A Sense of Ice and Fire: Exploring Thermal Feedback with Multiple Thermoelectric-cooling Elements on a Smart Ring

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Abstract

In this paper, we investigate the use of thermal feedback on a smart ring with multiple thermoelectric coolers (TECs). Our prototype aims to offer an increased expressivity with spatial thermal patterns. In a pilot study with nine participants, we investigated the affordance of applying multiple miniature TECs in a ring-type finger device, by comparing the user perception in three different ring settings: 4, 6, and 8 TECs. Results showed that users could reliably recognize 4 points with cold stimulation (97.2% accuracy) and still achieve decent accuracy with hot stimulation (82.4% accuracy). In the following two main experiments, involving 24 participants in total (i.e. 12 for each experiment), we investigated the use of 4 in-ring TECs to achieve two categories of spatial thermal patterns by combining two neighboring or opposite elements. The results revealed 12 thermal patterns that were reliably recognized by the participants with the accuracy averaging 87.5%, indicating their potential usage as the in-ring thermal icons.

The participants also suggested different applications for smart rings with multiple thermal modules, including direction cueing through neighboring patterns and artifact comparison through opposite patterns. This demonstrated interest in spatial thermal patterns in smart rings not only for notifications but also for various everyday activities.

Keywords: smart ring, thermal feedback, spatial thermal sensitivity

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1. Introduction

Smart rings can be used to convey information easily and discretely. As fingers are one of the more sensitive body locations to haptic stimuli [?], smart rings are especially desirable. Potential information that can be relayed ranges from simple notifications to more complex continuous information, such as training progress [?], or even direction information. However, smart rings are limited by their size, which makes it hard to embed multiple actuators of the same type in them, such as vibration motors. Thus, previous research done in this area [? ?] has primarily focused on using a single actuator. However, such systems can only convey simple information by using single-dimensional patterns, such as temporal [?], which usually affects the expressivity of the system.

Using multiple actuators allows for encoding of more complex information with spatial patterns. For example, a wristband with four or more output actuators (e.g. DC motors and vibration motors) could be used for navigation [?], or to perform more complex tasks, such as color comparison [?]. However, vibrotactile feedback with multiple actuators does not seem to be a usable strategy to create spatial patterns with the form factor of smart ring, as the vibration at one location could easily vibrate the whole ring, making it hard to locate the source of vibration.

Although early studies [? ? ?] on thermal localization showed that radiation-based non-contact heat was error-prone in localization due to the phenomenon of spatial thermal summation, later research suggested on-skin thermal stimuli through small thermal-haptic devices could improve the spatial acuity for tactile stimulation [?]. In addition, the cold stimulations were generally more perceivable than the hot ones [?]. Psychological research has also shown the phenomenon of illusional and referral thermal sensation [?], which implies that the perception of a thermal receptor could be triggered/altered by the concurrent stimulation on the other peripheral/closed-by receptors. In the field of human-computer interaction (HCI), this channel has been previously used in a wide variety of contexts, such as social activities [?], emotions [? ? ?] and navigation [?]. Thermal feedback is usually considered more stable to perceive in a moving or noisy situation and more private than other modalities [?]. Additionally, Roumen et al. [?] showed that heat sensitivity is positively impacted by physical activity, with heat being easier to perceive during walking or running activities. In addition, the results of NotiRing indicated the need for investigating thermal's potential as an in-ring notification channel with improved thermal devices that have more immediate feedback.

While early psychological studies revealed the poor spatial acuity for thermal sensation on finger-tips [?], it is unknown how the results may alter with miniature on-skin TEC modules and the wearable form factor of ring. Previous research on thermal feedback for HCI has mainly focused on body locations such as the thenar eminence, face, and wrist [? ? ? ? ? ? ?]. Existing research showed the form factor of ring afforded eight positions of pin-point poking stim However, in the limited research on ring-based thermal feedback [?], multiple thermal actuators on the ring were not used. In this paper, we present a prototype of a smart ring with multiple miniature TEC elements and investigate the use of spatial thermal patterns. In the pilot study, we determined the maximum number of TECs that can be accurately recognized by participants. A configuration with four elements (see Fig. ??) yields an accuracy of XXX% for cold stimuli and XXX% for hot stimuli. We then designed a set of in-ring thermal patterns (Fig. 9 & 12) by combining two neighboring or opposite TECs, each of which can be triggered as cold, neutral, or hot. In a series of main experiments, we assessed the feasibility of accurately perceiving the combinational thermal patterns. Results revealed XXX, indicating their potential usage as in-ring thermal icons. Based on the participants' elicitations, we propose a list of applications that can elaborate these thermal patterns, such as XXX.

The contribution of this paper is four-fold:

- Working prototypes of smart rings embedded with multiple TECs, of various sizes, which can be used with the thermal patterns described in the paper.

- Empirical study on user perception of spatial thermal patterns on the finger using a smart ring.

- A set of thermal patterns that leverage the finger's natural sensitivity to temperature to allow reliable recognition of single and combinational patterns from the smart ring;

- A set of user-elicited application scenarios that leverages the proposed set of in-ring thermal patterns.

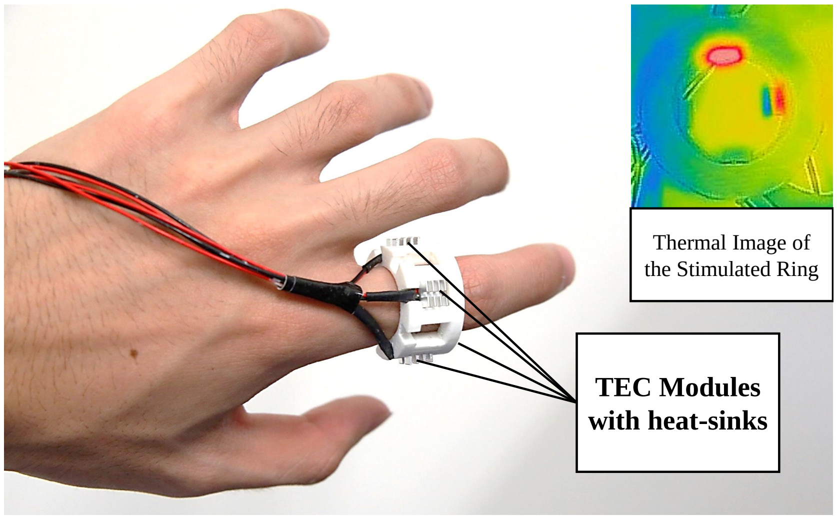

Figure 1: Smart ring prototype with four TEC modules around the finger.

2. Related Works

Our research is inspired by two emerging topics in HCI: thermal feedback, and multimodal haptic feedback on fingers.

2.1. Thermal Feedback in HCI

There have been extensive physiological [? ? ?], psychological [? ? ?], and HCI-related [? ? ? ? ? ? ? ? ? ? ?] research on thermal feedback, from which various applications have been proposed.

