. (d) The fully functional setup worn by the user on the wrist of the left hand.

Data acquisition and feedback control of the Peltier device was done using National Instruments data acquisition modules (Model NI cDAQ-9174, NI 9263, NI 9474, NI9205). A LabVIEW-based (National Instruments) graphical user interface (GUI) (see Figure 3.6) was used to send commands to control the Peltier module, and to record the skin temperatures continuously at 1 kHz. The baseline skin temperature was given as the input to the controller at the start of each trial, and was used as the reference temperature when the thermal stimulus was presented so that the same relative stimulus was delivered to all participants. A second computer was used to run a GUI on which the participants' responses were recorded.


Time t (s): 11

Tskin Set Pt (V): 2.49

Tpulse Set Pt (V): 2.49

Pulse Temp (°C): 25.2

Delta Temp (°C): 0

Skin 1 Temp (°C): 25.2

Skin 2 Temp (°C): 20.8

Figure 3.6 Screen shot of the GUI developed in LabVIEW used to send commands to the controller and record the temperatures from the thermistors.

Thermal Stimuli

Similar to the set of thermal patterns used in the previous experiments, this set of thermal patterns was also designed by varying two stimulus dimensions, the amplitude and rate of change in temperature. As shown in Figure 3.7, the quality (i.e. warming or cooling the skin), intensity (magnitude of change) and duration (rate of change) were used to create these thermal icons. The initial temperature (T_i) was set at the baseline skin temperature, which means that the intensity or magnitude of the temperature change was relative to the temperature measured by thermistor 3.

Each of the three basic thermal profiles (square wave, step and ramp) provided a different rate of temperature change and varied in direction (warming or cooling) to give a total of six patterns. Preliminary experiments were conducted to evaluate how skin temperature changed in response to the short duration thermal profiles. These pilot studies were used to observe the time course of changes in skin temperature in response to various thermal inputs, and to determine the rate of temperature change, intensity and duration of the stimuli.

The intensity (ΔT) was kept fixed at 6 °C for both warming and cooling. The total duration of each of the six patterns was 8 seconds preceded by a 5 seconds calibration period in which the display maintained its surface at the baseline skin temperature. Patterns A and D were based on a square wave input, B and E were based on a step input, and C and F were linearly decreasing and increasing ramps. The average rate of change of temperature was 3 °C/s for A and D, 1.5 °C/s for B and E, and 0.7 °C/s for C and F. The maximum rate of change of the temperature was limited by the dynamics of the thermal display system. The difference in the direction of temperature change (warming or cooling) in the above pairs made them distinguishable.

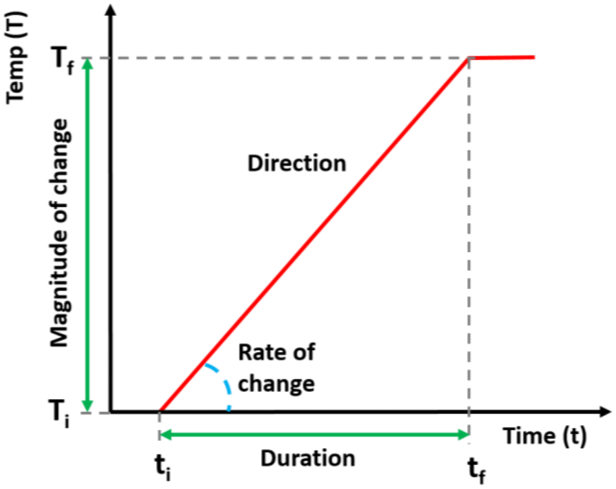


Figure 3.7 Stimulus dimensions used to create the thermal icons – direction (warming or cooling), intensity (magnitude of temperature change) and rate of temperature change.

Procedure

Prior to starting the experiment, the procedure was explained to participants and the thermal display was placed on the wrist and then the strap was tightened to a comfortable level. Participants read the instructions on the computer screen. They were then familiarized with the thermal patterns that would be presented. In the familiarization period participants selected each stimulus in turn using a computer mouse and the stimulus was presented on the wrist while they looked at the visual display. After this, there was a series of practice trials in which stimuli were presented and participants had to indicate which pattern they felt. Feedback was provided after each response. After the practice session which typically lasted 5 minutes, the experiment began. The initial skin temperatures of the participants ranged from 30 to 32 °C with a mean of 31 °C. The ambient temperature was maintained at 25 °C, as measured with a thermocouple in free air. The thermal display was maintained at the baseline skin temperature between the trials before each stimulus was presented.

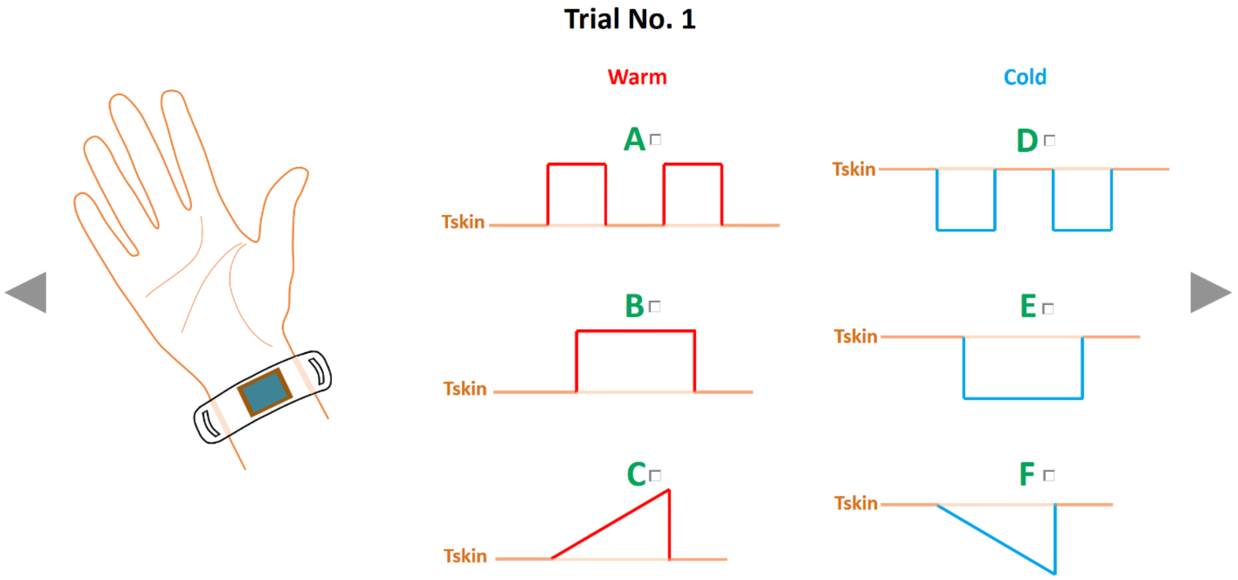


Figure 3.8 Screen shot of the GUI presented on the computer screen in front of the participants, and used by them to record their responses. It shows the placement of the thermal display on the wrist and visual depiction of the six thermal patterns.

Each trial lasted 13 seconds with a calibration period of 5 seconds prior to stimulus presentation which lasted 8 seconds. During the calibration period, the display temperature was maintained at the baseline skin temperature as measured by thermistor 3. Each stimulus was presented eight times in a randomized order to give a total of 48 trials. Two different auditory cues were provided to signal the start and finish of each stimulus presentation. After the second auditory cue, participants indicated their responses by selecting the checkbox beside the letter (A-F) associated with the visual pattern on the GUI on the screen (see Figure 3.8). The GUI as shown in Figure 3.8 depicts the placement of the thermal display on the wrist of either the left or right hand of the participant. Responses had to be made within 10 seconds and on most trials participants made their responses within a couple of seconds. After every six trials, participants switched the display to the other wrist in order to avoid any adaptation effects. A rest break was provided when requested. No feedback regarding the correctness of the responses was provided during the main experiment.

3.3 Results

The temperatures measured on the three thermistors averaged across all the participants are shown in Figure 3.9. The plots show temperature measurements in the first 11 seconds of a trial which includes the initial calibration period. These data indicate that thermistor 2 records the change in skin temperature when the stimuli are presented on the display. It is evident from the plots that the skin temperature changed more slowly than that of the display due to the thermal dynamics of the skin. The skin temperature measured at thermistor 3 is the baseline skin temperature and did not change during stimulus presentation due to its location.

The percentage of correct responses for each stimulus among participants averaged across all stimuli ranged from 81% to 100% correct with an overall mean of 89% correct. Figure 3.10 shows the mean percentage of correct responses for each of the six stimuli. Patterns A and D, which were based on a square wave profile and had two temperature pulses were more distinct than the other patterns and were the easiest stimuli to identify with 99% and 100% correct responses across participants. Pattern F, which was a linear decrease and then increase in temperature from cold to warm had the lowest percentage of correct responses at 73%. Pattern B which was a step change from the baseline skin temperature to a warm temperature was also one of the more difficult patterns to identify with 81% correct. The results of a non-parametric ANOVA (Friedman's test) indicated that there was a significant main effect of thermal stimuli ($p<0.001$).

The confusion matrix of the participants' responses (Table 3.1) indicates that participants confused patterns F with E, in which the skin temperature decreased with the rate of change in temperature being the differentiating factor. The reason for such a confusion can probably be attributed to the similar pattern of change in skin temperature, as can be seen in Figure 3.9. A similar observation can be made for patterns B and C, which had same direction of temperature change and differed in the rate of change. Surprisingly, participants sometimes confused pattern B with pattern A.

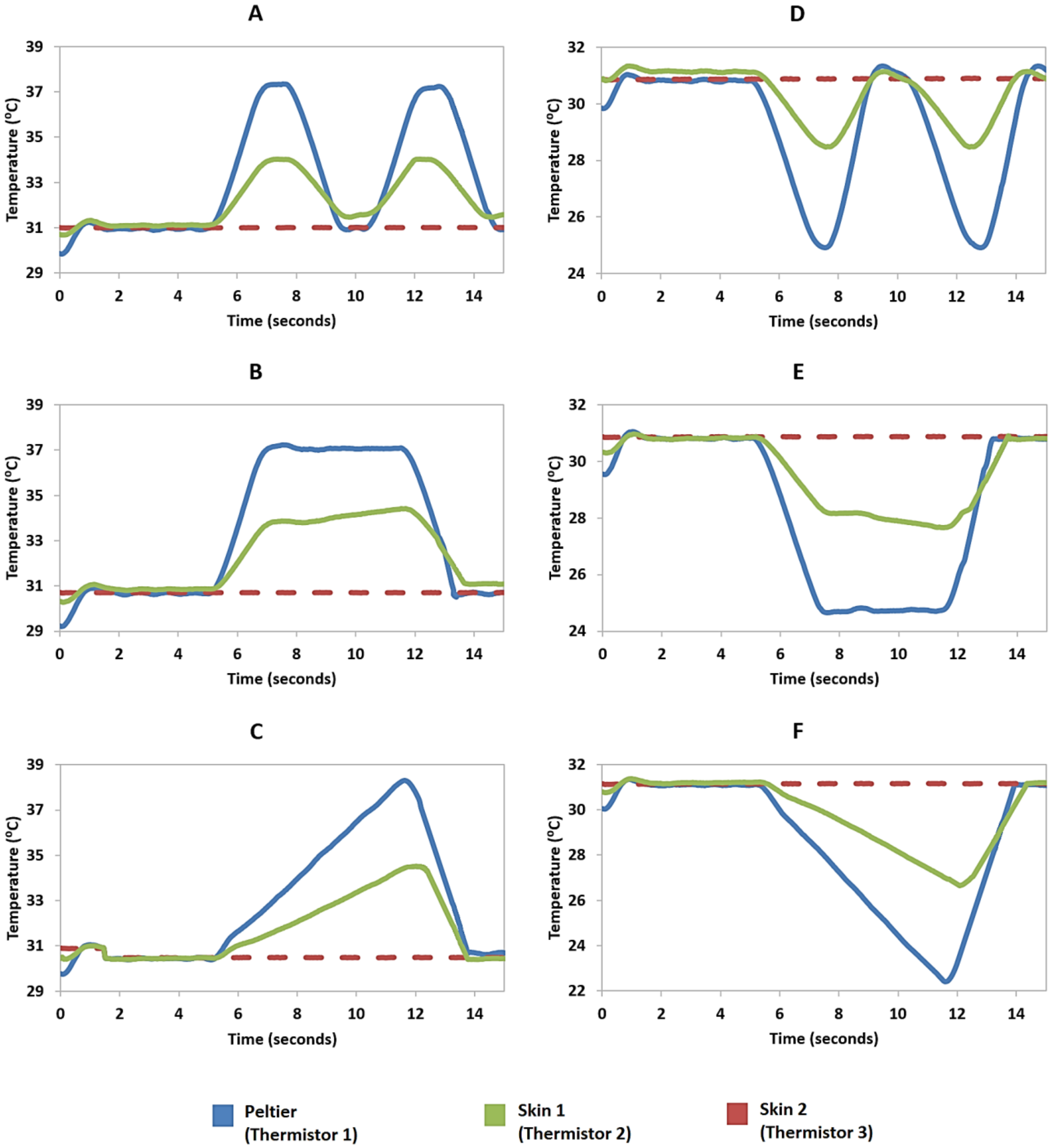


Figure 3.9 Temperatures measured on the Peltier module and two locations on the wrist with three thermistors throughout the trial, averaged across trials and subjects for each of the six thermal stimuli.

