# Dimensionality of Thermal Icons

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*Abstract*— **The thermal sensory modality provides a novel dimension to present information to users of a variety of hand-held devices provided the inputs are tailored to the properties of the sensory system. The objective of the present experiment was to measure thermal pattern identification on the thenar eminence at the base of the thumb using a set of six stimuli that varied with respect to the direction, magnitude and rate of temperature change. An absolute identification paradigm was used in which each stimulus was presented eight times and participants had to identify which stimulus was presented using a visual template that depicted the thermal icon. The individual mean scores averaged across all stimuli ranged from 80% to 98% correct with an overall mean of 91%, indicating that the thermal icons were relatively easy to identify. The Information Transfer values ranged from 1.76 to 2.49 bits across participants with a group mean of 2.26 bits. These findings indicate that thermal icons offer considerable potential for presenting information as part of a haptic interface, and that the information transfer capabilities of the thermal sense may rival those achieved with vibrotactile inputs, although at the cost of a prolonged presentation time.**

## I. Introduction

An understanding of how changes in skin temperature are encoded in the periphery and transmitted in the central nervous system (CNS) is essential to the development of effective thermal displays. The cold and warm thermo-receptors 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 [1]. 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 [2]. These properties 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.

The sensitivity of skin to thermal stimulation in part determines the placement of a thermal display. 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 [3]. 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 [3]. 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 [3, 4], 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 [5]. 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 [6]. These fundamental properties of the thermal sensory system provide a framework for defining the optimal characteristics of stimuli presented in a thermal display.

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 [7]. 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. The objective of the 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 [8]. 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 [7, 9, 10]. For this application of thermal interfaces 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 [9, 11-14]. 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 [7].

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 [15] or to present scalar information that is mapped onto temperature [16]. 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

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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. 16, 17]. 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 [18, 19]. 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 [20]. 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 [21-23]. 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 [22]. 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 [23], to 83% correct for a similar set of four icons [24].

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. The objectives of the present experiment 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 [19]. The basis for designing thermal icons has not been well delineated, and so the thermal responses of the skin to thermal 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.

## II. 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 of temperature had been presented. The thenar eminence at the 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 [3]. In addition, 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. 25, 26].

### *A. 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.

### *B. 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 Fig. 1.

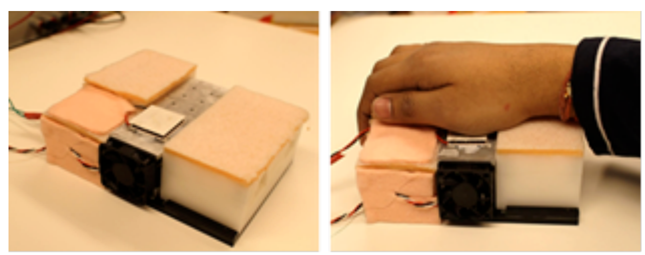

Figure 1. Thermal display with thermoelectric module mounted on a heat sink and fan (left) and with the thenar eminence over the thermoelectric module during stimulus presentation (right)

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 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 Fig. 1). 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.

### C. *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. 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.

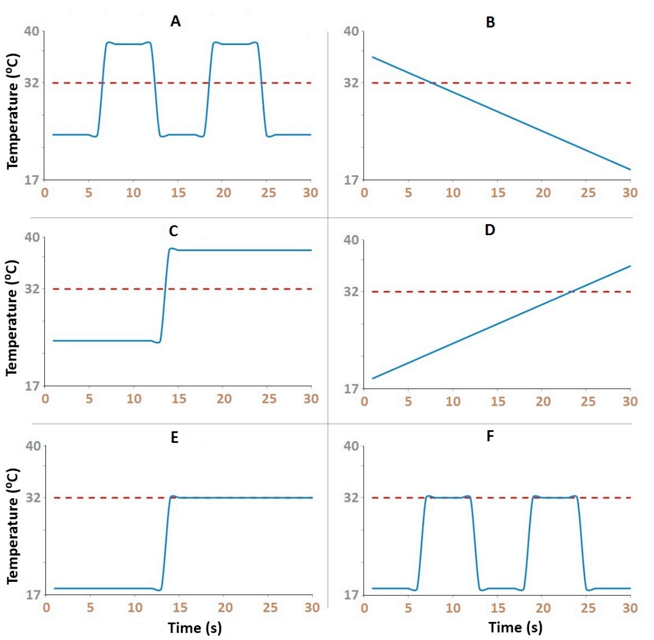


Figure 2. Visual depiction of the six thermal patterns that varied with respect to intensity and rate of change in temperature. The dashed line indicates the baseline skin temperature. In the template that participants viewed there were no numeric values on the axes.