Jones and Berris [?] distilled a list of useful features and design suggestions for the thermal display based on virtual reality (VR) research and psychological evidence. Wettach et al. [?] designed a peltier-based thermal device attached to a mobile phone, and showed that users could differentiate three different hot temperatures with the error rate of 25% after long-term training. Sato and Maeno [?] created a 2x2 matrix of TECs to reduce the reaction time to thermal stimulation on the fingertip.

Wilson et al. conducted a series of comprehensive investigations on thermal feedback in HCI, which provided important insights on design: 1) hand is a highly thermally sensitive body part [?]; 2) 1°C/sec rates of change were appropriate for thermal displays [?]; 3) the perception of thermal feedback could be strongly affected by clothes [?] and the environment [?]; 4) a set of thermal icons on mobile phones (overall accuracy of perception:

83%) can be designed based on the speed and the direction of temperature change [?]; 5) there was a strong agreement among users on the application of thermal feedback in social communication and rating-related information representation [?]; and 6) thermal feedback could be applied to represent emotion [?] and widen the range of emotion representation along with other feedback modalities [?]. Following Wilson et al.'s insights, Tewell et al.'s research showed that thermal feedback enhanced the affective perception of text messages [?] and could be used to facilitate navigation [?]. More recently, thermal feedback was integrated in the head-mounted display to enhance the experience of presence in VR [? ? ?].

Research showed that people preferred to associate personal emotional information with smart wearable accessories [?]. Thus, the characteristics of being private, robust, and well-associated with affective feeling makes thermal feedback a good candidate for the output channel in smart wearable accessories. In the extensive HCI research available on thermal feedback, the thermal modules studied were mostly large and attached to the palm and the forearm (besides the integration with the head-mounted display). There has been little investigation on thermal feedback in the form factors of wearable accessories, especially as a finger ring, given physiological research results that show that fingers and the palm have similar high temperature sensitivity among different body parts [?].

2.2. Multimodal Haptic Feedback on Fingers

Numerous works have studied multimodal feedback such as vibration [? ?], poking [?], resistor-based thermal [?], and skin dragging [?], on the finger, either in a general setting or in a specific application context. The stimulated locations covered mainly two parts of the finger: the distal phalange (including the side of finger, finger pad, and the nail) and the proximal phalange where a ring is usually worn.

The haptic devices on the distal phalange were usually associated with touch and applied in virtual and augmented reality. Yem et al. [?] developed FingAR, combining electrical and mechanical stimulation to selectively stimulate different types of mechanoreceptors and to achieve high-fidelity tactile sensation during user touch of a virtual surface. More recently, Feng et al. [?] developed Submerged Haptics consisting of 4 3D-printed miniature airbags to provide fingertip haptic feedback with air inflation. Murakami et al. [?] developed AlteredTouch, a fingertip haptic display with integrated force, tactile, and thermal feedback in a miniature form factor with integration of two DC motors and one peltier module. Hsieh et al. [?] developed NailTactors, a nail-mounted array of tactors to provide eyes-free vibrotactile patterns through spatial encoding of vibration (perception accuracy of 89%).

Haptic output on the proximal phalange with a finger ring has also received an increasing yet unequal amount of interest, compared to haptic feedback on the distal phalange. As a type of digital jewelry, smart rings benefit from the same social acceptability and emotional bond as traditional jewelry [?]. Pradana et al. [?] developed RingU, supporting remote communication through visual and vibrotactile feedback in the ring. Roumen et al. [?] compared five types of in-ring notifications: visual, audio, vibrotactile, poke, and thermal. Their results showed that vibrotactile feedback was the most reliable and fastest channel for notification, while thermal channel, which was implemented using resistors, was the slowest. This specific limitation was caused by the hardware, as their system needed more than 7 seconds of warming versus 1 second for a TEC. Despite this limitation, they found consistent and accurate thermal perception by some participants, and suggested interesting scenarios in which thermal feedback could be desirable, such as a notification channel for moderately urgent messages. Je et al. [?] developed tactoRing, a ring-size tactile display that provides haptic feedback by dragging a small gear tactor on the skin around the finger, achieving an accuracy of 94%. More recently, Han et al. [?] designed Frictio, providing in-ring friction-based force feedback, with requirement of input from the non-wearing hand.

While visual, auditory, vibrotactile, poking, and skin-dragging feedbacks have been investigated in the context of a finger ring with optimal technical implementation, the existing attempts for in-ring thermal feedback were based on resistor heat generation, which is slow and unidirectional. There is a lack of research on how TEC-based bidirectional thermal feedback can be integrated and elaborated in a finger ring setting. In this paper, we present a prototype of a finger ring with multiple TECs that can achieve different levels of thermal feedback around the finger.

3. Hardware Design

In the prototype of the thermal ring, we used a 55 mm TEC element (Model No.: TEC1-00701) attached to a 6×6 mm heat sink, as shown in Fig. ??. The rings were 3D printed with PLA. As shown in , each ring contained 6 or 8 6x6 mm square holes (Fig. **??**), for easy installment and removal of the TEC modules. Once the TEC modules were installed in the ring, the ring was further tightened with a rubber band, ensuring the TEC modules attached firmly to the skin.

Each TEC module was connected to an external motor-driver circuit (L298N). An external power supply with 9V2A was connected to the motor driver through a relay circuit. Due to the miniature size of the TEC module, it was challenging to embed the thermistor in the module. Therefore, we adopted the sensorless temperature-control method proposed by Odhner and Asada [**?**]. The system was controlled by the Arduino Mega 2560 connected to a PC through USB, to ensure the fine control of the temperature through Pulse Width Modulation (PWM). Through empirical pilot tests, we found that a 3-second stimulation at a rate of +/- 1°C/s could provide a reliable yet not painful thermal sensation, while stimulation with +3 °C/s could cause painful sensation even in a short duration (1 second). Therefore, the TEC module was tuned to change the temperature at a rate of +/- 1 °C/s for 3 seconds. Fig. **??** illustrates the arrangement and assembly of the TEC modules in the three settings.

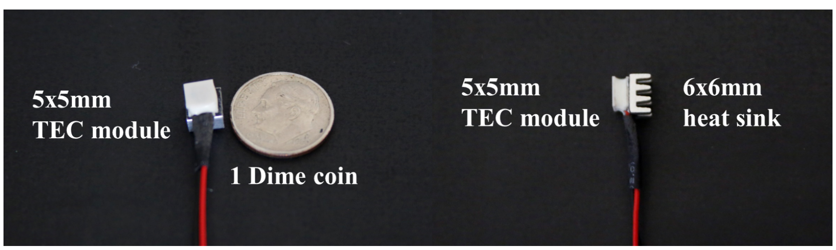

Figure 2: TEC Module. Dime for scale.