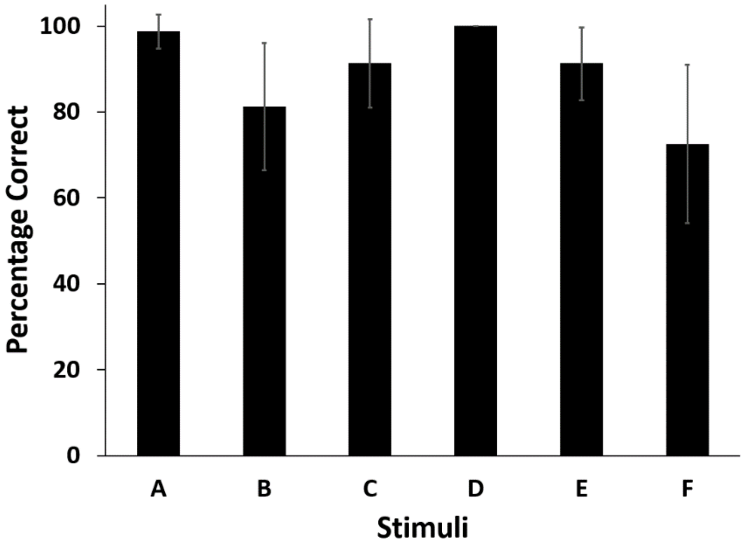


Figure 3.10 Group mean percent of correct responses for each thermal pattern. The standard deviations are shown.

Table 3.1 Confusion matrix of the group responses with scores out of the total of the 80 trials presented for each stimulus. The highlighted diagonal represents correct responses.

Stimuli	**A**	**B**	**C**	**D**	**E**	**F**
A	79	1	0	0	0	0
B	4	65	10	0	1	0
C	0	7	73	0	0	0
D	0	0	0	80	0	0
E	0	0	0	1	73	6
F	0	0	0	0	22	58

The IT values, calculated from the confusion matrix from each participant, ranged from 1.98 to 2.6 bits across participants and the group mean value was 2.13 bits. This is interpreted as indicating that for this set of six stimuli 4.4 patterns can be correctly identified.

3.4 Discussion

The results from the present experiment indicate that the performance of participants is similar to that recorded in the previous experiments on the thenar eminence. The overall performance in this experiment with thermal stimuli presented on the wrist was 89% correct which is similar to the 91% correct reported on the thenar eminence with the earlier set of thermal icons. The results are much better than the 83% reported by Wilson et al. [30] and the 80% recorded on the fingertips in the previous experiment. The stimulus duration of 10 seconds used in this study is same as that used by Wilson et al. [30]. Overall, the results from the present experiments indicate that small sets of thermal icons created by varying the direction, magnitude and rate of temperature change can be readily identified with little training.

The effectiveness of the revised set of 6 thermal icons used in this experiment was evaluated in terms of Information Transfer (IT), and the IT values were comparable to those of other tactile modalities such as vibrotactile inputs. The overall performance in the present experiment supports the use of thermal displays in applications in which the device has a wearable or hand-held form factor. The shorter stimulus presentation time of 10 seconds in the revised set of thermal icons is preferable to 30 seconds presentation time used in the earlier study on the thenar eminence. Other studies [29, 30] used a stimulus duration of 10 seconds followed by an adaptation period of 20 seconds. However, these long durations of more than 10 seconds for each thermal icon, which no doubt contributes to better performance, limits their application in thermal displays. The results of the current experiment indicated the effectiveness of presenting the thermal icons on the wrist, which is one of the most thermally sensitive regions in the upper extremity and supports user-based applications of thermal displays in the form of a wearable device.

The revised set of thermal icons was created with the three distinct input temperature profiles of square wave, step and ramp, similar to those used in the earlier set of thermal icons. The range of temperature and the direction of the change in temperature were modified to create a more distinguishable set of six patterns which were shorter in duration. This achieved one of the objectives of the experiment to use the stimulus features that were accurately identified to create shorter, highly salient, thermal icons.

Continuous monitoring of the skin temperature at the periphery of the contact area provided information about changes in skin temperature during stimulus presentation and gave insights into the induced thermal sensations, and thus the responses made by participants.

Patterns A and D were the easiest to distinguish and had the highest accuracy in terms of identification. Both of these were based on the square wave temperature profile and only differed in the direction of temperature change. The participants were able to easily identify these presumably due to occurrence of two peaks or valleys in the temperature during a single stimulus presentation. The two pairs of icons which were the most difficult to identify were patterns E (a step) and F (a ramp), and patterns B (a step) and C (a ramp). The skin temperature measurements made while these were presented indicated that the change in temperature was very similar for the two icons in each of these pairs (see Figure 3.9). Table 3.1 indicated that the Patterns E and F, which have a decreasing temperature profile, were confused more frequently than Patterns B and C, which have an increasing temperature profile. In future experiments it will be important to determine whether this result is dependent on the difference in the perception of cold as compared to warmth [9, 10].

Thermal adaptation is a challenge in implementing thermal icons in a display. It arises due to the decrease in neural responsiveness to stimulation with continuous exposure to the stimulus [10]. In the current experiment, participants switched the display to the other wrist to avoid any adaptation effects after every 6 trials. Under normal conditions the resting temperature of the skin of the hand can vary between 25 and 36 °C across individuals [37, 38]. In the present experiment, the baseline skin temperatures ranged between 30 and 32 °C for the participants. In order to present the same change in temperature to all users, the thermal stimulus was presented relative to the user's skin temperature. This was achieved by having an additional temperature sensor which recorded the baseline or unaffected skin temperature, and this temperature served as one of the inputs to the temperature controller. This set of thermal icons induced similar thermal sensations by presenting the same change in temperature to all users. In the earlier experiment on the thenar eminence, the same absolute change in temperature was presented to all the participants. The skin temperature was recorded at the periphery of the contact area only to monitor the change in temperature of the skin in contact with the display, and was not used as an input to the thermal display. This means that thermal stimuli such as those used in the previous experiment on the thenar eminence can evoke very different perceptual responses across individuals because the same stimulus may warm or cool the skin depending on its initial temperature.

The mean IT of 2.13 bits for the stimulus presentation on the wrist was surprisingly high given previous findings on thermal icon identification [29, 30]. Although, in the latter studies the participants were mobile and outdoors and so the thermal conditions were much more dynamic. The IT value of 2.13 bits is comparable to the IT value of 2.11 reported for the stimulus presentation on the thenar eminence and much better than IT value of 1.83 for presentation on the fingertips. With six stimuli, the IT value of 2.13 is interpreted as indicating that between four and five thermal patterns can be identified. For the tactile modality, IT values of around 2.4 bits have been reported for sets of nine vibrotactile tactons presented at a single site on the hand [24].

3.5 Conclusion

The results from this experiment indicate that small sets of thermal icons created by varying the direction, magnitude and rate of temperature change can be readily identified with little training. The revised set of thermal icons created using the same parameters, but overcoming the shortcomings of the previous set of icons, produced similar overall performance. The duration of the revised set of thermal icons presented on the wrist was 10 seconds which was much more suitable than a longer stimulus duration of 30 seconds for any application of thermal displays. To eliminate the factor of variability in the participants' skin temperature and in order to present same temperature stimulus, the revised thermal icons used the baseline skin temperature as an input to the temperature control system. Continuous monitoring of the skin temperature at the periphery of the contact area indicated that the skin temperature tracked the thermal display temperature but did not reach the minimum and maximum intensities of the display within the presentation time. The individual mean scores associated with the six thermal stimuli ranged from 81% to 100% on the wrist with overall mean of 89%. The information transfer values for the wrist averaged 2.13 bits, which was comparable to the 2.11 bits recorded for the thenar eminence. These findings demonstrate that the information processing capabilities of the thermal sensory system may rival those achieved with vibrotactile inputs, when the set of thermal icons are created with shorter durations at a thermally sensitive location on the body. The results provide support for the applications of thermal displays in the form of a wearable device on the wrist.

Chapter 4

Effect of Space-time Interactions on Thermal Perception

4.1 Introduction

Studies of perceptual illusions have provided insight into the cognitive mechanisms people use to perceive the world and internally represent the stimuli they experience. For the haptic modality, these illusions have been used to enhance the display of information by compensating for missing components of a perceptual experience and as a metric for evaluating the degree of realism in virtual environments [42-44]. A number of haptic and tactile illusions have been described and these can be classified in terms of those that relate to objects and their properties, such as the size-weight and thermal grill illusions, and others that pertain to the haptic perception of space, both with respect to the body and the external environment [45].

A number of tactile illusions involve distortions in the spatial representation of tactile stimuli applied to the skin such as the perceived location of the stimulus or the perceived distance between points of stimulation. Such illusions typically result from interactions between the temporal and spatial properties of the stimuli and show how the spatial representation of stimuli on the skin critically depends on the temporal properties of stimulation. One of the classic demonstrations of these effects involves presenting successively three equally spaced tactile stimuli on the skin of the forearm and asking subjects to judge whether the distance between the first and second stimulus is equal to, or shorter or longer than the distance between the second and third stimulus. Subjects overwhelmingly judge the distance to be shorter when the temporal interval between the first and second stimulus is brief (250 ms) and longer with greater temporal intervals (500 ms). This illusion which demonstrates the dependence of space on time in estimations of tactile space is known as the tau effect and has also been shown to occur in vision and audition [75]. It is often not observed at very short time intervals, but it can occur tactually when there are long delays (1500 ms) between the two pairs of comparison stimuli. It has been suggested that the ratio between the two temporal intervals should not be greater than 3 to 4 to 1 for the illusion to occur [71].

Sensory saltation is another one of the best known tactile spatial illusions, which refers to the illusory feeling that a mechanical stimulus delivered sequentially at a number of discrete locations is moving progressively across the skin. This illusion was first described by Geldard and Sherrick [46] who delivered a series of short pulses at three different loci on the skin and noted that participants perceived the stimulus moving across the skin “as if a tiny rabbit was hopping” in a smooth progression from the first mechanical stimulator to the third (p. 178). They demonstrated that the optimal number of mechanical stimuli for the illusion is between three and six, but it will occur with as few as two and as many as sixteen stimuli. Under the latter condition, the illusion is considerably reduced in strength. In addition to the number of mechanical pulses delivered to the skin the time between stimuli influences the strength of the illusion, with intervals between 20 and 250 ms being optimal. With shorter intervals the stimuli are perceived as being closer together spatially, until at 20 ms there is no perceptible spatial separation at all [47]. At intervals around 300 ms and higher, the mechanical stimuli are accurately localized [48].

For tactile stimuli, it is possible to create cutaneous illusory movement in two or more directions by optimizing the temporal and spatial activation of the mechanical stimuli. The original demonstration of sensory saltation involved three stimulators spaced along the forearm, but many subsequent experiments involved what is referred to as a ‘reduced rabbit’ paradigm in which three stimuli were presented at two sites [48-50]. In these studies, subjects were asked to report whether a tactile stimulus was felt at the mid-point between the two sites of stimulation.

Subjects' performance under this condition was then compared to their performance when a stimulus was actually delivered at the mid-point, which provides an index of the strength of the saltatory illusion [51]. Across different studies the illusion has been reported to be robust, that is it occurs on 80-90% of trials, and under optimal conditions subjects are unable to distinguish between real and illusory stimuli [51].

