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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. Our pilot study showed that users could reliably recognize 4 single points with cold stimulation (97.2% accuracy). In the following two main experiments, 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 three neighboring patterns and five opposite patterns that could be reliably recognized by the participants with the average accuracy above 80%. A follow-up experiment suggested that it could be confusing for users by combining four single-spot cold stimulations, three neighboring patterns, and five opposite patterns in the same group (average accuracy: 50.2%). We conducted two more follow-up studies, showing that the participants could identify the thermal patterns in the combined group of the single-spot cold stimulations and the neighboring patterns (average accuracy: 85.3%), and the combined group of the single-spot cold stimulations and the opposite patterns (average accuracy: 89.3%). We further conducted three design workshops, involving six product/interface designers, to investigate the potential applications of these thermal patterns. The designers suggested different mappings between the given thermal patterns and the information, including direction cueing through single-spot and neighboring patterns, artifact comparison through opposite patterns, notifying incoming calls/messages from different persons with different locations and temperatures of the TECs, etc. This demonstrated interest in spatial thermal patterns in smart rings not only for notifications but also for various everyday activities.

1. Introduction

Smart rings are receiving more and more interest from both industry and academics. It can be used to convey information easily and discretely. As fingers are one of the more sensitive body locations to haptic stimuli (Stevens and Choo, 1996), smart rings are especially desirable. Potential information that can be relayed ranges from simple notifications to more complex continuous information, such as training progress (Cauchard et al., 2016), or even direction information. However, smart rings are limited by their size, which makes it hard to embed multiple actuators of the same type, such as vibration motors, in the form factor of a finger ring. Thus, previous research done in this area (Hsieh et al., 2016; Pradana et al., 2014) has primarily focused on using a single actuator. However, such systems can only convey simple information by using single-dimensional patterns, such as triggering a single vibration motor with one particular specification (e.g., frequency and intensity) at a time (Saket et al., 2013), 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 or headband with four or more output actuators (e.g. DC motors and vibration motors) could be used for target searching (Chen et al., 2018), navigation (Hong et al., 2017; Strasnick et al., 2017), or to perform more complex tasks, such as color comparison (Carcedo et al., 2016). However, vibrotactile feedback with multiple actuators does not seem to be a usable strategy to create spatial patterns with the form factor of a smart ring, as the vibration at one location could easily vibrate the whole ring, making it hard to locate the source of vibration.

Although a few existing studies (Cain, 1973; Taus et al., 1975) on thermal localization showed that radiation-based non-contact heat was error-prone in localization due to the phenomenon of spatial thermal summation, some other work suggested on-skin thermal stimuli

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through small thermal-haptic devices could improve the spatial acuity for tactile stimulation (Stevens, 1982). In addition, the on-skin cold stimulations were generally more perceivable than the hot ones (Wilson et al., 2011). Psychological research has also shown the phenomenon of illusional and referral thermal sensation (Green, 1977), which is a cortical perceptual process similar to "filling in" in the visual modality, and requires both tactile and thermal stimulation to occur. In the field of HCI (Human-Computer Interaction), thermal feedback has been previously used in a wide variety of contexts, such as social activities (Wilson et al., 2015), emotions (Tewell et al., 2017a; Wilson and Brewster, 2017; Wilson et al., 2016) and navigation (Tewell et al., 2017b). Halvey et al. (2011) stated that *"(Thermal feedback) can act as a non-visual notification channel for situations that are too bumpy or noisy for vibrotactile or audio feedback. It can enhance both visual and non-visual feedback by adding extra depth to the interaction experience, e.g. thermal feedback could be used to add affect that is not provided by other modalities* (Iwasaki et al., 2010; Nakashige et al., 2009). *Thermal output is also entirely private; audio may be heard by others, vibrotactile may be heard and felt by others and visual may be seen by others."* In addition, Roumen et al. (2015) showed that heat sensitivity could be positively impacted by physical activity, with heat being easier to perceive during walking or running activities. Furthermore, the results of NotiRing (Roumen et al., 2015) 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 (Yang et al., 2009), 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 (Halvey et al., 2012a; 2013; 2011; Peiris et al., 2016; 2017; Ranasinghe et al., 2017; Wilson et al., 2013). Existing research also showed that the form factor of a ring afforded eight positions of pin-point poking stimulation (Je et al., 2018). However, in the limited research on ring-based thermal feedback (Roumen et al., 2015), the usage of multiple thermal actuators on the ring were not explored. 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. 1) yields an average accuracy of 97.2% for cold stimuli and 82.4% for hot stimuli. We then designed a set of in-ring spatial thermal patterns (Figs. 10 & 13) by combining two neighboring or opposite TECs, each of which can be triggered as cold or hot. In a series of main experiments, we assessed the feasibility of accurately perceiving the combinational thermal patterns. Results revealed two separate groups of thermal patterns (i.e. three neighboring patterns and five opposite patterns) that can be identified by the participants with the average accuracy above 80%. Our follow-up experiments further

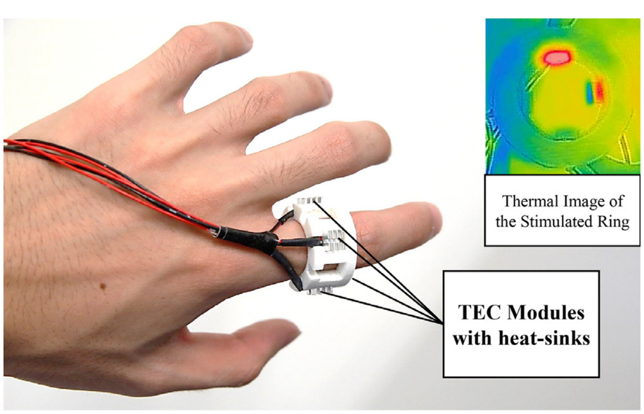

Fig. 1. Smart ring prototype with four TEC modules around the finger.

showed that the participants can reliably identify the thermal patterns in the combined group of single-spot cold stimulations and neighboring/opposite patterns, indicating their potential usage as in-ring thermal icons. We further conducted three design workshops, and distilled a list of application scenarios that can make use of these thermal patterns, such as direction cueing through single-spot and neighboring patterns, artifact comparison through opposite patterns, notifying incoming calls/messages from different persons with different locations and temperatures of the TECs, etc.

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.
- The results of our empirical studies 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 designer-elicited application scenarios that leverages the proposed set of in-ring thermal patterns.

2. Related work

Our research is inspired by two emerging topics in HCI: thermal feedback, and multimodal haptic feedback on fingers. We also discuss finger sensitivity to thermal stimuli.

2.1. Thermal feedback in HCI

There have been extensive physiological (Cain, 1973; Stevens and Choo, 1998; Taus et al., 1975), psychological (Jones and Berris, 2002; Singhal and Jones, 2016; Zhang et al., 2010), and HCI-related (Halvey et al., 2012b; 2013; 2011; Jones and Ho, 2008; Sato and Maeno, 2012; Wettach et al., 2007; Wilson et al., 2012; 2013; Wilson and Brewster, 2017; Wilson et al., 2015; 2016) research on thermal feedback, from which various applications have been proposed.