4. Pilot Experiment

In our pilot experiment, we investigated the resolution of the thermal ring, i.e. the maximum number of discrete points users could perceive around a single finger. We chose three conditions for this experiment: a ring with 4, 6, or 8 TEC elements.

4.1. Participants

Nine participants (5 females, 8 right-handed) ranging from 23 to 31 years old (M=26.76, SD=2.78) were recruited from within the university commu-

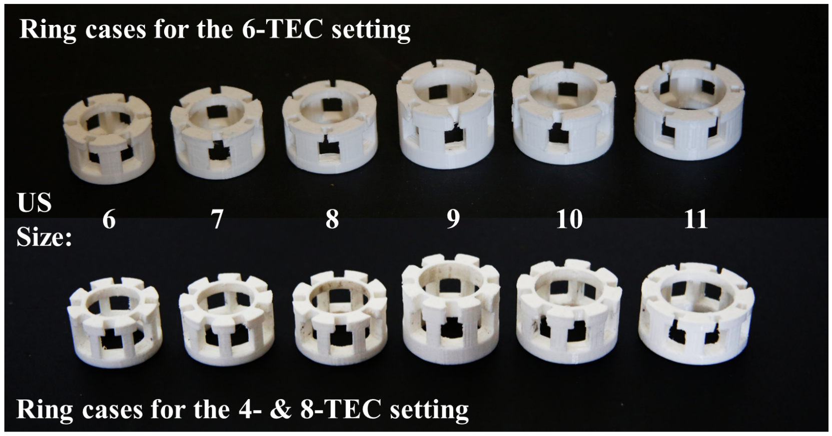

Figure 3: Set of rings of different sizes (6 to 11 US sizes) used in this paper.

nity. The average skin temperature on the finger was 32.6 °C (SD = 1.342). Research showed that XX could potentially cause pain. To ensure the well-being of participants and the execution of the experiment, we conducted a 2-minute pre-study session to test the thermal and pain threshold of the recruited participants, and excluded those with overly-sensitive skin.

4.2. Apparatus

For this experiment, we designed 12 ring prototypes in sizes ranging from US 6 (diameter of 16.45 mm) to US 11 (diameter of 20.6 mm), as shown in Fig. 3. Each ring contained 6 or 8 TEC elements on them. For the 4-TEC condition, we only installed 4 TECs in the 8-TEC ring. At the beginning of the experiment, we selected the ring best fit each participant. The rings were worn on the index finger of their non-dominant hand. An iPad Air 2 was used to display the GUI webpage content for training and testing, and allow the participants to select their answers. The GUI webpage was connected to the PC server through a web-socket protocol. All sessions were facilitated by the same experimenter and conducted in a university office with central air-conditioning, maintaining a stable room temperature of 27 °C.

4.3. Tasks and Stimuli

During each test trial, one of the elements would get activated on two temperature levels we chose (hot : + 1 °C/s and cold : -1 °C/s) for 3 seconds. The TECs started the temperature change from the skin temperature of the user.

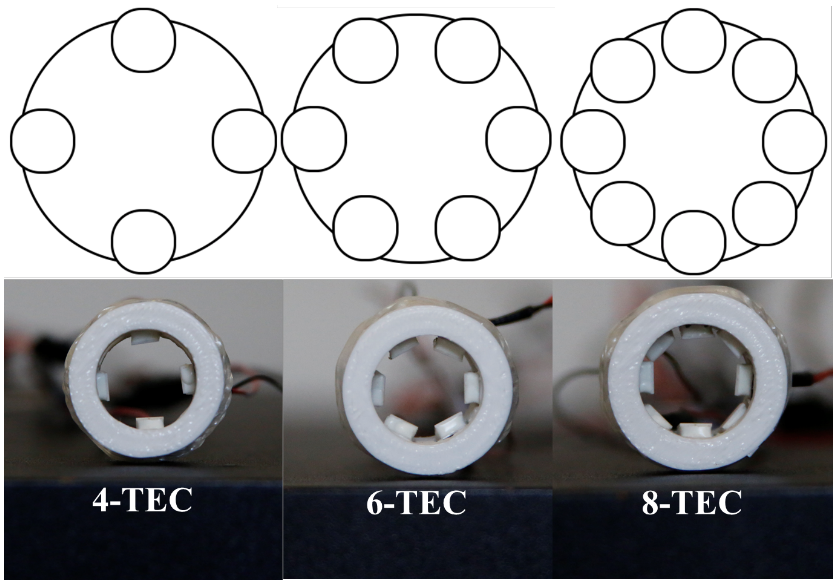

Figure 4: Arrangement and assembly of the TEC modules in the three different settings.

The participant would then, without looking at their hand, determine on which elements the stimulus happened by selecting the correct element on the iPad Air 2. There was a 15-second break between trials, to allow the skin naturally return to the resting temperature which was record before the experiment.

4.4. Procedure

Participants began the experiment by filling a pre-test questionnaire with demographic information. Their skin temperature on the finger was collected. Before starting, the experimenter helped the participant choose and put on a ring that would best fit on their finger among the six different sizes. The ring was then put on the finger to reach the positions shown in Fig. **??**.

The experiment was divided into three sections (one for each TEC setting). Each section started with a training block where each stimulus was triggered clockwise sequentially starting from the bottom element for the 4-TEC and the 8-TEC setting, and the left element for the 6-TEC setting. During each stimulus in the training, the iPad Air 2 showed the corresponding location being highlighted in blue for cold stimulus or red for hot stimulus (Fig. **??**b). This was repeated twice. After training, participants completed two test blocks, where stimuli were presented in a randomized order. The

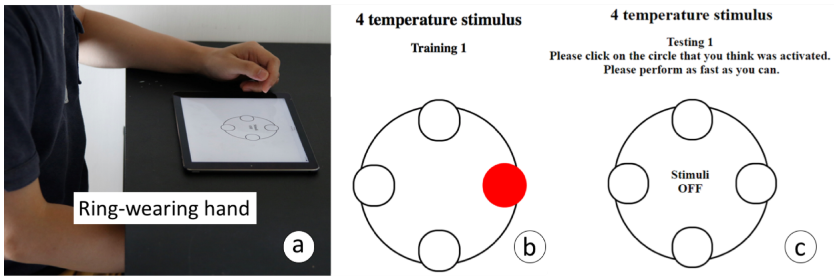

Figure 5: (a) Experiment setup; (b) Training Interface for the 4-TEC setting; (c) Testing Interface for the 4-TEC setting.

selection interface was displayed after each stimulation, and participants selected the stimulated element by tapping on the smaller circle in the web page (Fig. **??**c). After completing each test block, participants filled a post-experimental questionnaire to measure the perceived level of difficulty and comfort using a 7-point likert scale (1 - not difficult /comfortable at all, 7 - extremely difficult/comfortable).