The area over which the tactile stimuli are delivered also determines whether sensory saltation occurs. On the glabrous surface of the index finger the area is small, around 2.28 cm^2, whereas on the forearm it is 145.7 cm^2. The size of the saltatory area therefore appears to be negatively correlated with the density of sensory innervation, which is in turn directly related to the size of the cortical receptive field [52]. A number of experiments have been conducted to evaluate how the anatomical organization of the somatosensory system constrains sensory saltation. The illusion does not occur across the body's midline unless mechanical stimuli are actually delivered to the midline [48], but the mechanical stimulus can appear to "hop out of the body" onto an external object such as a stick laid across the tips of the index fingers [53].

In contrast to the wealth of information regarding tactile spatial and temporal illusions, there has been substantially less research on illusions involving the thermal sensory system. One of the few illusions that has been studied is the thermal grill illusion which refers to the burning pain sensation that can result from touching interlaced warm (36-42 ^{o}C) and cool (18-24 ^{o}C) stimuli [54-56]. When touched individually such stimuli are perceived to be innocuous. If participants are asked to match the thermal sensation associated with making contact with the interlaced warm and cool stimuli to that of a uniform thermal surface, the matching temperatures are around 46 ^{o}C [56]. It has been proposed that the burning sensation results from the activation of polymodal C-nociceptors that are normally inhibited by activity in afferent fibers from cold thermoreceptors.

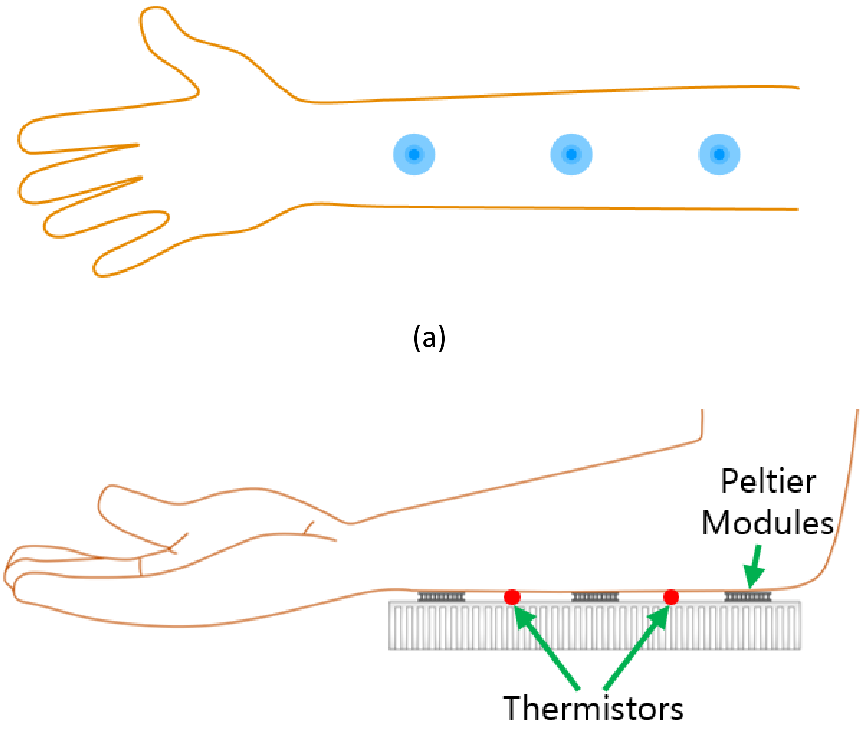
Reports of spatio-temporal illusions involving the thermal system are sparse. A number of factors may contribute to this, in particular the pervasive nature of spatial summation which limits the capacity of individuals to localize precisely the site of thermal stimulation [13]. In one of the few studies of these illusions, Békésy reported that when there was a delay of 140 ms between two warm stimuli delivered to the skin the sensation of heat was completely localized to the first stimulus presented. Moreover, the perceived intensity of this stimulus was larger than that of a single stimulus delivered at the same site, a phenomenon that he referred to as "funneling" [56]. A serendipitous observation was reported by Rózsa and Kenshalo [58] during their experiments on spatial summation of cooling pulses delivered to each forearm. They noted that when there was a delay of about 250 ms between the onsets of the temperature change in the two arms, subjects reported that a cool sensation appeared to move from one forearm to the other. This apparent movement of thermal sensation is similar to the "phi" phenomenon reported for vibration [59], and persisted until the onset interval between the two stimuli was less than 100 ms. Thermal stimuli within the nociceptive range have been used in conjunction with mechanical inputs in tactile sensory saltation studies to determine if such stimuli can be used to "tag" mechanical pulses. Geldard [48] reported that a cold stimulus was more effective than a hot stimulus in producing sensory saltation. One illusion that involves an error in perceiving varying intensities of thermal stimuli displayed across the skin is known as thermal referral. In this illusion, first described by Green [60], thermal sensations arising from a finger change as a function of the sensations experienced at the two adjacent fingers. When the index and ring fingers are placed on thermal stimulators that either heat or cool the fingers and the middle finger is placed on a thermally neutral stimulator, all three fingers feel warm or cool. On the basis of their experiments on the perceived intensity of the thermal stimuli resulting from thermal referral, Ho et al. [61] proposed that this illusion is mediated by two separate processes, one of which determines the perceived intensity from the physical intensity and the area of thermal stimulation, and the other determines the localization of these sensations based on tactile stimulation.

Thermal sensory saltation has been described in the context of stimuli that are within the range of temperatures that elicit painful sensations. Trojan et al. [62] used a CO_2 laser to deliver three 20 ms infrared laser pulses to the forearm at 15.3 and 25.4 ^{o}C above skin temperature. The first two stimuli were delivered at one location with an inter-stimulus interval of 1000 ms and the third stimulus was presented 105 mm from the first two stimuli after a variable delay ranging from 60-516 ms. With this setup the stimuli are invisible and there is no mechanical stimulation of the skin. The perceived position of the second stimulus was displaced in the direction of the third stimulus by an average of 51 mm, and this mislocalization increased slightly with decreasing delays. The stimuli in this experiment were perceived as being unpleasant and/or painful indicating that both warm and nociceptive fibers would have been activated. These results are consistent with the tau effect rather than saltation, as the illusion is one of a change in perceived position rather than an illusory movement.

These studies suggest that the spatio-temporal interactions reported for other sensory modalities also apply to thermal sensory processing. However, the boundary conditions that define when these illusions occur thermally have not been specified. In contrast to the sense of touch, the ability to localize precisely thermal stimulation is limited and as compared to other sensory systems the thermal senses are relatively sluggish [13].

The present study evaluates the spatio-temporal effects of thermal stimulation on the forearm. Cold stimulation exhibits better thermal sensitivity and detection than warm stimulation on all the body regions [63-64]. To independently evaluate the spatio-temporal interactions of cold and warm stimuli, two separate experiments were designed and conducted. The experimental setup, method and parameters were kept the same in both experiments. The only difference was the direction of the temperature change in the set of thermal patterns presented.

The forearm was chosen as the site of study as it provides an extensive surface area, and its thermal sensitivity is superior to the fingertips but inferior to the face, the most thermally sensitive region of the body [9]. The thermal pulses were presented on the forearm at three locations. The concept of the thermal display with thermal stimuli presentation is shown in Figure 4.1. Pilot studies were conducted to determine the distance between the stimulation sites on the forearm and the parameters of the thermal stimulation, including the intensity of the pulses and the delays between them.



(a)

(b)

Figure 4.1 (a) Concept for presenting thermal stimuli at three different points on the forearm. (b) The forearm placed on the thermal display which is made up of three Peltier modules mounted on a heat sink is shown.

The development of a thermal display capable of presenting short duration cold and warm thermal pulses on the forearm is presented in this chapter. The experimental design using the thermal display and the results of the experiments are also described. The objectives of the present set of experiments were: (1) to determine whether the perceived location of thermal stimuli changes as a function of the temporal parameters of the stimulation; (2) to find out whether there are differences in thermal space-time interactions for cold and warm stimuli and (3) to evaluate the parameters of the thermal patterns which can result in these spatio-temporal effects.

4.2 Experiment 1: Perceived Location of Cold Stimuli

The present experiment evaluated whether the perceived location of a cold stimulus changes as a function of the temporal parameters of stimulation. Cold stimuli are more easily detected than warm stimuli [10][12][63], and the reaction time for detecting cold sensations is significantly shorter than that for warmth [64]. The stimuli were presented on the forearm.

4.2.1 Experimental Design

A thermal display based on thermoelectric modules (Peltier devices) was designed and built to present thermal stimuli on the forearm. The thermal stimuli varied with respect to the location at which they were presented and the delay between pulses.

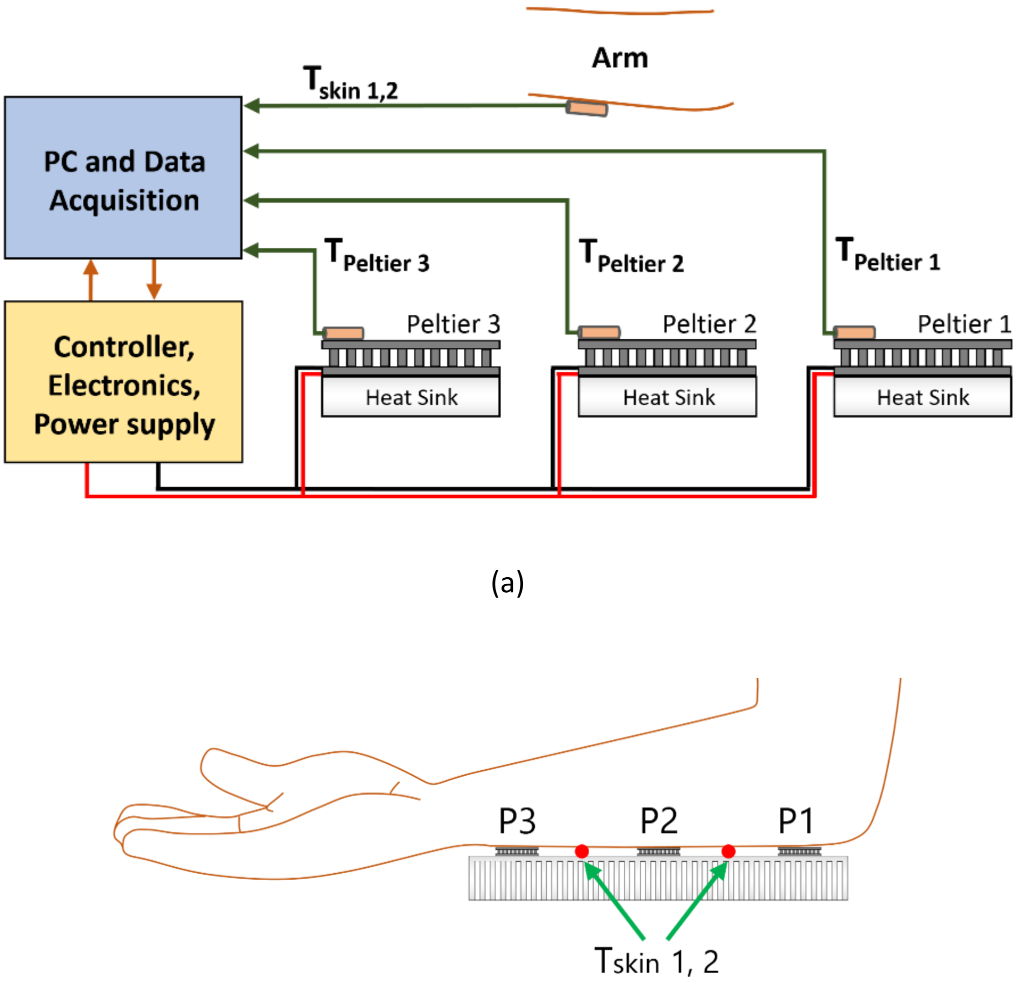
Participants

Ten normal healthy individuals, 9 males and 1 female, ranging in age from 24 to 29 years old (mean: 27 years) participated in the experiments. They were all right-handed and had no known abnormalities of the skin or peripheral sensory or vascular systems. None of the participants had any significant experience in tactile or thermal perception studies. They all signed an informed consent form that was approved by the MIT Committee on the Use of Humans as Experimental Subjects.