Jones and Berris (2002) 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. (2007) designed a resistance-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 (2012) created a 2×2 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 (Halvey et al., 2011); 2) 1 °C/s rates of change were appropriate for thermal displays (Wilson et al., 2011); 3) the perception of thermal feedback could be strongly affected by clothes (Halvey et al., 2011) and the environment (Halvey et al., 2012b); 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 (Wilson et al., 2012); 5) there was a strong agreement among users on the application of thermal feedback in social communication and rating-related information representation (Wilson et al., 2015); and 6) thermal feedback could be applied to represent emotion (Wilson et al., 2016) and widen the range of emotion representation along with other feedback modalities (Wilson and Brewster, 2017). Following Wilson et al.'s insights, Tewell et al.'s research showed that thermal feedback enhanced the affective perception of text messages (Tewell et al., 2017a) and could be used to facilitate navigation (Tewell et al., 2017b). More recently, Singhal and Jones (2018) evaluated thermal pattern recognition on the hand and arm with single thermoelectric module, and proposed the model-based approach for designing thermal icons. Peiris et al. (2019) designed and evaluated the form factor of bracelet with multiple TEC modules. In addition, thermal feedback was integrated in the head-mounted display to enhance the experience of presence in VR (Peiris et al., 2016; 2017; Ranasinghe et al., 2017).

Research showed that people preferred to associate personal emotional information with smart wearable accessories (Polydorou et al., 2017). 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 (Stevens and Choo, 1998).

2.2. Multimodal haptic feedback on fingers

Numerous works have studied multimodal feedback such as vibration (Hsieh et al., 2016; Roumen et al., 2015), poking (Je et al., 2018; Roumen et al., 2015), resistor-based thermal (Roumen et al., 2015), and skin scratching (Je et al., 2017), 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 phalanx (including the side of finger, finger pad, and the nail) and the proximal phalanx where a ring is usually worn.

The haptic devices on the distal phalanx were usually associated with touch and applied in virtual and augmented reality. Yem et al. (2016) 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. (2017) developed Submerged Haptics consisting of 4 3D-printed miniature airbags to provide fingertip haptic feedback with air inflation. Murakami et al. (2017) 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. (2016) 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 phalanx with a finger ring has also received an increasing yet unequal amount of interest, compared to haptic feedback on the distal phalanx. As a type of digital jewelry, smart rings benefit from the same social acceptability and emotional bond as traditional jewelry (Polydorou et al., 2017). Pradana et al. (2014) developed RingU, supporting remote communication through visual and vibrotactile feedback in the ring. Roumen et al. (2015) 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 s of warming versus 1 s 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. (2017) developed tactoRing, a ring-size tactile display that provides haptic feedback by scratching the skin around the finger using a small gear tactor, achieving an accuracy of 94%. Han et al. (2017) designed Frictio, providing in-ring friction-based force feedback, with requirement of input from the non-wearing hand. More recently, Je et al. (2018) developed PokeRing, a smart-ring capable of delivering information via poking eight different locations around the finger.

While visual, auditory, vibrotactile, poking, and skin-scratching feedback 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 bi-directional 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 types of thermal feedback around the finger.

2.3. Thermal sensitivity on the fingers

While the finger, more specifically finger tips, is highly sensitive to vibrotactile stimulation, it is not the case for thermal stimulation. This can be explained by the fact that heat is perceived by different skin receptors compared to vibrotactile or force stimulation.

Stevens and Choo (1998) investigated thermal sensitivity on different body parts, including fingers, palm, forearm, toe, lips. They showed that people are usually more sensitive to cold stimuli, and that thermal sensitivity declines with age. Dufour and Candas (2007) found that the thermal detection threshold was higher in adults older than 60 years compared to adults aged between 20 and 50 years. Furthermore, people may have lower thermal pain threshold. This may be why some of our participants experienced pain during our experiments.

In addition, Treede et al. (1995) found that the responses to the thermal feedback (mainly heat) on hairy skin may be significantly faster than on glabrous skin does, due to the distribution of different types of nociceptors. In our present studies, the drop of accuracy observed on the bottom (palmar) location in our studies for hot temperature seems to corroborate these results.

3. Motivation

In this research, we investigated thermal feedback for the form factor of finger ring. Smart-rings are an increasingly popular research topic in HCI. Existing research showed that smart rings can provide convenient/always-available input (Chung et al., 2018; Ghosh et al., 2016; Han et al., 2017; Ketabdar et al., 2012; Marti and Schmandt, 2005; Shilkrot et al., 2015) or output (Je et al., 2018; 2017; Roumen et al., 2015). Most of the existing research on haptic smart rings focused on the force-based feedback, such as vibration (Roumen et al., 2015), poking (Je et al., 2018; Zhang et al., 2010) and skin dragging (Je et al., 2017). Vibrotactile would seem like a natural candidate, since the finger base (i.e. the proximal phalanx) is sensitive to touch-based tactile stimulation in gap detection with 6 mm as the largest size of the contactor (Gibson and Craig, 2005). However, considering the dimension of the common vibration motor (e.g., linear resonant actuator with the diameter of 10 mm), the spatial acuity of finger base is not good enough to embed more than one vibration motor on a smart ring. Poke, as another option, has already been investigated in PokeRing (Je et al., 2017), providing promising results for multi-positional haptic feedback on a ring. To this day however, no ring with multiple thermal actuators have been explored, given the potential advantage that the thermal feedback could be more private than the vibration and the poking feedback.

Additionally, Roumen et al. (2015) suggested a few applications for in-ring thermal feedback, and highlighted its interest with increased sensitivity when performing physical activity. The kind of notifications suggested is "non-urgent" notifications (e.g. calendar event, low battery, app update). As we already highlighted, this previous work did not use optimal hardware for thermal feedback, with a very slow resistor-based process, which likely impacted their results. With the present work, we thus want to further explore information transfer/notifications using in-ring spatial thermal feedback. We also envision smart rings with multiple sensors embedded in it, which could include other modalities that could pair nicely with multiple TECs as presented in this

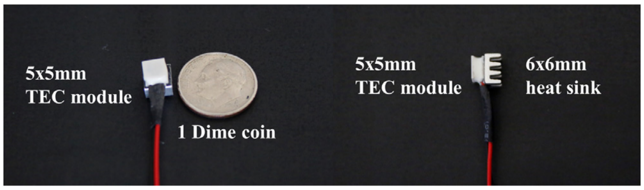

Fig. 2. TEC module. Dime for scale.

paper.

Last but not the least, while wrist could be an alternative position for around-hand haptic feedback, users tend to prefer the two different form factors (wrist band and finger ring) for different occasions (Lappalainen et al., 2016). Whereas the wrist bands could be practical for active lifestyle, users see the form factor of finger ring generally being more beautiful, aesthetic and contributing to the wearer's social image. As the form factors of smartwatch and smart wristband have been extensively studied in HCI, little research has been done on smart ring until recently. Therefore, there is a need to further investigate new haptic feedback in smart ring.

4. Hardware design

In the prototype of the thermal ring, we used a 5*x*5 mm TEC element (Model No.: TEC1-00701) attached to a 6 × 6 mm heat sink, as shown in Fig. 2. The rings were 3D printed with PLA (Polylactic Acid). Each ring contained 6 or 8 6 × 6 mm square holes (Fig. 3), 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 (2006). 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).

Skin pain might occur during the thermal stimulation due to the use of miniature TECs, as the highly localized stimulations might be perceived more intense. Through empirical pilot tests, we found that a 3-s 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 s). Therefore, the TEC module was tuned to change the temperature at a rate of +/- 1 °C/s for 3 s. The stable change of temperature was achieve by a PID controller. To achieve the desired performance, we tuned and validated the system by using the sensorless temperature-control method with a single miniature TEC module and a thermistor. Fig. 4 shows a time plot of temperature changes using the system, warming from 30 °C to 33 °C in 3 s. We then used the tuned PID parameters in the ring prototypes. Fig. 5 illustrates the arrangement and assembly of the TEC modules in the three settings.