4.5. Experiment Design

A 3 × 2 within-subject design was used with two independent variables: number of TECs (4, 6, 8) and temperature change cold (-1 °C/s), hot (+1 °C/s). The number of TECs was counterbalanced using Latin Square and temperature was randomized within blocks. We measured two dependent variables: element accuracy and response time (i.e. time to complete a trial after the stimulation). A trial was considered successful when the participant was able to identify the correct element that was activated. Participants could take voluntary breaks between blocks.

Each participant performed the experiment in one sitting (Fig. **??**a), placing his/her ring-wearing hand on the keyboard drawer of the table, thus he/she couldn't see the ring. The experiment lasted for around 70 minutes. In total, each participant did a total of 3 conditions (number of elements) × 2 temperatures × [1 training block + 2 test blocks] × (4+6+8) stimuli = 216 trials.

4.6. Results

A repeated measures ANOVA test was conducted for the two dependent variables: the accuracy of element identification and the response time.

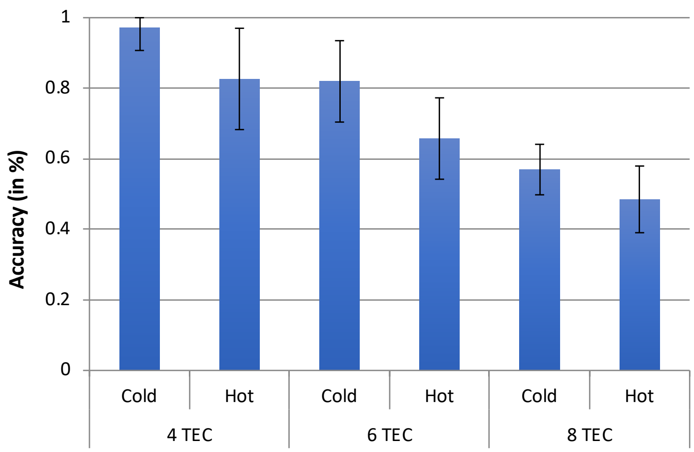

Figure 6: Accuracy of Element identification for the pilot study. Error bars show .95 confidence intervals.

4.6.1. Accuracy of Element Identification

The accuracy of element identification was significantly affected by the number of TECs (F(2,16) = 77.45, p <0.0005, $\eta_p^2 = 0.906$) and the direction of temperature change (F(1,8) = 21.34, p < 0.005, $\eta_p^2 = 0.727$). There was no significant difference between two blocks in term of accuracy. A post-hoc Tukey HSD Test showed the accuracy of element identification in the 4-TEC setting (89.9%) was significantly higher than the accuracy in the 6-TEC setting (73.8%, p < 0.0005), which was significantly higher than the accuracy in the 8-TEC setting (52.7%, p < 0.0005). The accuracy of element identification with cold stimulation (78.7%) was significantly higher than the accuracy with hot stimulation (65.6%, p < 0.005).

There was no significant interaction effect among the block, the number of TECs, and the direction and temperature change. In all settings, the participants could perceive the stimulated position more accurately with cold stimulation than hot stimulation. More specifically, the participants achieved an accuracy of 97.2% for cold stimulation and 82.4% for hot stimulation in the 4-TEC setting (Fig. **??**).

4.6.2. Individual Accuracy in 4-TEC setting

The 4-TEC setting afforded the highest accuracy of element identification. To compare the accuracy of each individual TEC (Fig. 7), we had a new factor, which was the actuator location (top, right, bottom, left). We ran a repeated measures ANOVA test, and found a significant main effect of TEC location ($F(3, 24) = 7.53$, $p < 0.005$, $\eta_p^2 = 0.485$) on the accuracy, while there was no significant difference between the two sequential blocks. More specially, a pair-wise comparison showed that the average accuracy of perceiving the top TEC (97.2%) was significantly higher than the accuracy of the bottom TEC (80.6%, $p < 0.05$). There was no significant difference between the average accuracy of the top TEC and the average accuracy of the left or right TEC (left: 88.9%, right: 88.9%).

The direction of temperature change also placed a significant effect on the accuracy ($F(1, 8) = 11.13$, $p < 0.05$, $\eta_p^2 = 0.582$). A post-hoc pair-wise comparison showed that the average accuracy of identifying the positions of cold stimulus was significantly higher than the the accuracy of hot stimulus ($p < 0.05$). In addition, there was a significant interaction effect between the TEC position and the direction of temperature change. More specifically, a post-hoc pair-wise comparison revealed that the accuracy of identifying the top TEC was significantly higher than that of the right ($p < 0.05$), the left ($p < 0.05$), and the bottom ($p < 0.05$) TECs with the hot stimulus, while there was no significant difference among the four positions with the cool stimulus.

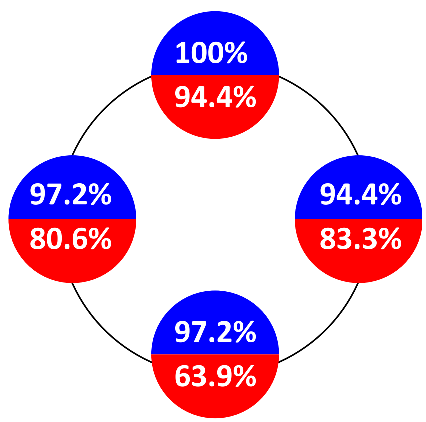

Figure 7: Accuracy of Individual Element Identificantion for the 4-TEC setting. Blue: cold stimulation, Red: hot stimulation.

4.6.3. Response Time

Response times are summarized in Fig. ??. Similarly to the accuracy of element identification, a repeated measures ANOVA showed the number of

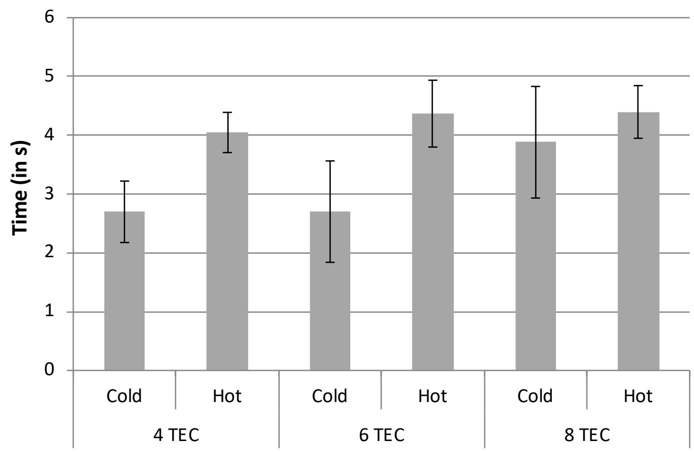

Figure 8: Response Time for the pilot study. Error bars show .95 confidence intervals.