Apparatus

A thermal display was built to provide short thermal pulses to the skin. The display consisted of three thermoelectric modules (Model TE-83-1.0-1.5, TE Technology, Inc.) mounted on a heat sink. The thermoelectric modules were Peltier devices 22 mm long and 19 mm wide, with a thickness of 3.8 mm, giving a contact area of 418 mm^2. The center-to-center distance between the Peltier modules was 75 mm and the length of the display was 200 mm.

Five thermistors, 457 µm in diameter and 3.18 mm in length (Model 56A1002-C8, Alpha Technics) were used in the experiment. A thermistor was placed on each of the Peltier modules to feedback the temperature to the controller. Two other thermistors measured the temperature at two locations on the skin not in contact with the Peltier devices. Data acquisition and independent feedback control of each of the Peltier devices was done using National Instruments data acquisition modules (Model NI cDAQ-9174, NI 9263, NI 9474, NI 9205).



(a)

(b)

Figure 4.2 (a) Schematic illustration of the thermal display with three Peltier modules mounted on heat sink, and thermistors measuring the temperature of the modules and of the skin on the forearm (b) The numbering of the Peltier modules with respect to the forearm, and the position of thermistors measuring skin temperature.

A schematic of the thermal display with thermistors and the control setup is shown in Figure 4.2. A fixture was fabricated using laser-cut acrylic sheets to hold the Peltier modules and heat sink. Multiple fans were mounted in the fixture to provide forced convection cooling. The surface of the Peltier modules was flush with the acrylic surface so that the locations of the Peltier devices were not perceptible based on tactile cues. Skin temperature was used as the calibration temperature at the start of each trial. A second computer was used to run a GUI on which the participants' responses were recorded.

Thermal Patterns

Each thermal pattern comprised four short temperature pulses in a fixed sequence of A, B, C and D. The amplitude (ΔT) and duration (t_P) of each pulse were constant across patterns. The temperature decrease was 8 °C, and the pulse duration was 2 seconds. Figure 4.3 provides a schematic illustration of the different parameters of the patterns. Prior to the start of Pulse A, the temperature of all three Peltier modules (P1, P2 and P3 as numbered from the elbow) was set at the average skin temperature as measured concurrently at two locations on the forearm for 5 seconds (t_C). The first location was midway between Peltier 1 and 2 (P1 and P2), and the second between P2 and P3.

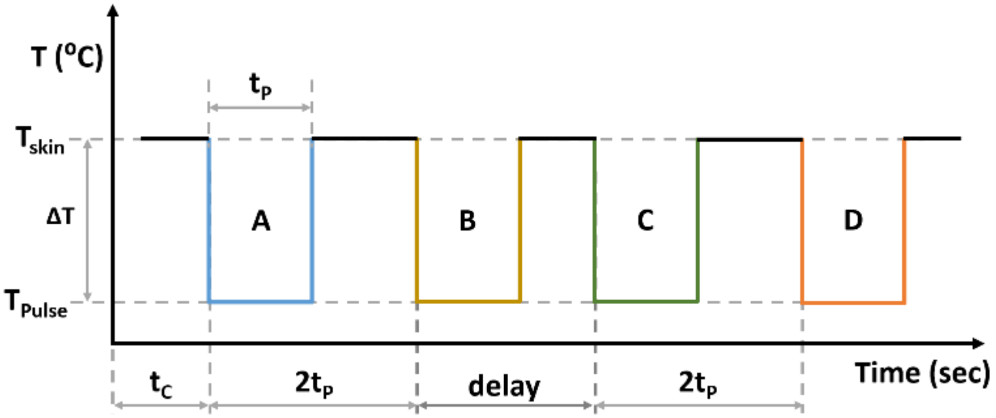


Figure 4.3 Different parameters of the four temperature pulses used to create the patterns.

The time between the onsets of pulse A and B, and between pulse C and D was fixed at 4 seconds. The direction of activation of the Peltier modules, the specific Peltier modules cooled, and the delay between the onset of pulse B and C, were the parameters used to create a total of eight patterns, as depicted in Table 4.1. With a delay of 4 seconds between the onsets of pulse B and C all the pulses were evenly distributed in time; a shorter delay of 0.2 seconds was chosen to determine whether an illusory change in position occurred. Pulses A and B, and pulse D were always presented at either the first (P1) or the third Peltier (P3) module depending on the direction of activation. The location of pulse C varied between the second (P2), first (P1) or third (P3) Peltier module depending on the direction of activation. Each pattern lasted 20 seconds and was presented 5 times, giving a total of 40 trials for each participant. The order of presentation of the trials was randomized.

Table 4.1 Thermal patterns created based on varying the Peltier modules (P) activated, the direction of activation and the delay (in seconds) between pulse B and C.

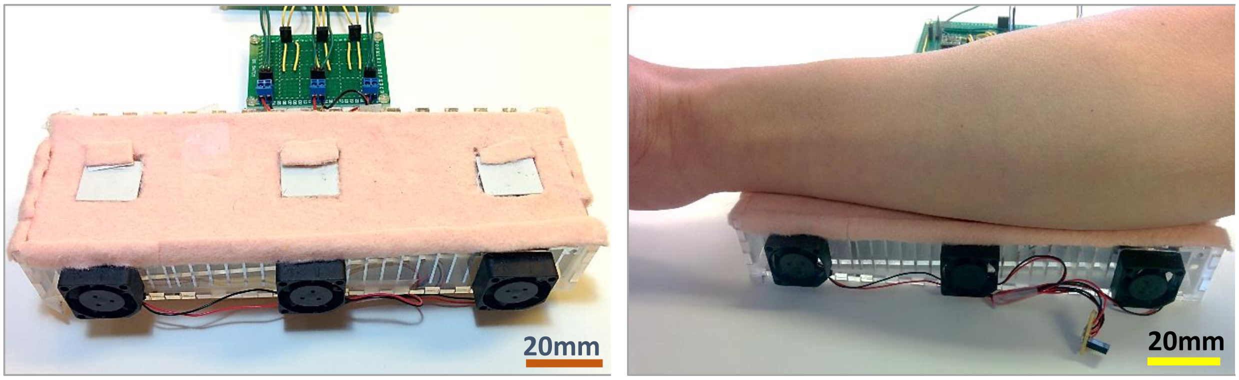
Pattern	Sequence	Delay	Direction	P1	P2	P3
1	AB-C-D	4	P1 P2 P3	AB	C	D
2	AB-C-D	0.2	P1 P2 P3	AB	C	D
3	AB-C-D	4	P3 P2 P1	D	C	AB
4	AB-C-D	0.2	P3 P2 P1	D	C	AB
5	AB-CD	4	P1 - P3	AB	-	CD
6	AB-CD	0.2	P1 - P3	AB	-	CD
7	AB-CD	4	P3 - P1	CD	-	AB
8	AB-CD	0.2	P3 - P1	CD	-	AB

Procedure

Prior to starting the experiment, the procedure was explained to participants and they were familiarized with the temperature pulses that would be delivered. They were told that four temperature pulses each with the same duration and intensity would be delivered to their forearms and that the pulses could be presented on any of the Peltier devices in the display and start from any position. At the end of each trial they had to indicate the positions of the first two pulses, A and B. The initial skin temperatures of the participants ranged from 30 to 32 °C with a mean of 31 °C. The ambient temperature was maintained at 25 °C, as measured with a thermocouple in free air.

At the start of the experiment participants placed their right forearm on the display (see Figure 4.4). Markers on the thermal display guided the participants as to the correct placement of their forearm. One of the eight patterns was then presented on the display (see Table 4.1). At the end of each trial an auditory cue signaled to the participants to indicate the locations at which they perceived the first two pulses. A visual depiction of the forearm and the thermal display surface was presented in a GUI on a computer screen in front of the participants (see Figure 4.5).

They moved a cursor to indicate the location of each of the pulses. The position for each pulse was measured from the wrist. Responses had to be made within 10 seconds and on most trials participants made their responses within a couple of seconds. After every two trials, participants switched the forearm that was on the display in order to avoid any adaptation effects. A rest break was provided when requested. No feedback regarding the correctness of the responses was provided during the experiment.



(a) (b)

Figure 4.4 (a) Thermal display assembly with three Peltier modules, heatsink and fans (b) The placement of the forearm on the thermal display by the user.

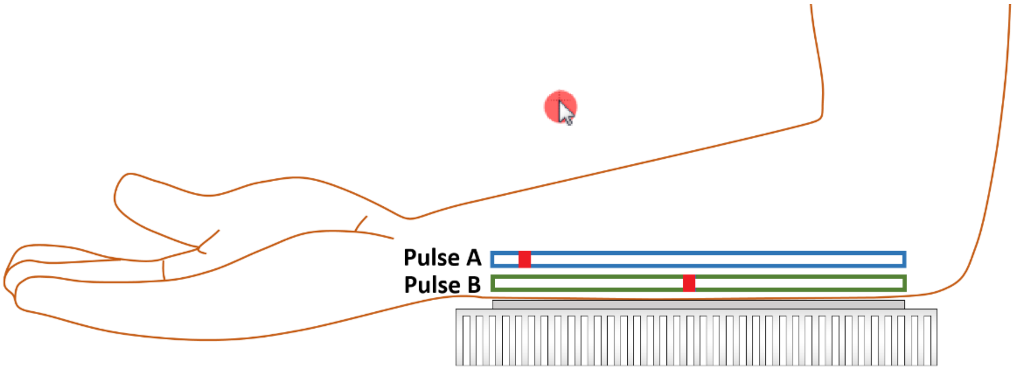


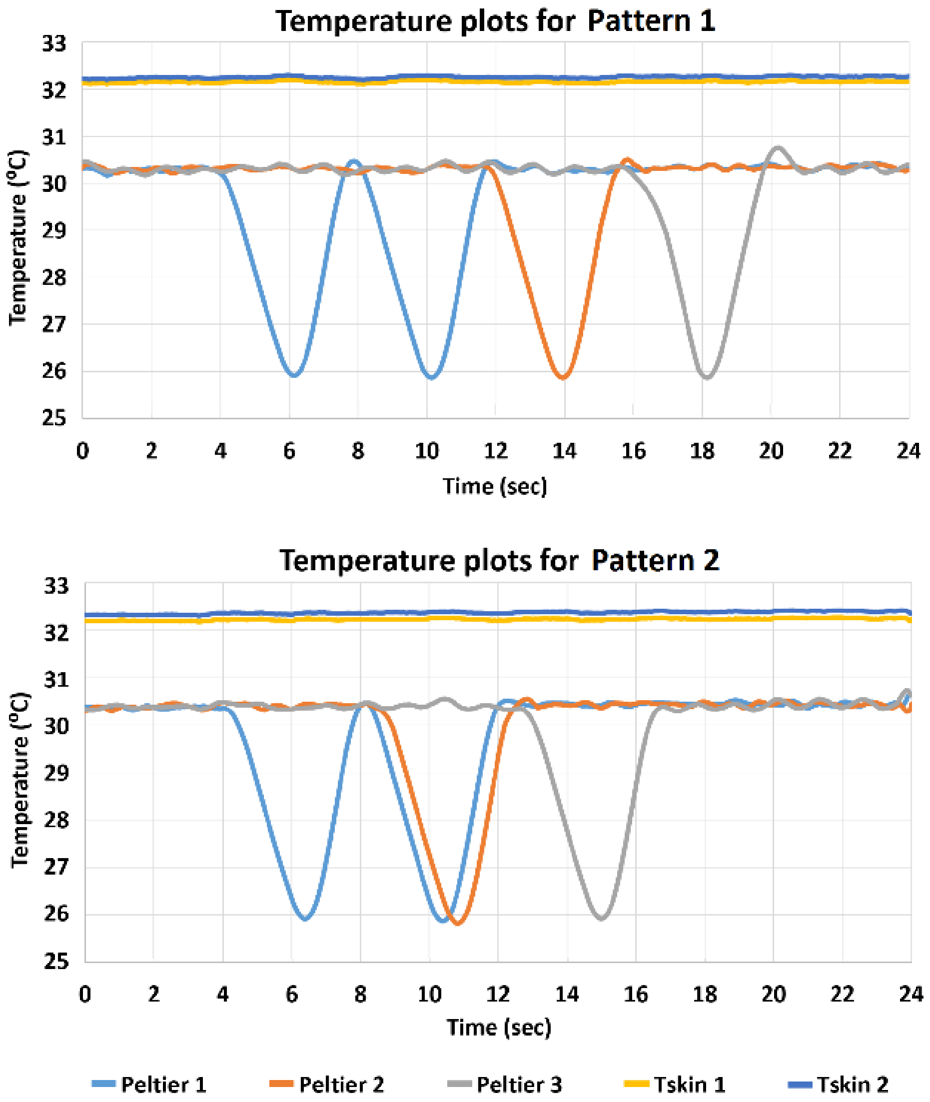
Figure 4.5 Screen shot of the GUI presented on the computer screen in front of the participants, and used by them to record their responses

4.2.2 Results

The temperature measured on the Peltier modules and on the skin is illustrated for two patterns in Figure 4.6. It is evident that the temperature of the skin not in contact with the Peltier devices remained constant throughout the trials, indicating that the temperature change during stimulation was well localized to the contact region.