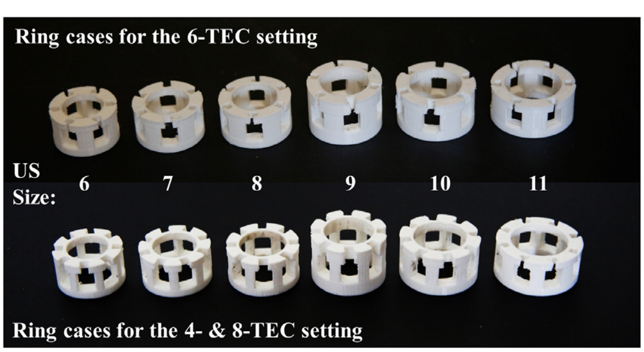

Fig. 3. Set of rings of different sizes (6 to 11 US sizes) used in this paper. During the experiment, the TECs are added to the ring case. For the 4 TEC configuration, we put TECs in half of the holes.

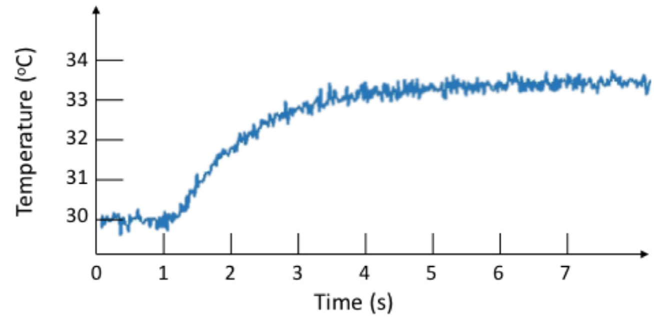

Fig. 4. Temperature plot.

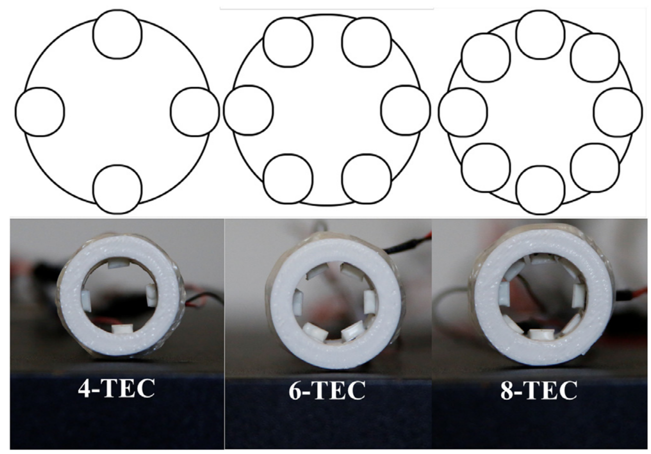

Fig. 5. Arrangement and assembly of the TEC modules in the three different settings.

5. 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.

5.1. 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 community. The average skin temperature on the finger was 32.6 °C (SD = 1.342). Some of our original pool of participants did experience pain when trying the device. The pain could be due to the use of miniature TECs, as the highly localized stimulations might be perceived more intense. Stevens (1982) showed that changing the temperature of a small tactile stimulating object could increase the spatial acuity of the tactile sensation, suggesting that the skin might process strong and small hot/cold stimulations as condensed points. To ensure the wellbeing of participants and the execution of the experiment, we conducted a 2-min pre-study session to test the thermal and pain threshold of the recruited participants. Through the pre-study sessions, we excluded three participants who felt pain in the pre-study session. The average skin temperature of the three excluded participants was 31.2 °C.

5.2. 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 either 6 or 8 slots in which we put the TEC elements. 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.

5.3. 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 s. The TECs started the temperature change from the skin temperature of the user. 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 (Fig. 6). The participant was instructed to input his/her response as quickly and accurately as possible. There was a 25-s break between trials, to allow the skin to naturally return to the resting temperature which was recorded before the experiment. The 25-s duration of the break was decided based on our empirical test with the thermistor.

5.4. 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. 5.

The experiment was divided into three sessions (one for each TEC setting). Each session 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. 6b). This was repeated twice. After training, participants completed two test blocks, where stimuli were presented in a randomized order. The selection interface was displayed after each stimulation, and participants selected the stimulated element by tapping on the smaller circle in the web page (Fig. 6c). 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).

5.5. 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. In addition, the participant was instructed to remove the ring device, and washed his/her hand during the break. The experiment facilitator marked the position of wearing the ring on the participant's finger, and helped the participant to put on the device at the same position before the new block started.

Each participant performed the experiment in one sitting (Fig. 6a), placing his/her ring-wearing hand on the keyboard drawer of the table, thus he/she could not see the ring. The experiment lasted for around 70 min. In total, each participant did a total of 2 temperatures × [1 training block + 2 test blocks] × (4+6+8) stimuli for each condition × 2 repetitions per block = 216 trials.

5.6. Results

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

5.6.1. Accuracy of element identification

The accuracy of element identification was significantly affected by the number of TECs ($F_{2,16} = 77.45$, $p < 0.001$, $\eta_p^2 = 0.906$) and the direction of temperature change ($F_{1,8} = 21.34$, $p < 0.01$, $\eta_p^2 = 0.727$). There was no significant difference between two blocks in terms 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. 7).

5.6.2. 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. 8), 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

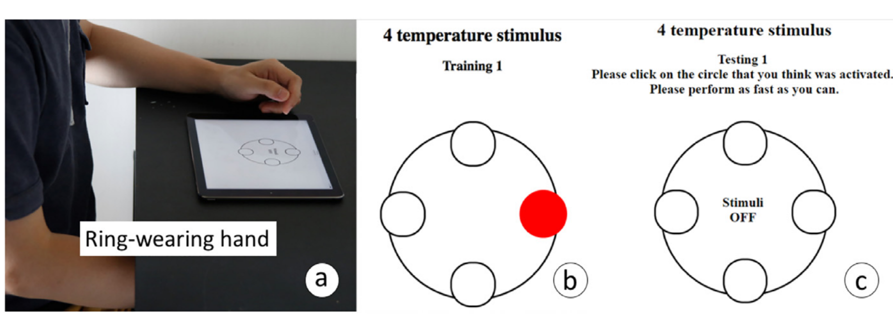

Fig. 6. (a) Experiment setup; (b) Training Interface for the 4-TEC setting; (c) Testing Interface for the 4-TEC setting.

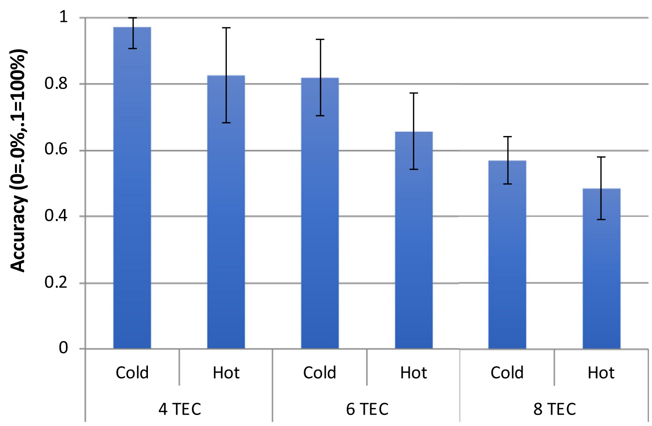

Fig. 7. Accuracy of element identification for the pilot study. Error bars show 0.95 confidence intervals.