TECs ($F(2,16) = 78.42$, $p < 0.0005$, $\eta_p^2 = 0.607$) and the direction of temperature change ($F(1,8) = 20.32$, $p < 0.0001$, $\eta_p^2 = 0.346$) had significant effect on the average response time on one trial. A post-hoc pair-wise comparison showed that there was no significant difference between the time spent by the participants in the 4-TEC setting (3.37 s) and 6-TEC setting (3.54 s), and the participants performed significantly faster in either of these two conditions than the 8-TEC setting (4.14 s, $p < 0.05$). The average response time was significantly shorter with cold stimulation than hot stimulation (3.0 s vs. 4.27 s, $p < 0.005$).

There was no significant interaction effect of the two independent factors (number of TECs and temperature change) on the average response time on one trial. In both the 4-TEC and 6-TEC settings, participants performed significantly faster with cold stimulation than hot stimulation (4-TEC: 2.70 s vs. 4.05 s, $p < 0.05$; 6-TEC: 2.70 s vs. 4.36 s). There was no significant difference between the average response time with cold stimulation and hot stimulation in the 8-TEC setting (3.88 s vs. 4.40 s).

4.7. Discussion

A significant observation of the pilot study is that participants found it easier to precisely locate a cold stimulation compared to a hot one. This result is in line with previous research on other body locations [**?**]. Additionally, response time was around 1.2 s faster for cold sensation compared to hot. A direct application of these results point to using a cold temperature change to convey information where correct location perception is crucial, for example, in a navigation scenario where each TEC encodes a direction.

In terms of ring design, our results suggest that participants are able to discriminate up to four locations on the smart ring with good average accuracy (89.9%). One-way ANOVA on the post-study questionnaire showed a significant effect of the number of TECs on the perceived difficulty of stimulation identification (F(2, 51) = 21.59, p < 0.005, $\eta_p^2 = 0.458$). The post-hoc Tuckey HSD test suggested that the perceived difficulty of stimulation identification for the 4-TEC setting (M = 2.4, SD = 1.4) and the 6-TEC setting (M = 3.2, SD = 1.0) were significantly lower than those the 8-TEC setting (M = 4.8, SD = 1.3). There was no significantly difference between the perceived difficulty of the 4-TEC setting and the 6-TEC setting. In addition, the perceived comfort of the 4-TEC setting (M = 5.5, SD = 1.1) was slightly but not significantly higher than those of the 6-TEC setting (M = 5.3, SD = 1.1) and the 8-TEC setting (M = 4.9, SD = 1.2). By focusing on each individual actuator on the ring, we also found that it was less accurate to perceive a stimulus on the bottom actuator. Therefore, potential spatial thermal patterns may want to make use mostly of the top, right, and left TECs.

5. New Thermal Patterns

Our pilot study confirmed that users can reliably perceive individual thermal stimulation with the 4-TEC setting. To gain a deeper understanding on the affordance and the expressiveness of the 4-TEC setting, we designed new spatial thermal patterns by combining a pair of neighboring or opposite TECs. Although early studies [? ? ?] on thermal localization showed that radiation-based non-

In our design, each element in a neighboring or opposite pair could be triggered in three thermal levels: hot, neutral, and cold. Therefore, there were eight thermal patterns for each pair. Fig. **??** shows the patterns on the neighboring pairs (i.e., Top+Left, Top+Right, Bottom+Left, and Bottom+Right). Fig. XX shows the patterns on the Top+Bottom and the Left+Right opposite pairs. To facilitate the data analysis, we coded the TEC elements in the 4-TEC setting with the following scheme: bottom - B, left - L, top - T, right - R. The directions of temperature change were coded as: +1 °C/s - h, -1 °C/s - c. For example, the pattern ThRc indicates that the top TEC is triggered with +1 °C/s, and the right TEC is triggered with -1 °C/s. As indicated by the pilot study, the heat stimulation at the bottom

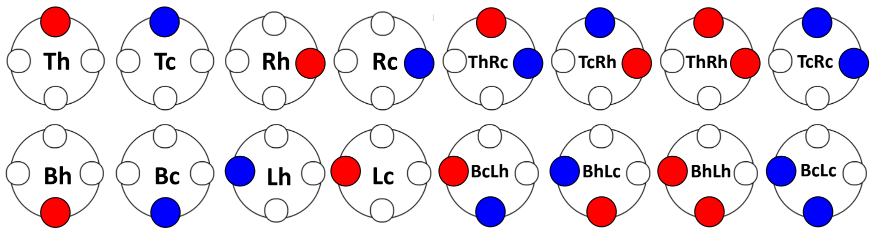

Figure 9: Patterns (with names) for neighboring TECs, applied on the Top+Right and the Bottom+Left TECs. Red: hot; Blue: cold; White: neutral.

TEC yielded the lowest identification accuracy, so we excluded the patterns involving the heat stimulation at the bottom TEC (i.e., BhLh, BhLc, BhRh, BhRc, ThBh, and TcBh).

Our pilot experiment showed that the participants perceived the cold stimulus 1.2 seconds faster than the hot stimulus. Therefore, while implementing the thermal patterns that contain both hot and cold stimulations (Fig. 9: ThRc, TcRh, & BcLh; Fig. 12: ThBc, LcRh, & LhRc), we placed a 1.2-second gap between the hot and the cold stimulation, meaning the cold stimulation was triggered 1.2 seconds after the hot stimulation, to provide a simultaneous sensation of hot and cold.

6. Experiment 1: Temperature Changes on Neighboring TECs

In this experiment, we investigated if participants could recognize temperature changes on neighboring TECs.

6.1. Participants

We applied the same recruitment strategy as the pilot study. Twelve participants (7 females, all right-handed) ranging from 18 to 31 years old (M=26.3, SD=3.52) were recruited from within the university community. The average skin temperature on the finger was 32.5 °C (SD = 1.52).

6.2. Apparatus

We used the same apparatus as in the pilot experiment: 6 ring prototypes (US size 6 to 11) with 4 TECs on them. The rings were worn on the index finger of the participants' non-dominant hands. An iPad Air 2 was used for the participants to select their answers.

6.3. Tasks and Stimuli

During a single trial, two TECs were activated at one of the three temperature levels (cold, neutral, hot). Our participants had to accurately recognize the temperature level of each TEC. We conducted the experiment with all possible neighboring pairs of TECs as shown in Fig. **??**.

6.4. Procedure

Similar to the pilot study, participants began the experiment by filling a pre-questionnaire with demographic information, and the experimenter would helped the participant to put on the ring that best fit their finger.

The experiment was divided into five blocks: two training blocks and three test blocks. In a given block, the XXX patterns were presented three times in a randomized order. In training block, the participant was told which pattern was just triggered with the visual patterns in Fig. **??** shown on the iPad Air 2, while in the test block, they had to recognize the pattern by selecting the stimulated elements and temperatures. Fig. **??** shows the selection interface we used in the test block. When the stimulation was off, a pair of red and blue circle buttons was shown next to each spot. The participant needed to make their selection by tapping on the buttons, and tapping the "Next" button to trigger a new stimulation. After completing the five blocks, participants filled out a post-experimental questionnaire to measure the perceived level of difficulty and comfort of detecting the thermal patterns using a 7-point likert scale, following the similar scheme in the pilot study. The participants also needed to elicit potential applications for the thermal patterns.