Participants indicated the perceived location of Pulses A and B by moving the cursor to the location on the GUI (Figure 4.5). These data were then digitized using the Image Processing Toolbox in MATLAB (Mathworks, Inc.). Distance was measured from the wrist as shown in Figure 4.7. The perceived location of the first stimulus (pulse A) for the eight patterns presented is shown in Figure 4.8. There is variability across participants, particularly when the sequence began at the elbow (P1-P2-P3) as compared to the wrist (P3-P2-P1). The group means vary by 22 mm for the former set of patterns but only by 8 mm for the latter set.

The perceived position of the second stimulus (pulse B) in each pattern is shown in Figure 4.9. The experimental condition that resulted in a substantial change in the perceived position of pulse B was the AB-CD sequence with a delay of 0.2 seconds. The perceived position of B has moved by 43 mm and 59 mm towards the location of pulse C. With the 4-second delay the positon of B is not perceived to change as a function of the spatial sequence presented (AB-C-D vs AB-CD).


Temperature plots for Pattern 1

Temperature plots for Pattern 2

Figure 4.6 Temperature recordings throughout two trials from the three Peltier devices and from the skin on the forearm not in contact with the Peltier devices.

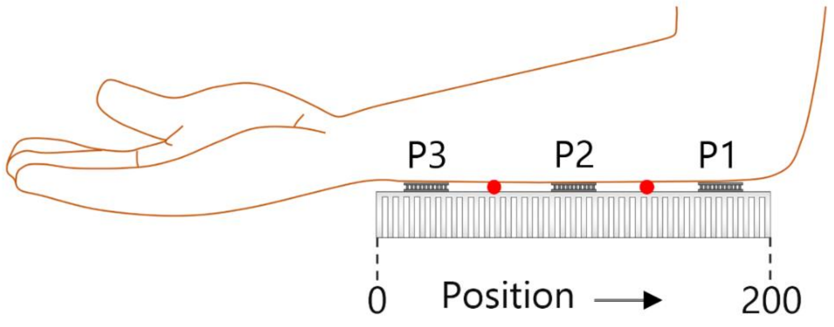


Figure 4.7 Position measurement with respect to the wrist of the participant.

The perceived location of pulse B in the various experimental conditions can best be visualized using a format devised by Goldreich [64] to conceptualize tactile length illusions. The schematic illustration shown in Figure 4.10 depicts graphically the temporal and spatial properties of the physical stimuli and the perceived position of pulse B on the forearm for each of the eight patterns. Each adjacent pair of patterns differ only with respect to where the third stimulus (pulse C) was delivered. This representation illustrates quite vividly how the position of pulse B was perceived to move in the direction of pulse C when the delay between pulses B and C was short and pulse C was delivered at some distance from pulse B. When the distance between pulses B and C was shorter (around 75 mm), there was no change in the perceived position of pulse B. Figure 4.8 also illustrates that participants were more accurate at localizing both the first and second pulse for the longer delay sequences when they occurred near the elbow as compared to the wrist. This may reflect the use of the elbow as an anatomical landmark to facilitate localization, as has been reported for tactile stimuli [66].

The effect of the various parameters used to create the thermal stimuli on perceived position was evaluated by analyzing the absolute difference in perceived location for pulses A and B. A three-way repeated-measures analysis of variance (ANOVA) was performed on these data with spatial sequence (AB-C-D and AB-CD), delay (0.2 and 4 s) and direction (first pulse on P1 and P3) as factors. The results indicated a main effect of sequence (F(1,9)=10.59, p=0.01), a main effect of delay (F(1,9)=15.79, p=0.003) and a main effect of direction (F(1,9)=10.37, p=0.01). These findings indicate that the perceived distance between pulse A and B was significantly greater for the AB-CD sequence, for the shorter 0.2-second delay and for sequences that began at the wrist as compared to the elbow. The only interaction that was significant was the interaction between delay and sequence (F(1,9)=10.78, p=0.009), reflecting the greater distances or change in perceived location associated with the shorter delay and AB-CD sequence.

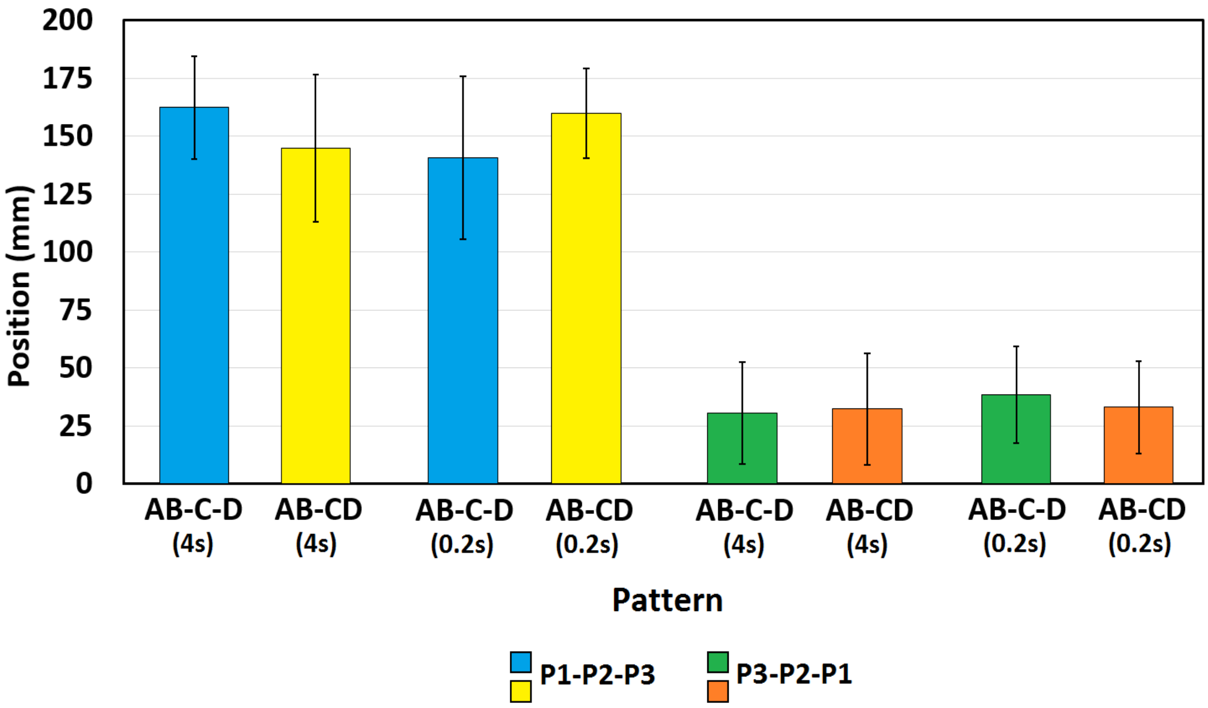


Figure 4.8 The group mean perceived position of the first pulse in each pattern. Standard deviations are shown.

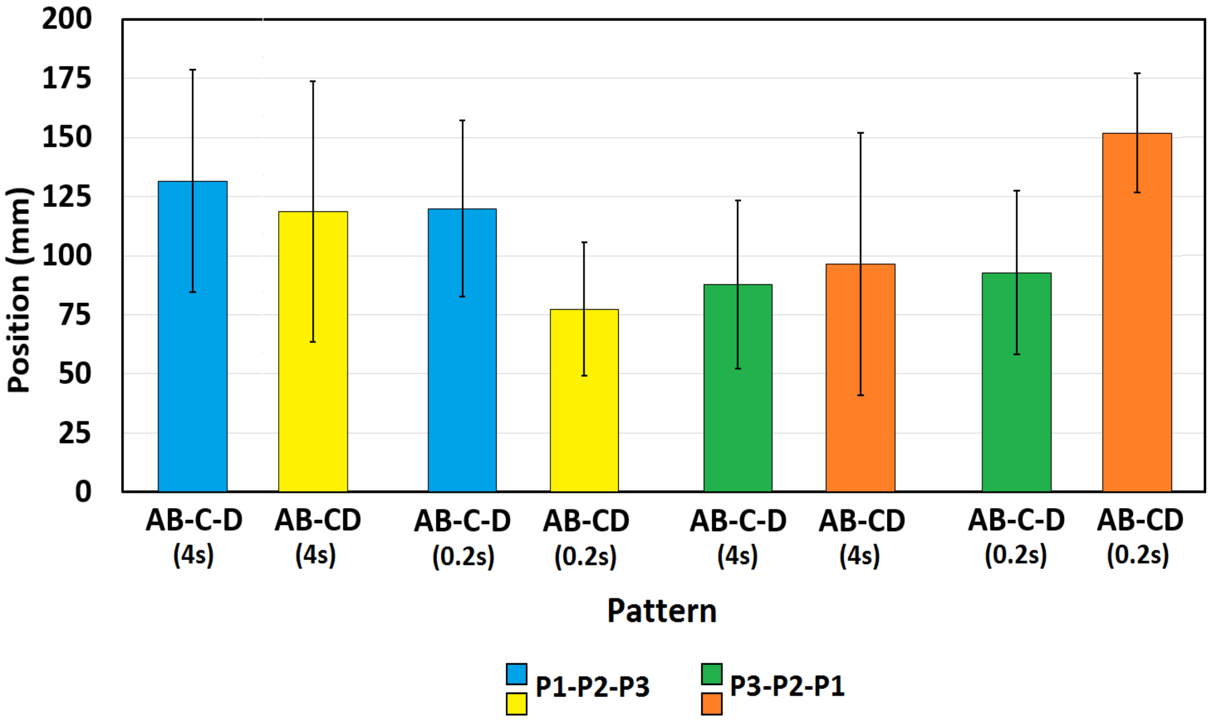


Figure 4.9 The group mean perceived position of the second pulse in each pattern. Standard deviations are shown.