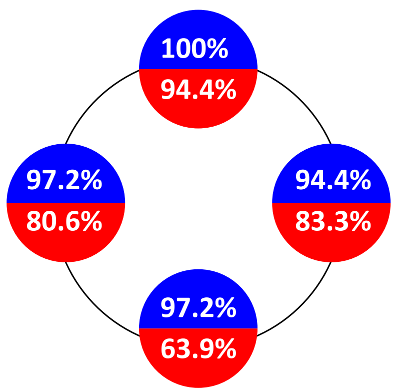

Fig. 8. Accuracy of individual element identification for the 4-TEC setting. Blue (upper semicircle): cold stimulation, Red (lower semicircle): hot stimulation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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%, $p < 0.05$). This was mainly due to the poor performance in identifying the warm stimulus when presented on the bottom of the finger base. 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 ($F_{1,8} = 11.13$, $p < 0.05$, $\eta_p^2 = 0.582$). The average accuracy of identifying the positions of cold stimulus was significantly higher than 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. Individual performance for 4-TEC condition is shown in Fig. 8.

5.6.3. Response time

Response times are summarized in Fig. 9. Similarly to the accuracy of element identification, a repeated measures ANOVA showed the number of 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

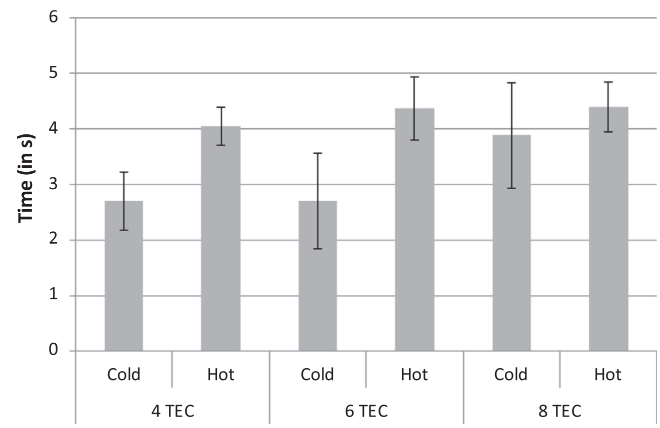

Fig. 9. Response time for the pilot study. Error bars show 0.95 confidence intervals.

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).

5.7. 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 (Halvey et al., 2011). Additionally, response time was around 1.2 s faster for cold sensation compared to hot. A direct application of these results points 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 suggested that participants were able to discriminate up to four locations on the smart ring with good average accuracy (89.9%). Repeated measures ANOVA on the post-study questionnaire showed a significant effect of the number of TECs on the perceived difficulty of stimulation identification ($F_{2,16} = 33.13$, $p < 0.005$, $\eta_p^2 = 0.702$). 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 ($M = 4.8$, $SD = 1.3$, all $p < 0.05$). There was no significant 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 ($M = 4.9$, $SD = 1.2$, all $p > 0.05$). 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. Previous work (Treede et al., 1995) suggests that the glabrous skin has higher heat threshold than the hairy skin. Therefore, potential spatial thermal patterns may want to make use mostly of the top, right, and left TECs.

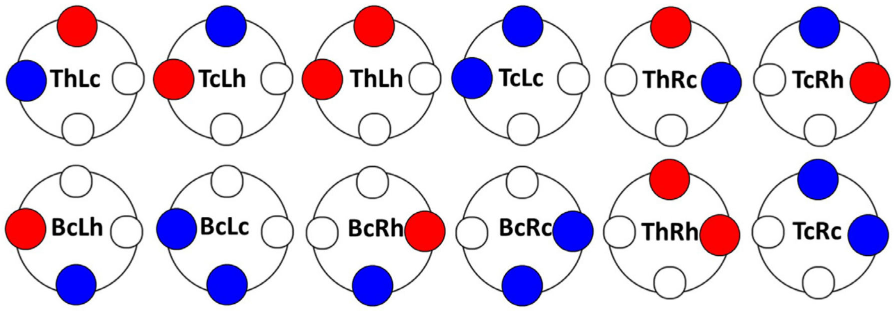

Fig. 10. Patterns used in Experiment 1 –for neighboring TECs. Red: hot; Blue: cold. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6. Spatial pattern generation

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 a few previous studies (Cain, 1973; Taus et al., 1975) 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 (Stevens, 1982). In addition, spatial summation would affect thermal intensity thresholds in that larger stimuli (i.e. those with a greater spatial extent) are perceived to be more intense. Therefore, two neighboring cold/hot simulation might be perceived colder/hotter than the single stimulation, further providing hints and assisting users to distinguish the patterns.

In line with previous literature on spatiotemporal vibrotactile patterns (Alvina et al., 2015; Yatani and Truong, 2009), our primary goal is to design a set of patterns that can be easily recognized and convey information quickly. To ensure better recognizability, we decided to use many dimensions with reduced set of values for each instead of fewer dimensions with larger set of values, in order to leverage chunking (Miller, 1956). A secondary goal is to discover the potential mappings between in-ring spatial thermal patterns and applications. The set of available dimension for vibrotactile pattern includes frequency, amplitude, waveform, duration, rhythm and spatial location (Brown et al., 2005; Chan et al., 2008; MacLean, 2008). Alvina et al. (2015) show that precisely locating a vibrotactile sensation may be problematic and propose a simple binary dimension instead of spatial location which is whether two consecutive pulses happen on the same motor. MacLean and Enriquez (2003) investigated similar dimensions for force feedback. Compared to vibrotcatile feedback, thermal feedback has its unique nature: a TEC will still remain either hot or cold after being turned off, and that kind of latency makes it hard to work with **rhythm** or **waveform**. Similarly, **amplitude**, which can be seen as the temperature change rate may induce pain, we thus chose a single value for it.

In order to design our patterns, we considered the following dimensions:

- Temperature Direction { Hot, Cold }
- Location { Top, Right, Left, Bottom }
- Grouping Strategy { Neighbors, Opposite } (for patterns involving two TECs)
- Temperature Change {1 °C/sec} (controlled)
- Temporality {Simultaneous} (for patterns involving two TECs, controlled)

We did not consider more complex spatiotemporal patterns, based on recommendations from Gallace et al. (2007) who suggested that participants may recognize simple shapes such as lines (by activating two actuators similar to two points), but only experts may detect more complex shapes. This also allows us to keep the patterns short duration-wise.

Carcedo et al. (2016) investigated the Temporality dimension and advocated to use a sequential temporality (i.e. sensors are not activated simultaneously). However, our initial testing with TECs did not show any drop of accuracy, allowing us to shorten the patterns by setting the Temporality to simultaneous.

The grouping strategies were tested in two different experiments, as to minimize to keep the number of varying dimensions close to MacLean (2008) recommendations, and, as results will show, to maximize recognizability. In order to investigate the potential mapping between patterns and commands, we ran a design workshop. MacLean (2008) presented guidelines for haptic icons. While we use different dimensions, we aim to design a set that can be easily mapped, at hopefully a low cognitive cost. The use of a spatial dimension allows us to create representational icons. For example, leveraging the similarities between cardinal points and our 4 TECs layout allows us to create a simple pattern set for navigation (e.g. activating the Left TECs for Left turn/West, or both Top/Left for North-West). Temperature can also be mapped with emotions (Tewell et al., 2017a; Wilson and Brewster, 2017), providing another option for simple mapping: a hot stimulus could be used to encode a positive meaning, or the priority of an event.

Finally, it is important to note that we did not consider multimodal icons, as investigated by previous work (Chan et al., 2008), as we wanted to specifically focus on thermal feedback. However, we do see a strong potential for multimodal icons combining thermal feedback and light, vibration or force feedback.

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. 10 shows the patterns on the neighboring pairs (i.e., Top + Left, Top + Right, Bottom + Left, and Bottom + Right). Fig. 13 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 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 s faster than the hot stimulus. Therefore, while implementing the thermal patterns that contain both hot and cold stimulations (Fig. 10: ThRc, TcRh, & BcLh; Fig. 13: ThBc, LcRh, & LhRc), we placed a 1.2-s gap between the hot and the cold stimulation, meaning the cold stimulation was triggered 1.2 s after the hot stimulation, to provide a simultaneous sensation of hot and cold.