6.5. Experiment Design

A within-subject design was used with one independent variable: pattern. We measured two dependent variables: accuracy, and response time. A trial was considered successful when the participant was able to identify the correct location and temperature level for both TECs. There was a 25-second break between two trials, for the skin to naturally return to the resting temperature.

Each participant performed the experiment in one sitting, including breaks. The experiment lasted for around 45 minutes. In total, each participant did a total of XXX patterns $\times$ [1 training blocks + 1 test block] $\times$ 3 repetitions = XXX trials.

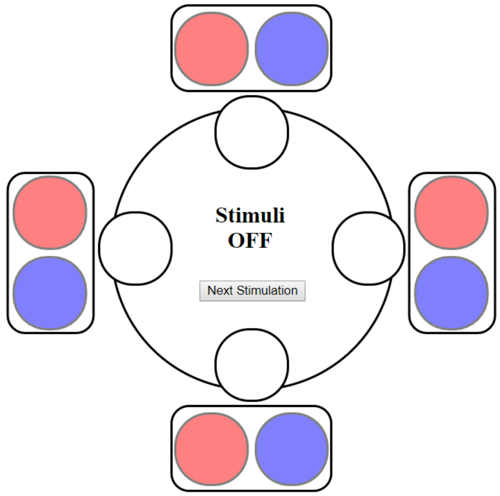

Figure 10: Selection interface for Experiment 1 & 2.

6.6. Results

The repeated measure ANOVA showed that the type of the neighboring thermal pattern significantly affected the identification accuracy ($F(11,121) = 5.42$, $p < 0.0005$, $\eta_p^2 = 0.33$), but had no significant effect on the average time. Fig. XXX shows the XXX. (The results of post-hoc pairwise comparison are indicated by *).

Generally, XXX are better than XXX.

6.7. Discussion

Pure Cold patterns are easily perceived.

7. Experiment 2: Temperature Changes on Opposite TECs

We believe that our proposed ring design can also be used to compare different quantities, such as the ratings of two shops, which could be encoded using different temperatures. We conducted another experiment similar to Experiment 1, which considered opposite TECs instead.

7.1. Participants

The same recruitment strategy was applied. Twelve participants (5 females, all right-handed) ranging from 19 to 31 years old ($M = 22.3$, $SD =$

	Bh	Bc	Lh	Lc	Th	Tc	Rh	Rc	BhLh	BcLc	BhLc	BcLh	TcRc	ThRh	ThRc	TcRh
Bh	66.7%	2.9%	11.4%			2.9%			22.9%	2.8%	5.9%	5.7%				
Bc		82.4%		17.1%						11.1%		5.7%				
Lh	8.3%		48.6%		5.1%				33.3%		11.8%	22.9%				
Lc	5.6%	5.9%		80.0%						19.4%	5.9%					
Th			2.9%		76.9%		6.7%							45.7%	5.4%	7.9%
Tc					5.1%	94.1%							10.5%			
Rh	8.3%				2.6%		78.9%							2.9%		5.3%
Rc								94.6%					2.6%	5.7%		
BhLh	11.1%		20.0%						45.7%		2.9%	8.6%				
BcLc		8.8%								66.7%	5.9%					
BhLc			5.7%	2.9%							64.7%	2.9%				
BcLh			11.4%								2.9%	54.3%				
TcRc						2.9%		5.4%					86.8%			
ThRh					10.3%		10.5%							45.7%	2.7%	2.6%
ThRc															86.5%	
TcRh							2.6%								2.7%	84.2%

Figure 11: Confusion table for the neighboring thermal patterns. Columns represent stimulated pattern and rows the participants' input.

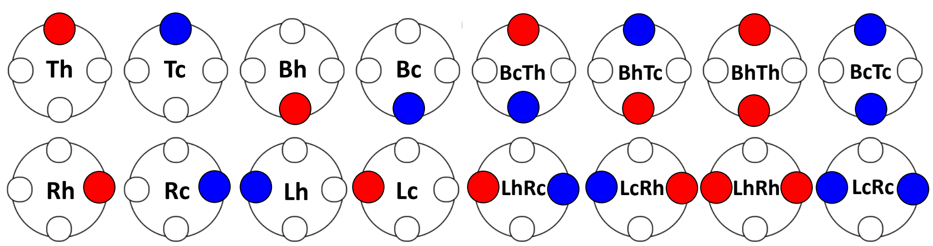

Figure 12: Patterns (with names) for opposite TECs, applied on the Top+Bottom and the Left+Right TECs. Red: hot; Blue: cold.

3.57) were recruited from within the university community. The average skin temperature on the finger was 33.6°C (SD = 1.53).

7.2. Apparatus, Task and Stimuli, Procedure

We used the exact same apparatus and procedure as Experiment 1. The XXX patterns are shown in Fig. 12.

7.3. Experiment Design

The design of Experiment 2 was similar to Experiment 1. Our only independent variable was the TEC pattern, which was randomized within blocks. We measured location accuracy, temperature accuracy, and the response time. A trial was considered successful when the participant was able to identify the correct temperature level for both TECs. Each participant

	Bh	Bc	Lh	Lc	Th	Tc	Rh	Rc	BhTh	BcTc	BhTc	BcTh	LhRh	LcRc	LhRc	LcRh
Bh	77.8%	2.8%					2.8%		13.9%							
Bc		97.2%														
Lh	5.6%		63.9%	2.8%	11.1%				8.3%				22.2%	2.8%	11.1%	8.3%
Lc	2.8%			91.7%												5.6%
Th	2.8%		2.8%		80.6%	2.8%	5.6%		38.9%			8.3%				2.8%
Tc						94.4%				5.6%	33.3%					
Rh	5.6%						77.8%	2.8%	2.8%		2.8%	2.8%				
Rc								88.9%						2.8%		
BhTh	2.8%		2.8%		2.8%		5.6%		30.6%		2.8%	2.8%	11.1%			
BcTc						2.8%				91.7%						
BhTc											58.3%				2.8%	
BcTh											2.8%	80.6%				
LhRh	2.8%		25.0%		2.8%		5.6%		5.6%			5.6%	61.1%		2.8%	
LcRc				2.8%	2.8%			2.8%		2.8%				91.7%		
LhRc			5.6%					5.6%						2.8%	83.3%	
LcRh				2.8%			2.8%						5.6%			83.3%

Figure 13: Confusion table for the opposite thermal patterns. Columns represent stimulated pattern and rows the participants' input.

performed the experiment in one sitting, including breaks. The experiment lasted for around 45 minutes. In total, each participant did a total of XX patterns × [1 training block + 1 test blocks] × 3 repetitions = XX trials.