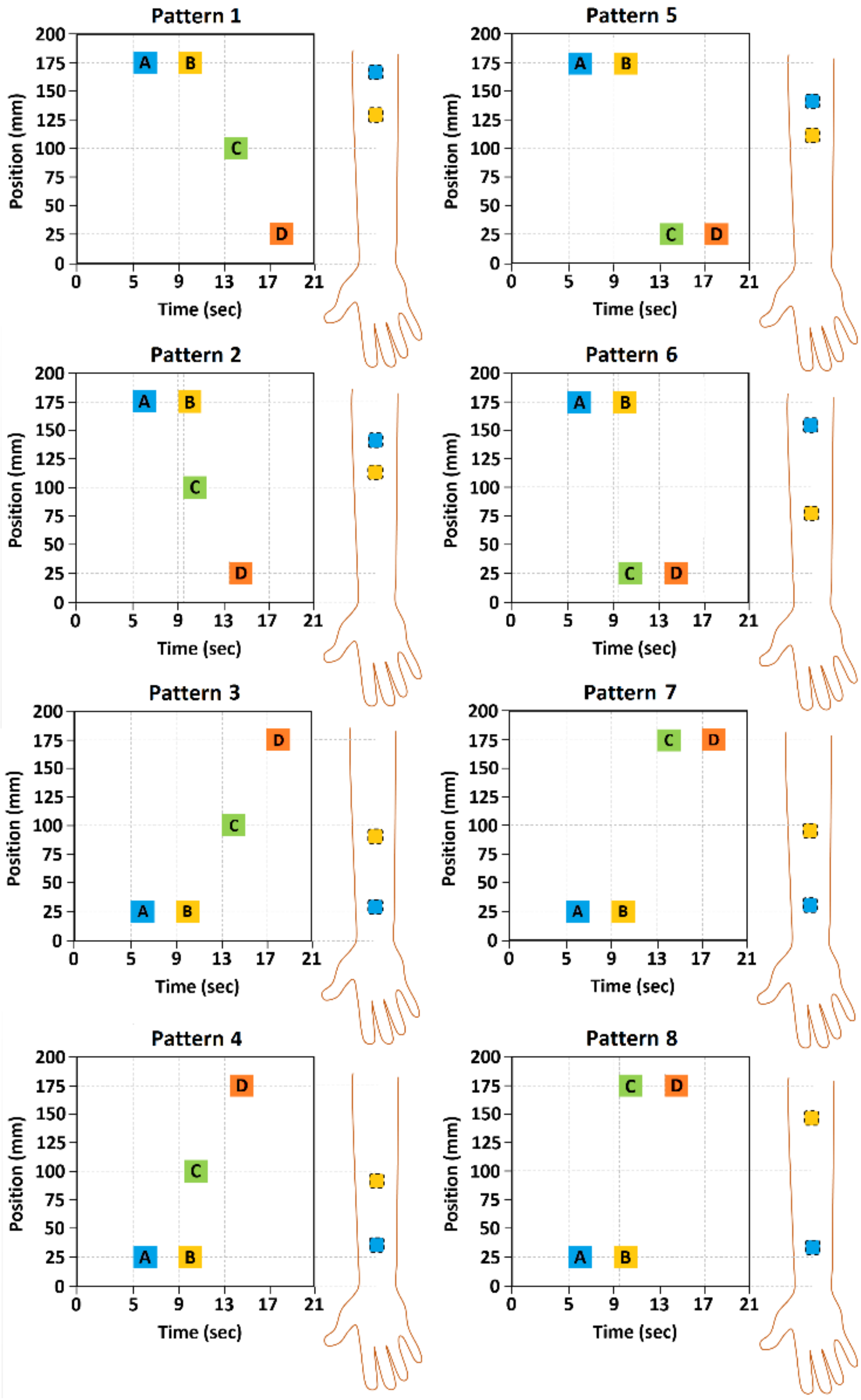


Figure 4.10 Schematic illustration of the group mean data for the physical stimuli depicted graphically and the perceived position of those stimuli on the forearm.

4.3 Experiment 2: Perceived Location of Warm Stimuli

The previous experiment demonstrated that when four cooling pulses were presented on the forearm in varying spatial and temporal sequences, the perceived position of the second pulse changed as a function of the temporal interval and distance between the pulses. The present experiment was designed to evaluate whether the perceived location of a warm stimulus also changes as a function of the temporal parameters of stimulation. It was hypothesized that spatio-temporal interactions for warm stimuli may be less robust and more variable than those found for cold because of the decreased sensitivity of all body regions for warmth as compared to cold [9], [10]. In addition, the time to detect warm sensations is longer than that for cold which is presumably a consequence of the slower conduction velocity of warm afferent fibers (1-2 m/s) as compared to cold fibers (10-20 m/s) [12] [68].

4.3.1 Experimental Design

Similar to the first experiment involving cold pulses, thermal stimuli in the form of four short pulses were delivered to the forearm using a thermal display (Figure 4.1 and Figure 4.4). These stimuli varied with respect to the location at which they were presented on the arm and the delays between pulses. The experimental design and all the stimulus parameters except the quality (warming instead of cooling) of the pulses were kept the same as in the first experiment.

Participants

Ten normal healthy males ranging in age from 24 to 36 years old (mean: 28 years) participated in the experiments. They had no known abnormalities of the skin or peripheral sensory or vascular systems. None of the participants had any significant experience in thermal perception studies and none of them took part in experiment 1 with cooling pulses. They all signed an informed consent form that was approved by the MIT Committee on the Use of Humans as Experimental Subjects.

Apparatus

The second experiment with the warm temperature pulses used the same apparatus as was used in the first experiment with the cold pulses (Figure 4.2). All the parameters of the thermal display were the same as those used in the first experiment with cold pulses. At the start of each trial skin temperature was used as the calibration temperature and the display was set to this temperature. This meant that the same relative stimulus was delivered to all participants. When each trial was completed the temperature of the display returned to the calibration temperature. Participants recorded their responses using a GUI running on a separate computer.

Thermal Patterns

All the dimensions of the thermal patterns, except the direction of change of temperature of the pulses, were kept same for the present experiment. The temperature increase for the four thermal pulses was 6 °C. Figure 4.11 provides a schematic illustration of the different parameters of the patterns.

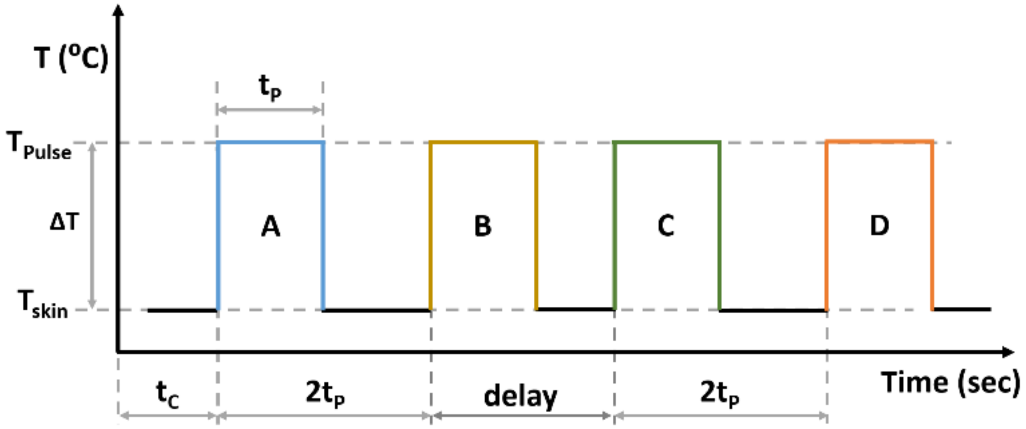


Figure 4.11 Different parameters of the four temperature pulses used to create the patterns for warm stimuli.

Table 4.2 Thermal patterns created for warm stimuli based on varying the Peltier modules (P) activated, the direction of activation and the delay (in seconds) between Pulse B and C.

Pattern	Sequence	Delay	Direction	P1	P2	P3
1	AB-C-D	4	P1 P2 P3	AB	C	D
2	AB-C-D	0.2	P1 P2 P3	AB	C	D
3	AB-C-D	4	P3 P2 P1	D	C	AB
4	AB-C-D	0.2	P3 P2 P1	D	C	AB
5	AB-CD	4	P1 - P3	AB	-	CD
6	AB-CD	0.2	P1 - P3	AB	-	CD
7	AB-CD	4	P3 - P1	CD	-	AB
8	AB-CD	0.2	P3 - P1	CD	-	AB

Procedure

The procedure was initially explained to participants and they were familiarized with the temperature pulses that would be delivered. They were told that four warm pulses each with the same duration and intensity would be presented. The pulses could be presented on any of the Peltier devices in the display and start from any position. At the end of each trial they had to indicate the positions of the first two pulses, A and B.

The initial skin temperatures of the participants ranged from 30 to 32 °C with a mean of 31 °C. The ambient temperature was maintained at 25 °C, as measured with a thermocouple in free air. At the start of the experiment participants placed their right forearm on the contact surface of the display using markers on the display that indicated the correct placement. One of the eight patterns was then presented (see Table 4.2) and at the end of each trial an auditory cue signaled that participants should indicate the locations of the first two temperature pulses. A visual depiction of the forearm and the thermal display surface was presented in a GUI on a computer screen in front of the participants (see Figure 4.5). They moved a cursor to indicate the location of each pulse. Responses had to be made within 10 s and on most trials participants indicated the location within a couple of seconds. After every two trials, participants switched the forearm that was on the display in order to avoid any adaptation effects. A rest break was provided when requested.

4.3.2 Results

Temperatures were measured during each trial on the Peltier modules and at two locations on the skin not in contact with the Peltier modules. The temperatures measured during presentation of Patterns 1 and 2 are illustrated in Figure 4.12. The skin temperature at the two locations not in contact with the Peltier modules remained constant, indicating that the temperature change was localized to the contact region.

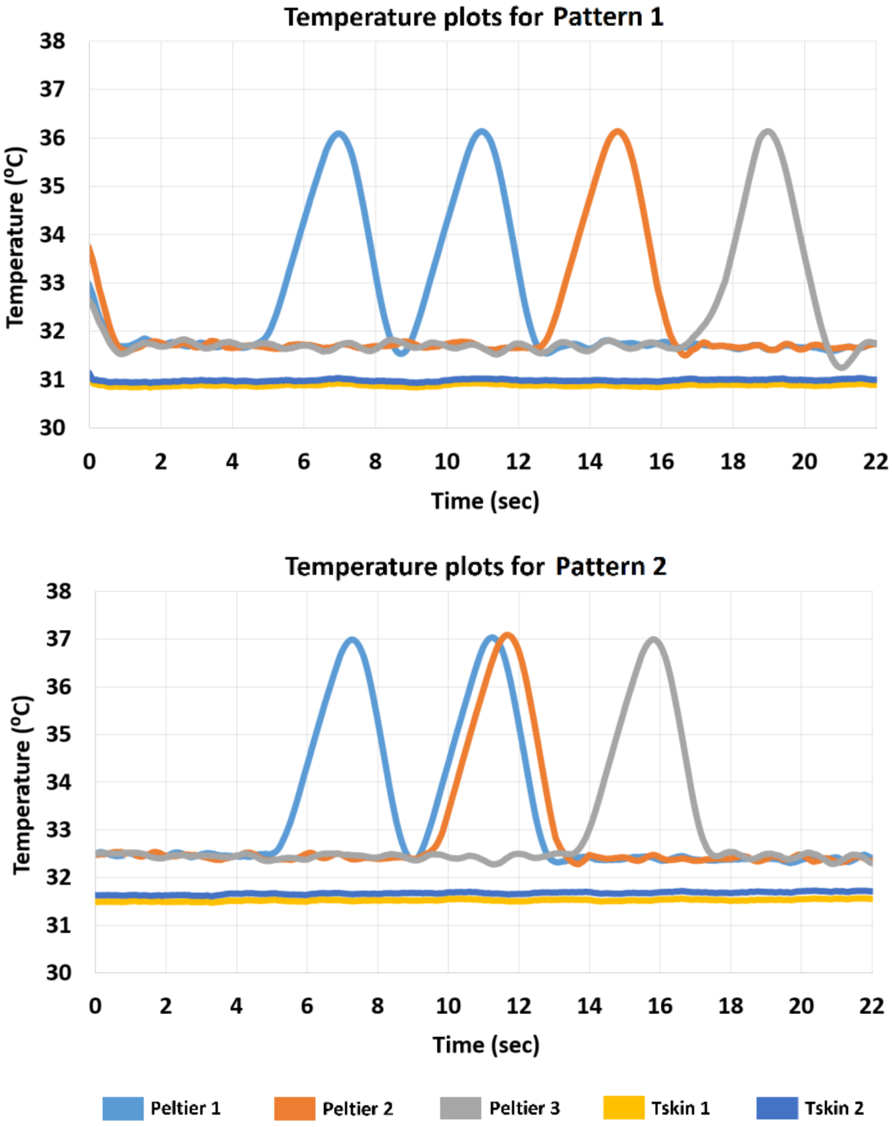


Figure 4.12 Temperature recordings throughout two trials from the three Peltier devices and from the skin on the forearm not in contact with the Peltier devices. The data are averaged across five participants across all trials.

The participants indicated the perceived locations of pulses A and B using the GUI shown in Figure 4.5; these data were then digitized using the Image Processing Toolbox in MATLAB (Mathworks, Inc.). The position of each pulse was measured from the wrist. Figure 4.13 shows the perceived location of pulse A and pulse B for the eight patterns, averaged across the 10 participants. When the sequence began at the elbow (distal direction) (patterns 1, 2, 5 and 6) the group mean perceived location of the first pulse varied across patterns by 15 mm. For sequences that started at the wrist (proximal direction) the position varied by 19.8 mm. pulse B was always delivered at the same location as pulse A, but as is evident in Figure 4.13, its perceived position changed substantially when there was a short delay between it and pulse C. On average the position of pulse B changed by 40 mm when the delay was 0.2 s and by only 7.5 mm when the delay was 4 s. The spatial sequence of stimulation (AB-C-D as compared to AB-CD) did not appear to have a marked effect on the perceived position of pulse B.