Fig. 2 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.

### D. *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™, Johnson & Johnson). 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 glabrous surface of the hand on the supporting fixture, and brought their thenar eminence in contact with the thermoelectric module's surface as illustrated in Fig. 1. The contact area between the hand and the Peltier device ranged from 600-750 $mm^2$ across participants. A visual depiction of the stimuli was presented on the computer screen in front of the participant (see Fig. 2). 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.

## III. Results

The group mean temperature measured on the hand and the thermal display during the experiment are shown in Fig. 3. 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 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.

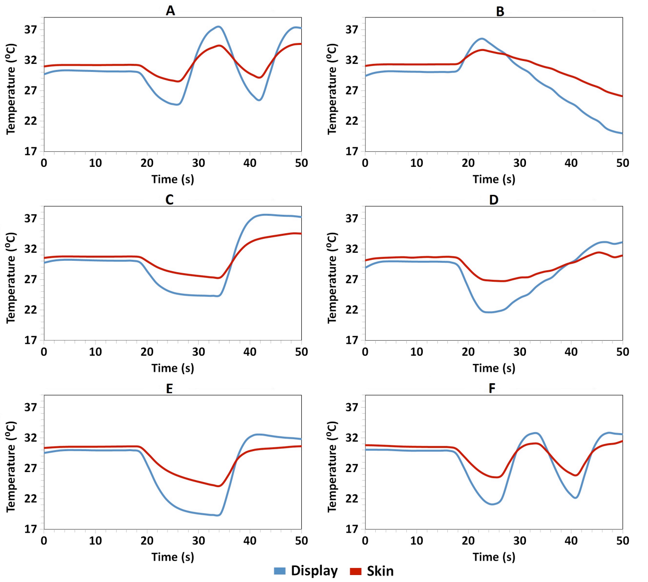


Figure 3. Temperatures measured on the skin and the display averaged across trials and subjects for each of the six thermal stimuli. The first 20 s of data prior to each stimulus presentation are also shown.

The 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 80% to 98% correct and an overall mean of 91% correct.

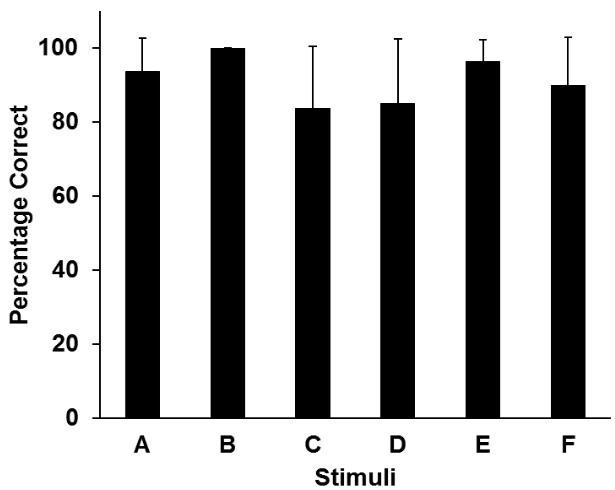


Figure 4. Group mean percent of correct responses for each thermal pattern. The standard deviations are shown.

Fig. 4 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 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.

Table 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.

| | Subjects' 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. [27]. 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. 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 [27]. The IT values ranged from 1.76 to 2.49 bits across participants and the group mean value was 2.26 bits. This is interpreted as indicating that for this set of six stimuli 4.8 patterns can be correctly identified.

## IV. DISCUSSION

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 overall performance of participants in the present study at 91% correct is better than the 83% correct reported by Wilson et al. [24] for a smaller set of four thermal icons. However, in the latter experiment 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 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 they 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 [3, 4]. 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 Fig. 3). In addition, they were both most likely to be misidentified as pattern E (see Table 1), 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 [28] 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 [4]. 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 [29]. Much of the research on the temporal aspects of thermal stimulation such as adaptation has focused on its effect on thermal thresholds [30], 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 [31, 32]. 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 (Fig. 2). As the responses depicted in Fig. 3 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 have been successfully employed previously [23].

The mean IT of 2.26 bits was surprisingly high given previous findings on thermal icon identification [23, 24]; 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 [19]. 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 [33]. 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. [34] 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 [35].

In summary, the properties of the thermoreceptive sensory system determine which features of thermal stimulation on the skin are encoded and how these characteristics can be used effectively to create unique thermal icons. In the present experiment with six thermal icons, participants were remarkably accurate at identifying the icons and achieved an average IT of 2.26 bits. Recordings of the changes in skin temperature revealed the importance of considering the thermal dynamics of the hand when designing thermal icons. 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.

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