7.4. Results

Similar to the neighboring patterns, one-way ANOVA showed that there was a significant difference among these opposite thermal patterns in terms of the identification accuracy (F(5, 55) = 5.55, p ¡ 0.0005, $\eta_p^2 = 0.335$) and the response time (F(5, 55) = 5.35, p ¡ 0.0005, $\eta_p^2 = 0.327$). Fig. 13 illustrates the confusion table for all opposite thermal patterns. Post-hoc Tukey HSD tests were conducted for pairwise comparison. The accuracy for BhTh (30.6%) was significantly lower than the other patterns except BhTc (58.3%) and LhRh (61.1%). The accuracy for BhTc was significantly lower than Bc (97.2%), Tc (94.4%), Lc (91.7%), BcTc (91.7%), LcRc (91.7%). The accuracy for LhRh was significantly lower than Bc.

7.5. Discussion

In terms of accuracy, we found 10 patterns with 80% accuracy or more: Bc, Lc, Th, Tc, Rc. BcTc, BcTh, LcRc, LhRc, and LcRh. An additional 2 patterns achieved more than 73% accuracy: Bh and Rh. We can classify these patterns as:

- involving a single TEC, with any non-neutral temperature change (plus Lh);

- or involving the Left+Right pair with at least one cold temperature change;
- or involving the Bottom+Top pair with a cold temperature change on the bottom TEC.

Besides having similar application as the neighboring thermal patterns (e.g., notification and VR), the feedback from the participants suggested that opposite TECs could be used to encode information with two dimensions. For example, the temperatures of the two opposite TECs could be used to represent the ratings on the food and the interior decoration of a restaurant. The participants also suggested that the thermal patterns of the opposite pairs could be used to perform an overall comparison of two artifacts. For example, when two restaurants, one on the left and the other on the right, are selected for comparison, the side with a higher temperature indicates a higher rating, and the colder side indicates a lower rating. It is essential to detect the difference between two temperatures in the opposite pair when performing the comparison. The participants achieved an overall accuracy of 81.5% for detecting different temperatures in the opposite pairs (i.e. all patterns except ThBh, TcBc, LhRh, and LcRc)

8. Selecting good patterns

Based on the pilot study, and Experiment 1 & 2, we selected the patterns that the users could potentially identify with a reliable accuracy. In the pilot study, as we found that the cold stimulation was significantly easier to identify than the hot stimulation, so we selected the four single-spot cold stimulations.

Based on the results of Experiment 1 & 2, we selected those with the accuracy higher than 80%.

9. Validating The Combination of Pattern Groups

9.1. (Single+)Neighbor+Opposite

XXX

9.2. Single+Neighbor

No significant difference on accuracy. all ¿ 80%. No significant difference on time.

9.3. *Single+Opposite*

There was significant difference among the patterns' identification accuracy ($F(8,88) = 4.58$, p ¡ 0.005, $\eta_p^2 = 0.294$). all ¿ 80% except 0h2c. Time: $F(8,88) = 6.58$, p ¡ 0.005, $\eta_p^2 = 0.374$

10. Elicitation of Application Scenario

To understand whether the designers can design reasonable application scenario using these selected patterns, we conducted a series of design workshops, involving six experienced product/interface designers.

Six categories of application that could potentially benefit from thermal feedback were derived from the literature: Navigation, Call/Message Notification, Emotion Representation, Rendering the properties of artefacts, Gaming, and Calendar. The designer

The designer was instructed to design the application scenario under each category, by using these patterns. The patterns were divided into three groups: single, neighbor, and opposite. Under the same category, the designer can use one category, or the combination of single and neighbor/opposite, but he/she couldn't use the combination of neighbor and opposite, since this combination yielded low accuracy as indicated by our experiment. The designers can reuse the patterns across the application.

11. Further Discussion

11.1. *Set of Reliable Patterns*

Independent t-test on the post-test questionnaire showed that the opposite pairs were slightly but no significantly less difficult (Mean = 1.9, SD = 0.9) and more comfortable (Mean = 4.9, SD = 1.0) to detect than the neighboring pairs (difficulty: Mean = 2.6, SD = 1.2; comfort: Mean = 4.2, SD = 1.2). By combining the results of both our experiments, we found a set of 12 unique patterns (Fig. 14) that our participants were able to recognize with an accuracy of at least 80%: each four individual locations with the cold stimuli (Bc, Lc, Tc, Rc), three patterns from the neighboring Top+Right pair (TcRc, ThRc, TcRh), and five patterns from the opposite pairs (BhTc, BcTc, LcRc, LhRc, LcRh). The average accuracy of these twelve patterns were 87.5% (SD = 0.043).

Depending on the applications and needs, three more patterns could be included, which generally achieved more than 70% accuracy: Bh, Th, and

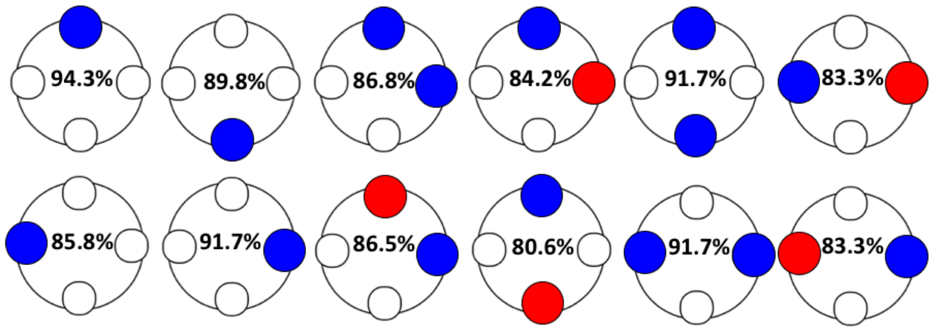

Figure 14: The set of smart-ring thermal patterns that achieved above 80% accuracy in the experiments.

Rh. Note that we did not consider all the possible patterns for neighboring pairs. However, based on our pilot study that there is no significant difference between the accuracy of identifying the left and the right TECs, there might be other candidates with the Top+Left pair.

In general, it appears that a good spatial thermal pattern is more likely to get recognized if the distance between both TEC is maximum (i.e. using opposite pairs). Also, since it is easier to perceive a cold change, patterns with hot temperature change are discouraged.

11.2. Cold vs. Hot Change

While a hot temperature change may be convenient to encode a positive emotion [**?**] or the general proximity to a point (e.g. "you're getting hot" to indicate that a person is getting closer to an objective) [**?**], the cold temperature change should be prioritized for information encoding. In-ring hot temperature change is more difficult to precisely locate, which impairs recognition. This could be further explained by the physiological fact that the density of cold receptors is higher than warm receptors on the skin [**?**].