The schematic illustration shown in Figure 4.14 depicts graphically the temporal and spatial properties of the physical stimuli and the perceived position of pulse B on the forearm for each of the eight patterns. Each pair of patterns (1 and 5, 2 and 6 etc.) differ only with respect to where the third stimulus (pulse C) in the sequence was delivered. This representation illustrates quite vividly how the position of pulse B was perceived to move in the direction of pulse C when the delay between pulses B and C was 0.2 s. When the delay between pulses B and C was longer (4 s) as in patterns 1, 3, 5 and 7, participants perceived the first and second pulses as being close together. Figure 4.14 also illustrates that at the longer delay participants were more accurate at localizing pulses A and B when they were presented near the elbow as compared to the wrist (1 and 5 as compared to 3 and 7).

The effect of the various parameters used to create the warm stimuli on perceived position was evaluated by analyzing the absolute difference in perceived location for pulses A and B. A three-way repeated-measures analysis of variance (ANOVA) was performed on these data with spatial sequence (AB-C-D and AB-CD), delay (0.2 and 4 s) and direction (first pulse on P1 and P3) as factors. The results indicated a main effect of delay ($F(1,9)=21.56$, $p=0.001$) and of direction ($F(1,9)=8.19$, $p=0.019$), but no effect of sequence. None of the interactions was significant. These findings reveal that the perceived distance between pulses A and B was significantly greater for stimuli with the shorter delay of 0.2 s and was greater for sequences that began at the wrist as compared to the elbow.

The results from the present experiment were compared to those from the previous experiment which had the same stimulus parameters except that cooling pulses were delivered to the skin rather than warming pulses. A comparison of the results from these two experiments which involved different participants is presented in Figure 4.15. The absolute difference in the perceived location of pulses A and B for cold and warm stimuli is shown as a function of delay and direction. It is evident that the perceived location of both cold and warm thermal stimuli can change as a function of the temporal parameters of stimulation. Figure 4.15 also illustrates that for both parameters cold stimuli resulted in a larger change in the perceived position of pulse B than warm stimuli. For cold and warm stimuli, sequences that started near the elbow and sequences with a shorter delay between pulses B and C resulted in a greater change in the perceived position of pulse B. The difference as a function of direction of stimulation was 34 mm for cold stimuli and 15 mm for warm stimuli. However, the change in perceived position with delay was more pronounced for warm stimuli, with a difference of 32 mm as compared to 24 mm for cold stimuli.

A repeated-measures analysis of variance (ANOVA) was performed on the combined dataset from both experiments, with thermal stimuli as a between-subjects factor and sequence, delay and direction as within-subjects factors. The results indicated a main effect of thermal stimuli ($F(1,18)=141.80$, $p<0.001$), of sequence ($F(1,18)=10.99$, $p=0.004$), of delay ($F(1,18)=34.57$, $p<0.001$), and of direction ($F(1,18)=18.48$, $p<0.001$). The interactions between sequence and thermal stimuli ($F(1,18)=6.07$, $p=0.02$) and between sequence, delay and thermal stimuli ($F(1,18)=10.27$, $p=0.005$) were also significant. The interaction between sequence and thermal stimuli reflects the effect of the spatial sequence (AB-C-D and AB-CD) on the perceived location of pulse B for the cold stimuli which did not occur with warm stimuli. The three-way interaction is consistent with the greater change in perceived location for cold stimuli at shorter delays within the AB-CD sequence.

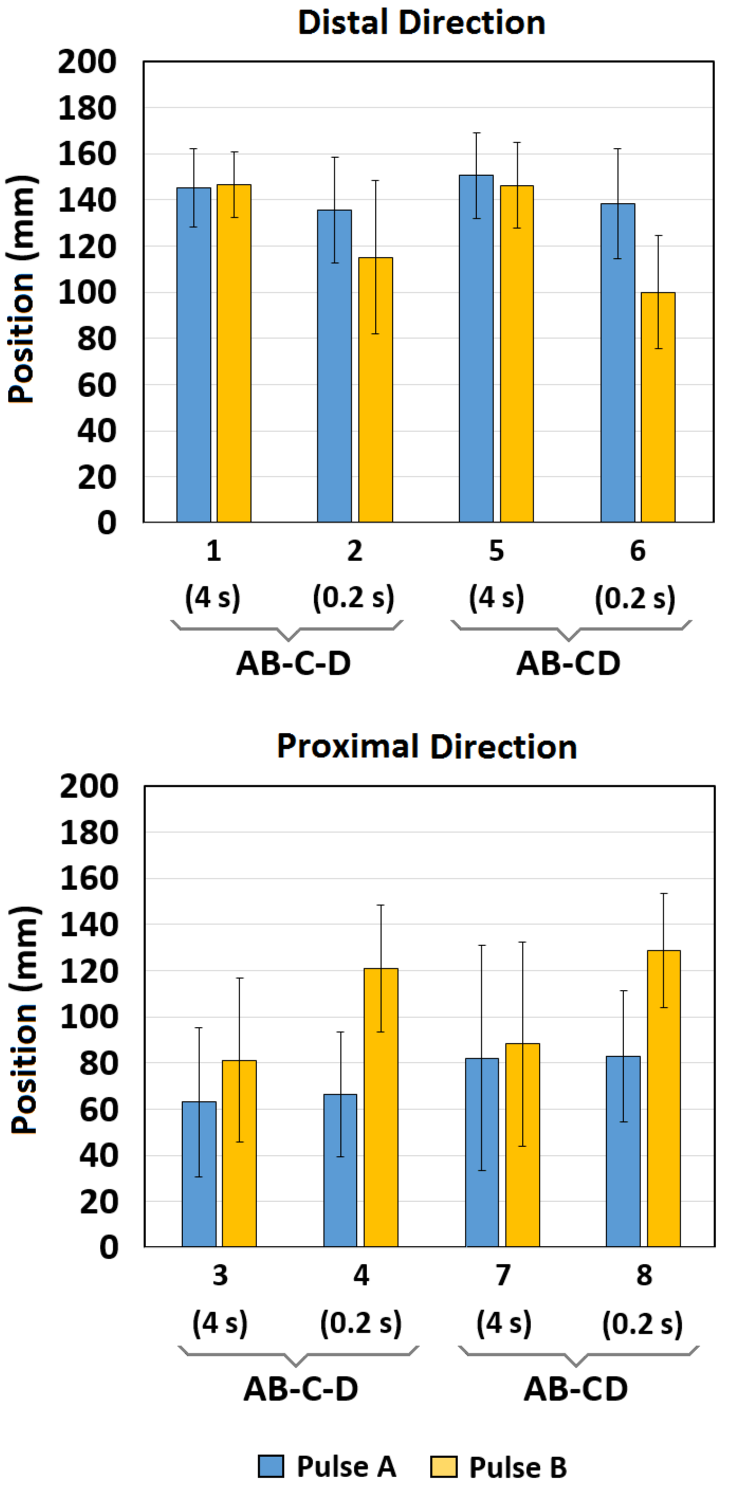


Figure 4.13 The group mean perceived position of the first and second pulse in each pattern, when the direction of the thermal display's activation was distal (P1-P2-P3) or proximal (P3-P2-P1). Standard deviations are shown.

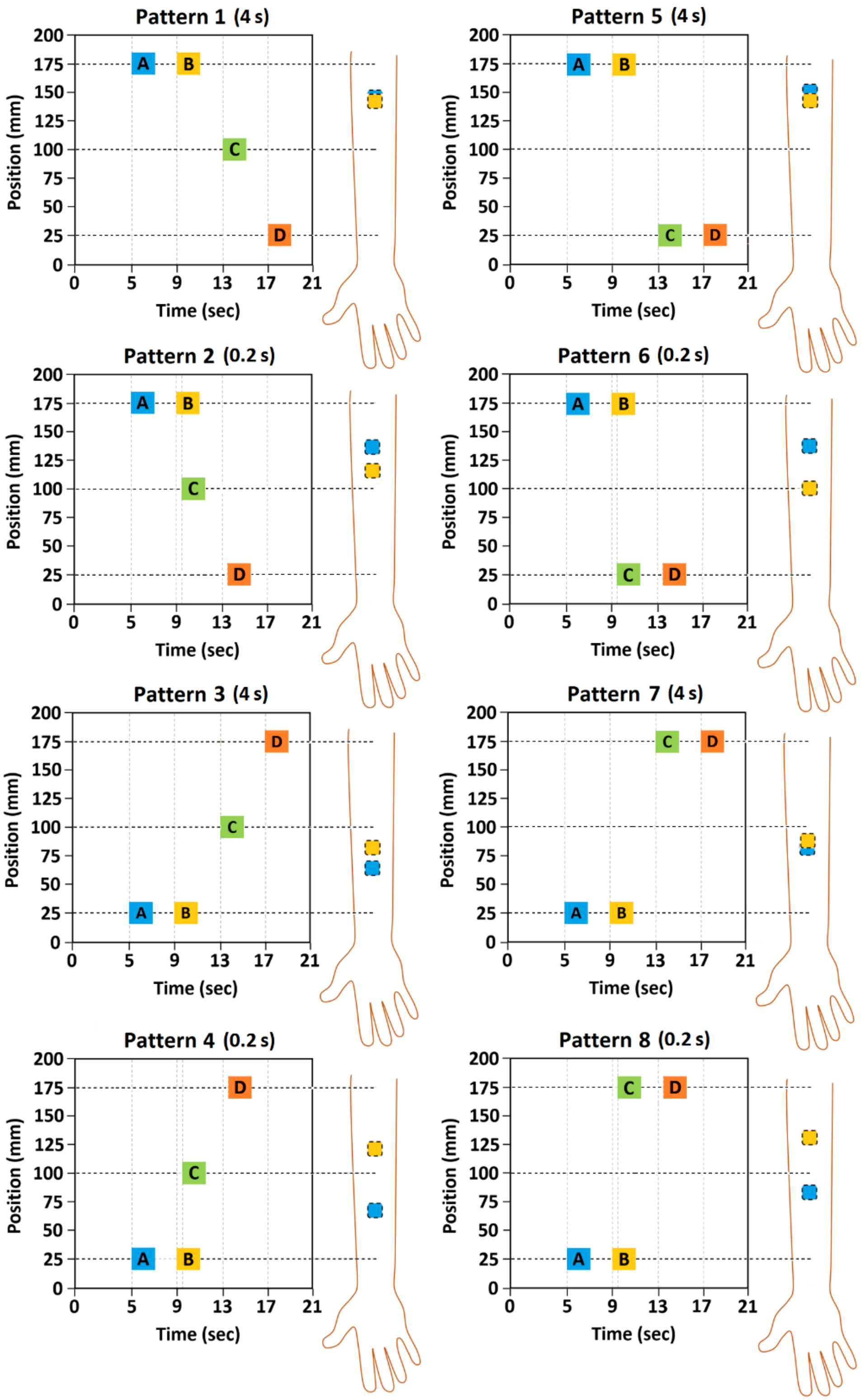


Figure 4.14 Schematic illustration of the group mean data for the physical stimuli depicted graphically and the perceived position of those stimuli on the forearm.