7. Experiment 1: temperature changes on neighboring TECs

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

7.1. 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 ($SD = 1.52$).

7.2. 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.

7.3. Tasks and stimuli

During a single trial, two TECs were activated at one of the two temperature levels (cold, and hot). The participant had to accurately recognize the temperature level of each TEC. We conducted the experiment with all possible neighboring pairs of TECs, excluding combinations with Bh because of its poor performance, as shown in Fig. 10.

7.4. 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. In addition, the participants were shown to the whole set of the patterns before starting the experiment.

The experiment was divided into two blocks: one training block and one testing block. In a given block, the twelve patterns were presented three times in a randomized order. In the training block, the participant was told which pattern was just triggered with the visual patterns in Fig. 10 shown on the iPad Air 2, while in the testing block, they had to recognize the pattern by selecting the stimulated elements and temperatures. Fig. 11 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 two 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 suggest potential applications for the thermal patterns in the post-experiment interview.

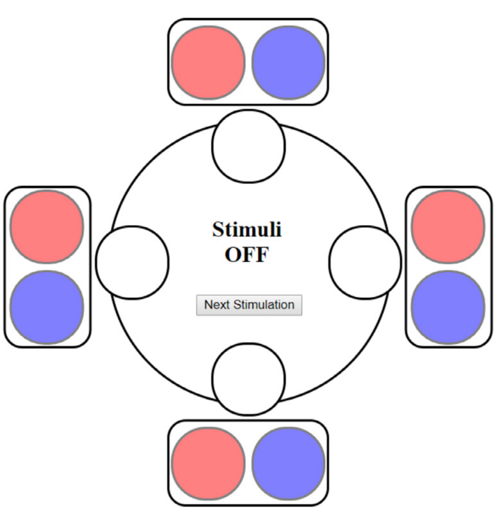

Fig. 11. Selection interface for Experiment 1 & 2.

7.5. 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-s 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 min. In total, each participant did a total of 12 patterns × [1 training blocks + 1 test block] × 3 repetitions = 72 trials.

7.6. Results

The repeated measures 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 (overall average time = 4.14 s, $SD = 0.19$). Generally, the participants could identify the patterns that combined two cold stimulations more accurately than the patterns with two hot stimulations and those with a mix of hot and cold stimulations. A post-hoc pairwise comparison on the identification accuracy revealed that TcRc (Mean = 83.3%) yielded significantly higher accuracy than TcLh ($p < 0.0005$, Mean = 20%), BcLh & ThLh ($p < 0.0005$, Mean = 43.3%), TcRh ($p < 0.05$, Mean = 53.3%), ThRh & ThLc ($p < 0.05$, Mean = 56.7%), and BcRh ($p < 0.05$, Mean = 60%). TcRc was also marginally more accurate than ThRc ($p = 0.067$, Mean = 70%). BcRc & TcLc (Mean = 80%) was significantly more accurate than TcLh ($p < 0.0005$), BcLh ($p < 0.05$), ThLh ($p < 0.05$), ThRh ($p < 0.05$), ThLc ($p < 0.05$), and BcRh ($p < 0.05$). The only cold-combination pattern with an average accuracy lower than 80% was BcLc (70.0%), and it was significantly more accurate than TcLh ($p < 0.0005$), and marginally more accurate than BcLh ($p = 0.053$), ThLh ($p = 0.059$), TcRh ($p = 0.071$), and ThLc ($p = 0.082$). Fig. 12 shows the confusion table for the neighboring patterns.

We further categorized the neighboring patterns into different groups, and compared the identification accuracy across the groups. Firstly, we grouped the patterns according to their similarity. The patterns with two TEC modules having the same temperature (i.e., ThLh, TcLc, BcLc, BcRc, TcRc) were categorized into the group of Same Temperature, while the rest (i.e., ThLc, TcLh, ThRc, TcRh, BcLh, BcRh) were categorized into the group of Different Temperature. The repeated measures ANOVA showed that the grouping significantly affected the identification accuracy ($F_{1,11} = 17.31$, $p < 0.005$, $\eta_p^2 = 0.61$, Same Temperature: 70.0% vs Different Temperature: 47.7%). Secondly, the patterns were grouped based on their horizontal sides (patterns on the left: ThLc, TcLh, ThLh, TcLc, BcLh, BcLc; patterns on the right: ThRc, TcRh, BcRh, BcRc, ThRh, TcRc). The repeated measure ANOVA showed that the grouping significantly affected the identification accuracy ($F_{1,11} = 16.14$, $p < 0.005$, $\eta_p^2 = 0.595$, patterns on the left: 50.9% vs patterns on the right: 66.7%). Last but not the least, we grouped the patterns based on their vertical sides (patterns at the top: ThLc, TcLh, ThLh, TcLc, ThRc, TcRh, ThRh, TcRc; patterns at the bottom: BcLh, BcLc, BcRh, BcRc). The repeated measure ANOVA showed that there was no significant difference on the identification accuracy between the

	TcRc	TcRh	TcLc	TcLh	ThRc	ThRh	ThLc	ThLh	BcLc	BcLh	BcRc	BcRh
TcRc	83.3%	3.3%	10.0%							3.3%		
TcRh	13.3%	53.3%	26.7%		3.3%							3.3%
TcLc	20.0%		80.0%									
TcLh	16.7%	20.0%	16.7%	20.0%	3.3%	3.3%	6.7%	6.7%	3.3%	3.3%		
ThRc				3.3%	70.0%	13.3%	6.7%	3.3%				3.3%
ThRh		13.3%			16.7%	56.7%		6.7%		3.3%		3.3%
ThLc					13.3%	10.0%	56.7%	20.0%				
ThLh		3.3%		13.3%		10.0%	26.7%	43.3%		3.3%		
BcLc									70.0%	23.3%	3.3%	3.3%
BcLh	6.7%				3.3%				6.7%	43.3%	13.3%	26.7%
BcRc	10.0%								6.7%	3.3%	80.0%	
BcRh		26.7%			6.7%	3.3%			3.3%			60.0%

Fig. 12. Confusion table for the neighboring thermal patterns. Rows represent stimulated pattern and columns the participants' input.

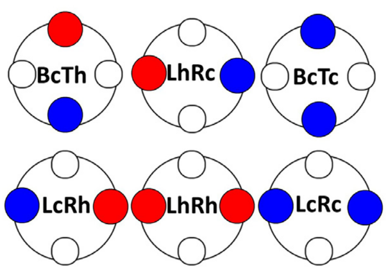

Fig. 13. Patterns used in Experiment 2 – for opposite TECs. Red: hot; Blue: cold. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

two groups.

7.7. Discussion

We noted that three neighboring patterns had over 80% accuracy: TcRc, BcRc, and TcLc. Additionally, BcLc achieved 75% accuracy. All these patterns combined two cold stimulations. This set of patterns confirms that participants had trouble precisely locating hot sensations in the neighboring patterns, either combining two neighboring hot TECs or mixing one hot TEC and one neighboring cold TEC. This could be explained with the previous research which revealed that cold perception is usually faster (Pertovaara and Kojo, 1985; Wilson et al., 2011) and more accurate (Kenshalo et al., 1968) than warmth perception.

Furthermore, we placed a 1.2-s gap between the hot and the cold stimulation, and the purpose was to provide a simultaneous sensation of hot and cold. In the post-experiment interview, we explicitly asked the participants if they felt the hot and the cold stimulation simultaneously or they felt the two stimulations in a temperal sequence. All the participants commented that they could not notice a time difference between the two types of thermal stimulation.