Additionally, during our experiments, seven participants reported an illusion of weight on the finger skin, feeling more heavily pressed with the hot temperature than with the cold temperature. This observation was contrary to the Weber's phenomenon [**?**], which reveals that a concomitantly cooling stimulus on hand will be perceived as significantly heavier than an identical stimulus of a neutral temperature. This contradiction could be explained by the non-uniformness of thermal perception across different body parts

[?], indicating a need for a deeper investigation on user perception when designing smart ring thermal feedback.

11.3. Applications Suggested by the Participants

Besides emotion communication, which has been proved as a common application for thermal feedback, our participants suggested several new applications (e.g., directional cueing, notification, artefact comparison, and so on) which could be unique with our ring design. Furthermore, we have developed a set of proof-of-concept applications based on the new applications commonly suggested by the participants.

11.3.1. Notifications

Our set of 10-15 spatial thermal patterns, which can be perceived with the accuracy over 80%, can be used as thermal icons to encode discrete notifications, similarly to any other modality. Our design leverages the simultaneous sensation of multiple TECs to achieve a rich expressivity that may not be obtainable with only one otherwise. Suggested by 18 participants, these unique spatial thermal patterns could be mapped to notifications from different applications, such as timer alarm, event reminder, incoming calls or messages from different persons or social networks. Previous research [?] showed that users preferred the resistor-based in-ring thermal feedback for non-urgent or moderately urgent information updates. The average response time below 3s in our experiments further suggested the potential of using TEC-based in-ring spatial thermal patterns as the channel of notification. Fig. **??**a shows the in-ring thermal pattern (TcRc) indicating a call from an unknown number.

11.3.2. Navigation

Thirteen participants suggested that the neigboring patterns can be used as the directional cues. The neighboring patterns can encode the four cardinal directions: straight forward, left, right and go-back, using cold temperature change on one specific TEC, and the intermediate points between two consecutive cardinal directions, such as front-left and front-right, using two TEC modules. As revealed by Roumen et al. [?], our sensitivity to thermal stimuli on finger would increase with physical activity. These suggest a potential usage of the in-ring spatial thermal patterns as directional cues during physical activities (e.g. running and biking). Fig. **??**b shows the neighboring pattern of ThRc suggesting a front-left-left direction for biking.

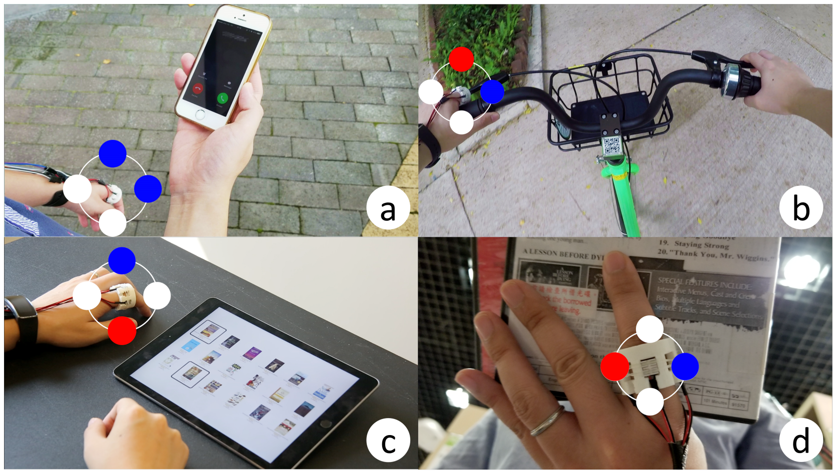

Figure 15: Application scenarios for smart-ring thermal patterns: (a) notification, (b) navigation, (c) comparison of digital artifacts, (d) comparison of physical artifacts.

11.3.3. Comparison

The reliable recognition of opposite thermal patterns supports artifact comparison through the difference of the temperatures on two TECs. Fig. **??**c shows the scenario of a user browsing an online bookstore. By selecting two books, the user toggles the comparison mode. Based on the spatial relation of the selected books (up-down/left-right arrangement), the ring automatically triggers the top-bottom/left-right thermal patterns. The higher temperature the representative TEC has, the more popular the book is. In a more futuristic scenario (Fig. **??**d), the user can compare two physical items, here the ratings of two movie DVDs, through the in-ring thermal patterns. This could be implemented by combining the in-ring TECs and in-ring camera or sensors.

11.4. Limitations

We identified a few limitations and improvement space in our work during the experiments.

The current smart ring prototype is in a wearable and testable form factor but requires connection to an external control circuit. Our prototype shares the similar limitation of existing thermal research prototypes on being power consuming. For the simultaneous usage of multiple TECs, each requires 1.5W power.

Some participants reported an issue with direct skin contact with the hard TEC surface. While we allowed the participants to take time to adapt to the ring before starting the actual experiment, the hard surface of the TECs could be challenging for the prolonged use of the ring. Future work may need to consider the choice of thermally conductive soft material (e.g. sponge) to buffer the interface between the finger skin and the TEC surface.

We observed a difference in the thermal sensitivity among the participants. Medical research has demonstrated that the skin sensitivity could be affected by race, culture, and living region [**?**]. We observed that all our participants were from the similar region and cultural background, thus could have similar skin sensitivity. In addition, it is implementable to allow users to customize the temperature change based on their own perception. We argue that our results in this paper would still be valid for other skin sensitivity when the temperature change is adjusted properly.

Furthermore, our study primarily focused on stimuli based on thermal parameters recommended from previous research [**?**]: 1°C/s for 3s, and the experiments were conducted with the participants sitting still indoor. While these factors ensured a perceivable and comfortable stimulus, there are more thermal parameters that could be adjusted for experimentation. Therefore, in our future studies, we wish to explore other variants of parameters such as the movement of participants, indoor/outdoor environments, rate of temperature change, stimulus duration, starting temperature, sequential temporal stimulation, etc., for smart-ring spatial thermal feedback.

12. Conclusion and Future Work

In this paper, we investigated smart ring thermal feedback with multiple TEC modules. In the pilot study, we showed that users could reliably recognize 4 locations with cold stimulation with 95.8% accuracy, and achieve decent accuracy with hot stimulation (82.3% accuracy). Further, we designed two types of spatial thermal patterns (neighboring and opposite) that can be achieved with 4 in-ring TECs. Experiments revealed 10 thermal patterns that can be reliably distinguished by participants, indicating their potential usage as in-ring thermal icons for notifications. Participants also elicited different applications, including direction cueing through neighboring patterns and artifact comparison through opposite patterns, demonstrating the interest of spatial thermal patterns in smart rings not only for notifications but also for various everyday activities. For future work, there is a need to investigate the effectiveness of the presented thermal patterns in different applications, such as emotion representation, notification, navigation, and comparison. Furthermore, we see the feasibility of integrating multiple feedback modalities (e.g. vibrotactile, poking, and thermal) in the form factor of a finger ring, and in investigating the interplay of multimodal feedback for smart ring.

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