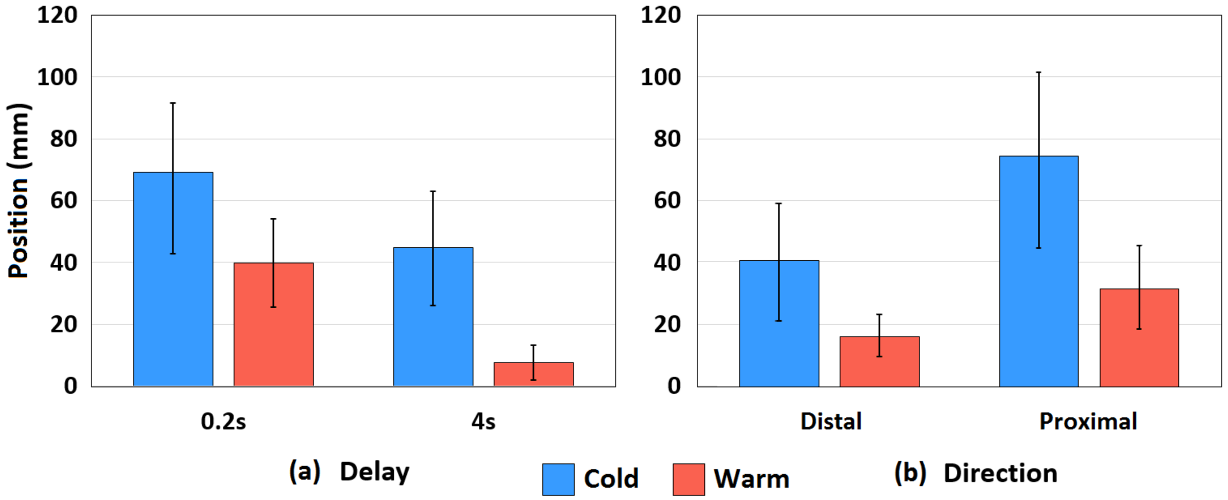


Figure 4.15 The group mean absolute difference in perceived location of the first and second pulse for cold and warm stimuli at (a) a delay of 0.2 or 4 s and (b) when the direction of the thermal display's activation was distal (P1-P2-P3) or proximal (P3-P2-P1). Standard deviations are shown.

4.4 Discussion

The objective of these two experiments was to determine whether illusions of space and time that have been demonstrated for mechanical stimulation on the skin also occur for thermal stimuli within the innocuous range of temperatures. This was studied using presentation of thermal pulses on the forearm in varying spatial and temporal sequences. The second pulse was always delivered at the same location as the first pulse, but its perceived position changed as a function of the delay between it and the third pulse.

In the first experiment, cooling pulses were presented on the forearm of the participants. The results indicate that the position of the second pulse changed substantially (on average between 43 and 59 mm) in the direction of the third pulse when the interval between these pulses was brief (0.2 seconds) and the distance between the second and third pulse was greater. At longer intervals (4 seconds) and shorter distances there was no change in perceived location. These findings indicate that the tau effect does occur for thermal stimuli and that stimuli that occur closer together in time are perceived to be spatially closer. The absence of any change in perceived location for pulse B when pulse C was close spatially may reflect the limited spatial acuity of the thermal perceptual system. The perceived location of pulse B in all conditions was in the direction of pulse C and so these two stimuli may have been difficult for participants to resolve spatially.

In the second experiment, all the stimulus parameters of the first experiment were kept the same except that warming stimuli were delivered to the forearm rather than cooling stimuli. The results of this experiment indicate that when the delay was short (0.2 s) the position of the second pulse was perceived to move by 40 mm on average towards the location of the third pulse. This occurred independently of whether the third pulse was close to (75 mm, Patterns 2 and 4) or further away (150 mm, patterns 6 and 8) from the second pulse. At longer delays (4 s) the position of the second pulse was perceived accurately, that is, at the same location as the first pulse. These findings provide strong evidence that for the thermal modality, similar to touch, the temporal interval between warm stimuli delivered to the skin can influence their perceived location. The optimal interval for such effects to occur is probably around 200 ms, although this needs to be further studied. For tactile stimuli, intervals between 200 and 250 ms are optimal [46].

A comparison of the results from the first experiment with cold stimuli and the second experiment with warm stimuli reveals some interesting differences between the thermal senses. First, the magnitude of the change in perceived position was greater for cold than warm stimuli (see Figure 4.15); second, at short delays the change in the perceived position of a cold, but not warm, stimulus was affected by the distance between the stimuli (i.e. pulses B and C). This suggests that the cold sensory system may provide better somatotopic information than the warm sensory system. Consistent with previous studies that have shown that there is better localization for cooling than for warming stimuli on the forearm [76], in the present experiments the position of the first stimulus was better localized for the experiment using cold stimuli. In summary, these results indicate that despite the limitations in the spatial and temporal processing of thermal stimuli, somatotopic information appears to be integrated similarly for tactile and thermal stimuli.

The paradigm used in this set of experiments was one that has frequently been employed in studies of tactile sensory saltation [50], [66]. It has the advantage that an objective measure of the position of a stimulus is provided and changes in perceived position can be related to factors such as inter-stimulus delays and the distance between stimuli. The mislocalization of pulse B in the present experiments in the direction of pulse C is consistent with the findings on sensory saltation reported for tactile stimuli [50], [66]. However, for the sense of touch it is clear that saltatory stimuli cause both a change in the perceived position of a stimulus and a perception of its movement across the skin. The thermal stimuli used in the present experiments were not perceived to move across the skin and the onset and offset of each stimulus was much less distinct than would occur with a mechanical input, no doubt reflecting the slow changes in skin temperature.

The results from these experiments provide several interesting insights into the perceptual mechanisms involved in processing the spatial properties of thermal stimuli. First, despite the number of studies that have documented the very poor spatial resolution for thermal stimuli [13], [40], [67], it was surprising to find that participants could identify reliably the location of the first thermal stimulus, particularly when it was presented in the area around the elbow (see Figure 4.8 and Figure 4.13). Stimuli were never mislocalized in terms of being perceived at the endpoint of stimulation, for example, the region around the elbow for sequences that started at the wrist. Measurements of the temperature of the skin not in contact with the Peltier devices confirmed that the decreases in skin temperature were well localized (Figure 4.6 and Figure 4.11). This is consistent with other studies that have shown that the changes in skin temperature during contact with different objects are localized to the contact area [69]. Although participants were informed that the pulses could be presented at any location, for all sequences they perceived the second pulse to be localized in the direction of the third pulse and not at the same location as the first pulse.

A second finding of interest relates to the time delay required for the illusion. A delay of 0.2 s between the second and third pulse was probably optimal for the change in perceived location to occur, although additional experiments would need to be performed with delays between 0.2 and 4 s to confirm this. For tactile stimuli it has been shown that the tau effect is optimal when the ratio of the two time intervals is no greater than 4 to 1 [70], [71].

4.5 Conclusion

In conclusion, this set of two experiments has demonstrated an interesting illusion in a sensory modality that is known for its limited spatial and temporal processing capacity. These findings demonstrate that the space-time interactions reported for other sensory modalities can also occur with thermal stimuli and so presumably represent a fundamental aspect of perceptual processes. These illusory phenomena not only offer insight into how the external environment is sensed but also provide tools that may be used to optimize the presentation of information in haptic and thermal displays. In particular, these findings demonstrate that by varying the onset of different thermal stimuli it is possible to create stimuli whose spatial location is perceived to vary. This provides an extra dimension to use to present information in a thermal display and potentially could result in a display that functionally has a higher spatial resolution than the number of thermal elements would indicate.

Chapter 5

Conclusions and Future Work

5.1 Summary and Conclusions

The goal of this thesis was to understand how different thermal stimulus parameters affect the response of the skin to thermal stimulation, and whether these changes in skin temperature are perceived. A set of thermal patterns, known as thermal icons, can be used to convey information when presented using a thermal display. The thermal responses of the skin were studied to understand which features of the thermal stimulus are important and can be perceived by the user. The effectiveness of these patterns was evaluated for applications of thermal displays involving hand-held or wearable devices. These thermal icons varied with respect to the temporal properties of thermal stimulation. Additional experiments were conducted to evaluate the relation between the spatial and temporal aspects of thermal stimulation within the innocuous range of temperatures. The results showed that the temporal properties of thermal stimuli can influence their perceived location.

In the first series of experiments, a set of six thermal icons was developed. These were presented to participants at two locations on the hand and they were required to identify the thermal icon. Preliminary experiments on the responses of the skin to various types of thermal inputs indicated that waveforms such as square waves, sinusoids and triangular waves resulted in very similar changes in skin temperature and so were unlikely to be perceptually distinguishable. The three profiles selected for the thermal icons did produce distinct changes in skin temperature and were perceptually distinguishable. The results from these experiments on the thenar eminence and the fingertips indicated that a small set of thermal icons created by varying the direction, magnitude and rate of temperature change can be readily identified with little training. The individual mean scores associated with the six thermal stimuli ranged from 80% to 98% on the thenar eminence and from 81% to 88% on the index finger with overall means of 91% and 84% respectively. The information transfer values for the thenar eminence averaged 2.11 bits and for the finger 1.83 bits.

The long duration of 30 seconds for each of the thermal icons in this set most likely contributed to the good performance of participants. The stimulus presentation time of 30 seconds limits the application of these icons in thermal displays. A revised set of thermal icons which were shorter and highly salient, was then created using stimulus features that could be accurately identified. An absolute identification experiment was conducted with this revised set of thermal icons each of which was 8 seconds in duration. The icons were presented relative to each participant's baseline skin temperature. In this study, the thermal display was mounted on the wrist of the participants, which offers higher thermal sensitivity and a location that can be used in a wearable device. The information transfer values for the wrist averaged 2.13 bits, which was comparable to the 2.11 bits recorded for the thenar eminence. These findings demonstrated that the information processing capabilities of the thermal sensory system may rival those achieved with vibrotactile inputs, and that a set of thermal icons with a duration of 10 seconds can be identified accurately. The results provided support for the application of thermal displays in the form of a wearable device on the wrist.

The third set of experiments was conducted to study whether the spatio-temporal interactions reported for other sensory modalities also occur with thermal stimuli. A thermal display consisting of three Peltier modules and capable of presenting short duration cold and warm thermal pulses on the forearm was used in this set of experiments. The results showed that the perceived location of thermal stimuli can change as a function of the temporal parameters of stimulation. These findings demonstrated that the space-time interactions reported for other sensory modalities also occur with thermal stimuli and so presumably represent a fundamental aspect of perceptual processes. These illusory phenomena not only offer insight into how the external environment is sensed but also provide tools that may be used to optimize the presentation of information in haptic and thermal displays. In particular, these findings demonstrated that by varying the onset of different thermal stimuli it is possible to create stimuli whose spatial location is perceived to vary. This provides an extra dimension to use to present information in a thermal display and potentially could result in a display that functionally has a higher spatial resolution than the number of thermal elements would indicate.

In summary, the work presented in this thesis explored and demonstrated important features of the thermal sensory system. These findings widen the scope of parameters that can be used to create effective thermal patterns for thermal displays. The results of these experiments may also be employed to create more realistic thermal and haptic displays for virtual environments and tele-operated systems.

5.2 Contributions

The research work conducted for this thesis was published in the form following peer-reviewed conference papers and a conference abstract:

- A. Singhal and L. A. Jones, "Dimensionality of thermal icons," IEEE World Haptics Conference (WHC), Evanston, IL, 2015, pp. 469-474, 2015.
- L. A. Jones and A. Singhal, “Thermal pattern identification on the hand”, Program No. 240.22/N15. 2015, Neuroscience Meeting Planner. Washington, DC: Society for Neuroscience, 2015. Online.
- A. Singhal and L. A. Jones, "Space-time interactions and the perceived location of cold stimuli," IEEE Haptics Symposium (HAPTICS), Philadelphia, PA, USA, pp. 92-97, 2016.
- A. Singhal and L. A. Jones, "Space-time dependencies and thermal perception," Eurohaptics, London, UK, 2016, in Press.

5.3 Future Work

The experiments described in this thesis included presentation of thermal stimuli to the skin and recording the change in temperature of the skin. In future studies, experiments could be focused on characterizing the thermal response of the skin from the thermal stimuli. Knowledge of the thermal characteristics of the skin would allow prediction of the changes in skin temperature when a thermal stimulus is presented. It is evident from the experiments conducted in this thesis that the skin temperature changes more slowly than that of the thermal display due to the thermal dynamics of the skin. Therefore, thermal characterization experiments should be designed with thermal stimuli which can capture the dynamic range of the skin's thermal response.

Contact based thermal sensors were used in all the experiments presented in this thesis. A small thermistor with low thermal mass was used on the periphery of the contact area to record the change in skin temperature due to thermal stimulation. Due to its position, the sensor was not able to detect the full extent of the temperature change during contact [5]. To overcome the limitations of conventional contact thermal sensors, a non-contact skin temperature measurement system based on infrared measurement could be developed and incorporated in future experimental setups. This more accurate measurement of the skin temperature could be used for characterization of the skin's thermal response. It has been reported that the skin's thermal response is influenced by contact pressure [5] [77]. To evaluate the influence of contact pressure on the skin's thermal response, the experimental setup could also include the measurement of contact force and area.

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