8. 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 for the opposite pair of TECs. We conducted another experiment similar to Experiment 1, which considered opposite TECs instead.

8.1. Participants

The same recruitment strategy was applied. Twelve participants (5 females, all right-handed) ranging from 19 to 31 years old ($M = 22.3$, $SD = 3.57$) were recruited from within the university community. The average skin temperature on the finger was 33.6 °C ($SD = 1.53$).

8.2. Apparatus, task and stimuli, procedure

We used the exact same apparatus and procedure as Experiment 1. The six patterns are shown in Fig. 13.

8.3. 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 performed the experiment in one sitting, including breaks. The experiment lasted for around 30 min. In total, each participant did a total of 6 patterns × [1 training block + 1 test blocks] × 3 repetitions = 36 trials.

8.4. Results

Similar to the neighboring patterns, repeated measures ANOVA showed that there was a significant difference among these opposite thermal patterns in terms of the identification accuracy ($F_{5,55} = 5.18$, $p < 0.01$, $\eta_p^2 = 0.330$). Fig. 14 illustrates the confusion table for the opposite thermal patterns. The accuracy for LhRh (61.1%) was significantly lower than TcBc (91.7%, $p < 0.05$), ThBc (91.7%, $p < 0.05$), LcRc (91.7%, $p < 0.05$), LhRc (83.3%, $p < 0.05$), and LcRh (83.3%, $p < 0.05$).

Besides the identification accuracy, repeated measures ANOVA suggested that the factor of pattern placed a significant effect on the average time for trial completion ($F_{5,55} = 4.20$, $p < 0.05$, $\eta_p^2 = 0.275$). Post-hoc pairwise comparisons showed that LhRh required significantly longer time (6.02s) for identification than all other patterns ($p < 0.05$, TcBc: 4.53s, LhRc: 4.65s, LcRc: 4.93s, ThBc: 4.99s), except LcRh (5.0s)

	BcTc	BcTh	LhRh	LcRc	LhRc	LcRh
BcTc	91.7%	5.6%		2.8%		
BcTh		91.7%				8.3%
LhRh			61.1%		27.8%	11.1%
LcRc				91.7%	8.3%	
LhRc		2.8%	13.9%		83.3%	
LcRh				5.6%	11.1%	83.3%

Fig. 14. Confusion table for the opposite thermal patterns. Rows represent stimulated pattern and columns the participants' input.

with which the difference was only marginal ($p = 0.06$).

We also categorized the thermal patterns into groups. Firstly, we group them based on the similarity (Same Temperature: TcBc, LcRc, LhRh; Different Temperature: BcTh, LcRh, LhRc). The repeated measure ANOVA showed no significant difference in terms of the identification accuracy (Same Temperature: 81.1%, Different Temperature: 86.1%) and the completion time (Same Temperature: 5.16 s, Different Temperature: 4.88 s) between the two groups. Secondly, we considered the direction of the combined patterns, and divided them into two groups (horizontal patterns: LhRc, LcRh, LhRh, LcRc; vertical patterns: BcTh, BcTc). The repeated measure ANOVA showed no significant difference in terms of the identification accuracy (horizontal: 79.9%, vertical: 91.7%) and the completion time (horizontal: 5.15 s, vertical: 4.76 s) between the two groups.

8.5. Summary

In terms of accuracy, we found five patterns with 80% accuracy or more: LcRc, BcTc, BcTh, LhRc, and LcRh. Similar to the former experiment on the neighboring patterns, the patterns involving two cold stimulation (i.e. BcTc and LcRc) resulted in highest accuracy (91.7%), and LhRh which involved two hot stimulations yielded the lowest accuracy, and the longest identification time. This could also be explained with the effect of spatial thermal summation which may confuse the participants more with hot stimulation than cold stimulation.

On the other hand, different from the neighboring patterns, the opposite patterns involving the mix of hot and cold stimulations could be identified with accuracy higher than 80%. Since the TECs involved were further away from each other compared to neighbors, effects of spatial summation were likely smaller, leading to better overall accuracy.

9. Selecting and validating reliable in-ring thermal patterns

Our pilot study showed that the participants could identify the single-spot cold TEC significantly better than the hot TEC, and Experiment 1 & 2 revealed a set of two-spot spatial thermal patterns with the average accuracy above 80%, including three neighboring patterns and five opposite patterns. Furthermore, the statistical analysis above suggested that these patterns yielded significantly higher identification accuracy than the others. However, these patterns were tested separately within their own categories. It is unknown whether users could reliably perceive them when these patterns were grouped together and presented as a whole set of in-ring thermal feedbacks. To answer this question, we conducted three follow-up experiments to validate different group combinations of the selected thermal patterns. These three follow-up experiments adopted the same participant-recruitment strategy, apparatus, procedure, and design as the Experiment 1 & 2, expect the different group combinations of thermal patterns. The participants in the follow-up experiments were different from those in the Experiment 1 & 2, but with similar background and age.

9.1. Follow-up experiment 1: single + neighbor + opposite

We first created a large group of thermal patterns by combining four single-spot cold stimulation (Tc, Bc, Lc, Rc), three neighboring patterns (TcRc, TcLc, BcRc), and five opposite patterns (BcTc, BcTh, LcRc, LhRc, LcRh). We investigated users' identification accuracy and time for each of them. Twelve participants (6 females, all right-handed) ranging from 22 to 30 years old ($M = 25.3$, $SD = 3.27$) were recruited from within the university community. The average skin temperature on the finger was 33.4 °C ($SD = 1.32$). The experiment lasted for around 60 min. In total, each participant did a total of 12 patterns × [1 training block + 1 test blocks] × 3 repetitions = 72 trials.

The descriptive results and the confusion table, as shown in Fig. 15, suggested that it was difficult for the participants to reliably perceive these twelve patterns all together in the same group. There were only two patterns with the accuracy above 80% (i.e., ThBc: 96.7%, and LcRh: 83.3%). The confusion table further revealed that the participants tended to confuse the neighboring patterns and the opposite patterns. For example, 30.6% of TcRc were identified as BcTc, 27.8% of BcRc were identified as LhRc, 34.2% of TcBc were identified as TcRc, and 50% of TcLc were identified as BcTc. The overall low accuracy may be explained by too many confusing combinations, which combined to spatial summation likely impaired recognition.

9.2. Follow-up experiment 2 & 3: single + neighbor and single + opposite

As the first follow-up experiment suggested that users could not accurately identify the thermal patterns from a large group, it was of our interest to investigate the feasibility of grouping the single-spot cold stimulations with either the neighboring or the opposite patterns. We first investigated the combination of the single-spot cold stimulations and the neighboring patterns. Twelve participants (6 females, all right-handed) ranging from 22 to 30 years old ($M = 24.2$, $SD = 2.42$) were recruited from within the university community. The average skin temperature on the finger was 33.4 °C ($SD = 1.26$). The experiment lasted for around 30 min. In total, each participant did a total of 7 patterns × [1 training block + 1 test blocks] × 3 repetitions = 42 trials. The confusion table in Fig. 16 showed that the participants could identify all seven patterns with the accuracy larger than 80%. Repeated measures ANOVA suggested no significance difference among the patterns in terms of accuracy and completion time ($p > 0.05$).

Another twelve participants, 6 females and 6 males, aging from 22 to 32 years old ($M = 25.1$, $SD = 3.22$), were recruited for third follow-up experiment to investigate the accuracy and time of identifying the grouped patterns of the single-spot cold stimulations and the opposite patterns. The experiment lasted for around 45 min. In total, each participant did a total of 9 patterns × [1 training block + 1 test blocks] × 3 repetitions = 54 trials. The confusion table in Fig. 17 showed that all these patterns yielded the accuracy above 80%, similar to the group combination of the single-spot cold stimulations and the neighboring patterns. Repeated measures ANOVA showed that there was no significant difference among these patterns in terms of the identification accuracy and trial-completion time ($p > 0.05$).

10. Design workshops for mapping in-ring spatial thermal patterns to information representation

The follow-up experiments suggested that the combined group of single-spot cold stimulations and neighboring/opposite patterns could be identified reliably with accuracy above 80%, suggesting the potential usage of these in-ring thermal patterns as thermal icons for information representation. To distill the potential mapping of these thermal patterns (4 single-spot cold stimulations, 3 neighboring patterns, and 5 opposite patterns) and the information in various application scenario, we conducted three design workshops, involving six experienced product/interface designers (3 females and 3 males, average age = 34.3 years old).

10.1. Workshop procedure

We conducted three design workshops, each of which involved two designers. Each workshop started with an initial ice-breaking session in which the facilitator introduced the concept of in-ring spatial thermal feedback and the purpose of the workshop. The designers then wore the ring and experienced the thermal patterns which were triggered in randomized order with the visual representations shown on the iPad 2. They could experience any of these thermal patterns at any time during the design workshop. The facilitator then asked the designers to select a subset of the twelve spatial thermal patterns (Fig. 18) for six common application categories that could be potentially benefit from thermal

	Tc	Rc	Bc	Lc	TcRc	BcRc	TcLc	ThBc	LcRh	LhRc	TcBc	LcRc
Tc	75.0%		2.8%	2.8%	2.8%		5.6%	5.6%				5.6%
Rc	8.3%	63.9%	2.8%		11.1%	2.8%			5.6%		2.8%	2.8%
Bc		2.8%	77.8%		2.8%	16.7%						
Lc	8.3%	2.8%	8.3%	55.6%		2.8%	5.6%		2.8%	5.6%		8.3%
TcRc		11.1%	2.8%		38.9%			8.3%			30.6%	8.3%
BcRc			8.3%		8.3%	38.9%	2.8%		5.6%	27.8%		8.3%
TcLc				19.4%	2.8%		22.2%	5.6%			50.0%	
ThBc								96.7%		3.3%		
LcRh								16.7%	83.3%			
LhRc	2.9%				11.4%	2.9%		8.6%	11.4%	25.7%		37.1%
TcBc		2.9%		11.4%	34.3%	8.6%	8.6%	5.7%			22.9%	5.7%
LcRc	2.8%	16.7%	5.6%	13.9%	11.1%	2.8%	11.1%	5.6%	2.8%	2.8%	2.8%	22.2%

Fig. 15. Confusion table for the large group of 14 spatial thermal patterns. Rows represent stimulated pattern and columns the participants' input.

	Tc	Rc	Bc	Lc	TcRc	TcLc	BcRc
Tc	86.1%	5.6%	2.8%		2.8%	2.8%	
Rc		83.4%	2.8%		2.8%	2.8%	8.3%
Bc			94.4%				5.6%
Lc	2.8%		2.8%	88.9%		5.6%	
TcRc	5.6%	8.3%			83.3%		2.8%
TcLc	13.9%			5.6%		80.6%	
BcRc		2.8%	8.3%				88.9%

Fig. 16. Confusion table for the combined group of single-spot cold stimulations + neighboring patterns. Rows represent stimulated pattern and columns the participants' input.

	Bc	Lc	Tc	Rc	BcTc	BcTh	LcRc	LhRc	LcRh
Bc	96.7%				3.3%				
Lc		90.0%					3.3%		6.7%
Tc			93.3%		6.7%				
Rc				86.7%			3.3%	10.0%	
BcTc			6.7%		90.0%		3.3%		
BcTh	3.3%					96.7%			
LcRc		3.3%		3.3%			90.0%	3.3%	
LhRc		6.7%		10.0%			3.3%	80.0%	
LcRh		6.7%					10.0%	3.3%	80.0%

Fig. 17. Confusion table for the combined group of single-spot cold stimulations + opposite patterns. Rows represent stimulated pattern and columns the participants' input.

feedback based on previous research (Halvey et al., 2012a; 2013; 2011; Tewell et al., 2017a; 2017b; Wilson et al., 2012; 2013; Wilson and Brewster, 2017; Wilson et al., 2015; 2017): emotion representation, call/message notification, navigation, artefact properties (e.g., ratings of service), calendar, and game. The facilitator also instructed the designers to follow these design rules: 1) The designer can create the mappings for multiple scenarios within one application category; 2) Each pattern should be used only once within one application scenario; 3) The patterns can be reused across difference scenarios; 4) The single-spot stimulations can be used with the neighboring or opposite patterns within one application scenario; 5) The neighboring and the opposite patterns can not be used within the same scenario; 6) The designers need to write clearly the rationale for every design choice in the given paper form. Additionally, we did not prime the designers with any potential meaning of the temperature (e.g., warm - welcoming, cold - unpleasant, etc.), as we would like to eliminate the potential bias. The workshop lasted around 1 h.

10.2. Workshop results

In total, there were 340 mappings created for 14 thermal patterns and 6 application categories. Considering the three groups of thermal patterns, Pearson Chi-Square Test ($\chi^2(10, N = 340) = 61.78, p < 0.001$, Cramer's $V = 0.301$) revealed that there was a significant relationship between the application category and the usage of the thermal patterns by the designers in the workshop.

Navigation. More specifically, the largest group of mappings (26.6%) for the single-spot stimulations were to the scenario of navigation. 69% of the mappings for the neighboring patterns were about the application of navigation. All of our participants mapped Patterns 1

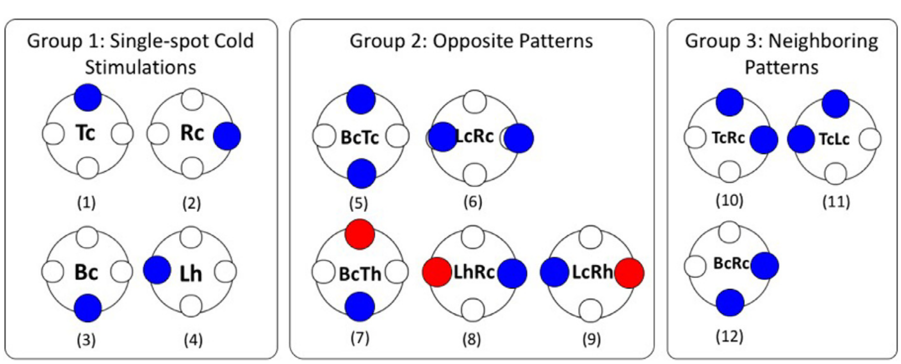

Fig. 18. Groups of patterns used during our workshop. The first group of four involve only 1 TEC (#1–4), the next group of five involve 2 opposite TECs (#5–9) and the last group of three involve neighboring TECs ((#10–12)).

(Tc), 2 (Rc) and 4 (Lc) with their respective directions. Four out of six participants also mapped Pattern 3 (Bc) with a South/Go backward direction, while the two other mapped them with respectively Pattern 7 (BcTh) and Pattern 6 (RcLc), with the rationale that going backwards, e.g. making a u-turn needs a stronger warning or less expected pattern compared to the other three directions. The neighboring patterns (#10–12) were also mapped to collateral directions, such front-left and front-right. These simple mapping while seemingly trivial are also potentially intuitive and easy to learn as they do represent direction in a clear way. Another interesting result we found that two designers mapped Pattern 11 (TcRc) to Front-Left and Pattern 12 (BcRc) to Front-Right. The designers explained that this type of mappings was specifically for driving when users, with the ring worn on their left hands, are grabbing the steering wheel, and their hands are perpendicular to the horizontal ground, so that the right position becomes the top position, with the top becoming left and the bottom becoming right. This suggests that actually knowing the orientation of the finger would allow us to dynamically change the patterns for specific directions in order to maintain a spatial consistency of directions. Finally, four participants also used pattern with hot stimulation to notify the user of an emergency, such as an obstacle, tunnel, red traffic light or unexpected traffic.

Incoming Messages and Calls. Our designers vastly (5/6) preferred single-spot patterns to encode four different categories of contacts (mainly friends, family, work, other). Similarly to navigation, patterns involving hot stimulation (7–9) were used by four designers as a warning of either an unknown contact calling/messaging, harassing call or an urgent call. The contrast with the otherwise cold stimulation was thus expected to catch the attention, as well as consistently mapping hot stimulation with emergency or warning.

Emotion and Mood. We asked our participants to select patterns and map emotion with them. Interestingly they tended to do so by mapping the position of each TEC to feelings. For example, positive emotions such as good mood/joy were associated with Pattern 1 (Tc) by four participants. Similarly, feelings of sadness or angryness were mapped with Pattern 3 (Bc): P3 reported *The bottom position means "I am feeling down"*. Other patterns involving the bottom position were also suggested, such as Pattern 12 (BcRc), chosen by two participants for sadness, as well as Pattern 7 (BcTh) suggested for anger by one participant. Pattern 7 was also used by one participant to notify users that their interlocutor should not be disturbed. Finally, patterns with hot stimulation were used to convey negative emotions: Pattern 7 and 9 were chosen to express anger (two participants) or sadness (two participants).

Properties of Artefacts. While being used for presenting artifact properties, all designers agreed that the opposite patterns can be used to compare two different 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. Patterns 7, 8 and 9 (hot stimulation) were once again suggested for warning, either on the weather for rainstorm or typhoon (two participants). Compared to pairwise comparisons, where hot encoded a better rating, two participants suggested to use one of Pattern 7, 8 or 9 for negative properties measured, creating an interesting contrasts with suggestions on comparisons between two places/objects. We noted another interesting property of our opposite patterns: they may be used to also encode a change of state. For example, one participant suggested to use Pattern 8 (LhRc) and 9 (LcRh) to show an important temperature change, respectively from hot to cold, or cold to hot.

Games. Once again, Patterns 1, 2 & 4 were suggested for navigation by our six designers, with Pattern 3 suggested for Going Back by four participants, while the two remaining one suggested Pattern 7, consistently with their navigation mapping. Hot stimulation, namely patterns 7, 8 and 9 were consistently suggested to notify the player that a specific event, e.g. death or imminent danger (three participants) or to notify that enemies are in the back of the player (Pattern 7, one participant), or that the game ended with a victory (Pattern 7, one participant).

Calendar/Time. Our participants did use hot stimulation to encode urgency or incoming meetings using Patterns 7–9 (four participants). Patterns 1–4 were suggested by four participants to encode overall time of the day, by mapping the TEC with its position on a clock, which may work but only for limited time intervals. Using other Cold/Cold patterns was suggested, specifically neighboring patterns to encode intermediate values (e.g. use Pattern 10 – TcRc to show a time between 12pm and 3pm). Incoming meetings and other type of notifications were encoded using hot stimulation as suggested by five participants.

In summary, we observed emerging trends during our workshops. Participants tried to use the position of each TEC to create mapping. This is especially clear for navigation purposes. Single-spot patterns were also used for notifying incoming calls/messages, and the designers tended to map different categories of contacts to different positions. For example, the cold stimulation at the top position was mapped to the family members, with the design rationale that it is easier and more comfortable to perceive the cold stimulation triggered by the top TEC. Similarly, our participants played on the up/down opposition to also encode emotions (positive emotions on the top TEC, negative one on the bottom TEC). Another general result is the usage of hot stimulation for emergency or unpleasant event: using these patterns creates a contrast compared to other patterns, which act as an alert for either event, undesirable phone calls or messages. It would thus be interesting to assess the learnability of our pattern sets for each application. We illustrated some suggested mappings in Fig. 19.

11. 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 1.5 W 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 (Farage et al., 2013). We observed that all our participants were from the similar region and cultural background, thus could have similar skin sensitivity. As a solution, an actual product could 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 (Wilson et al., 2011): 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

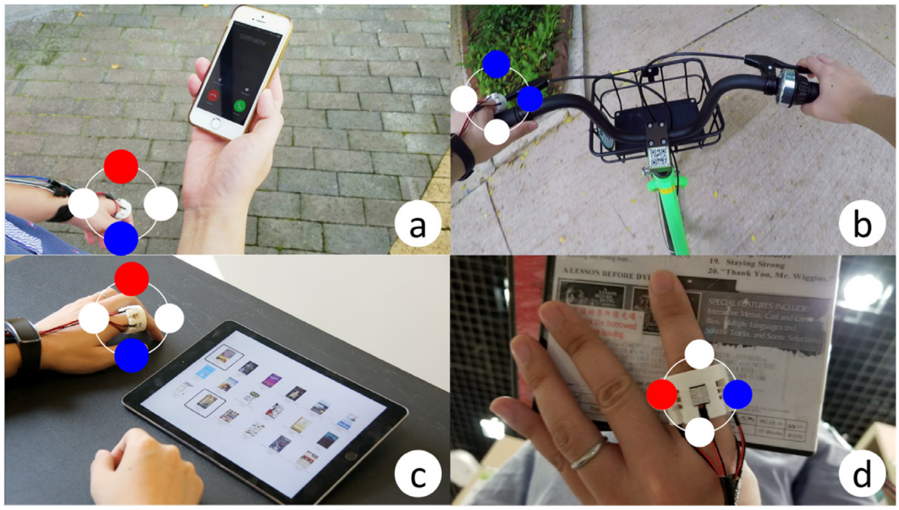

Fig. 19. Application scenarios for smart-ring thermal patterns: (a) notification, (b) navigation, (c) comparison of digital artifacts, (d) comparison of physical artifacts.

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.

Note that the same spatial thermal pattern could convey different information in different contexts, as we allowed the reuse of patterns. This may lead to the need of designing smooth change across applications. In the future work, we will investigate the possible mode-changing methods for switching smart-ring applications.

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 97.2% accuracy. Further, we designed two groups of spatial thermal patterns (neighboring and opposite) that can be achieved with 4 in-ring TECs. Our experiments revealed 3 neighboring patterns (TcRc, TcLc, and BcRc) and 5 opposite patterns (BcTc, BcTh, LcR, LhRc, and LcRh) that were reliably recognized by the participants with the accuracy above 80%. While the follow-up experiment suggested that it could be confusing for users by combining four single-spot cold stimulations, three neighboring patterns, and five opposite patterns in the same group (average accuracy: 50.2%), we conducted two more follow-up studies, each of which involved 12 participants, showing that the participants could identify the thermal patterns in the combined group of the single-spot cold stimulations and the neighboring patterns (average accuracy: 85.3%), and the combined group of the single-spot cold stimulations and the opposite patterns (average accuracy: 89.3%). Our design workshops further distilled different mappings between the given thermal patterns and the information, including direction cueing through single-spot and neighboring patterns, artifact comparison through opposite patterns, notifying incoming calls/messages from different persons with different locations and temperatures of the TECs, etc. This demonstrated interest in 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. Finally, this paper focuses on smart rings. It would be of interest to compare the users' perception, the appropriateness, and the application of multiple thermal actuators in smart rings and wristbands.

Conflict of interest

None.

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