ThermEarhook: Investigating Spatial Thermal Haptic Feedback on the Auricular Skin Area

Arshad Nasser
arshad.nasser@my.cityu.edu.hk
School of Creative Media, City University of Hong Kong
Hong Kong, China

Kexin Zheng
kexinzhengn@gmail.com
School of Creative Media, City University of Hong Kong
Hong Kong, China

Kening Zhu*
keninzhu@cityu.edu.hk
School of Creative Media, City University of Hong Kong
Hong Kong, China

ABSTRACT

Haptic feedbacks are widely adopted in mobile and wearable devices to convey various types of notifications to the users. This paper investigates the design and the evaluation of thermal haptic feedback on an earable form factor with multiple thermoelectric (i.e. Peltier) modules. We propose ThermEarhook, a wearable device that can provide hot and cold stimuli at multiple points on the auricular skin area. To investigate users' thermal perception on the auricular area, we develop a series of ThermEarhook prototypes with 3, 4, and 5 Peltier modules. While most existing research utilized the constant level of haptic signal for different users, our pilot study with ThermEarhook shows that the auricular thermohaptic threshold varies across the feedback locations and the users. With the user-customized thermohaptic signals around the ear, our first study with 12 participants reports on the selection of the auricular configuration with four TEC modules on each side, considering the users' identification accuracy (averagely 99.3%) and preference. We then conduct three follow-up studies and a total of 36 participants to further evaluate users' perception of spatial thermal patterns with ThermEarhook, and finalize a set of multi-points auricular thermal patterns that can be reliably perceived by the users with the average accuracy of 85.3%. Lastly, we discuss the user-proposed potential applications of the thermal haptic feedback with ThermEarhook.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Thermotactile, earhook, spatial thermal pattern, earable

ACM Reference Format:
Arshad Nasser, Kexin Zheng, and Kening Zhu. 2021. ThermEarhook: Investigating Spatial Thermal Haptic Feedback on the Auricular Skin Area. In *Proceedings of the 2021 International Conference on Multimodal Interaction (ICMI '21), October 18–22, 2021, Montréal, QC, Canada.* ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3462244.3479922

*Corresponding author.

ICMI '21, October 18–22, 2021, Montréal, QC, Canada

ACM ISBN 978-1-4503-8481-0/21/10…$15.00
https://doi.org/10.1145/3462244.3479922

1 INTRODUCTION

With the increasing amount of information available in our daily life, various mobile and wearable interfaces have been proposed to improve the accessibility of digital data. Besides the common channels of information communication through visual and audio techniques, the tactile/haptic modality is receiving more and more attention. The vibrotactile feedback has been applied for variety of applications including navigation [19, 31, 38] and notifications/warnings [29, 30]. Also, the vibrotactile feedback has been tested individually [19, 38] and in combination/comparison with other modalities [23, 29, 30] for notification on the move. However, sometimes it could be difficult for users to perceive the exact vibration location [19] in the context of multi-point spatial vibrotactile feedback, as the natural turbulence or movements during walking or driving may affect the perception of vibration [10, 15, 22, 23, 26].

Besides the vibrotactile feedback, there is an increasing amount of research interest in the recent years in the application of thermal feedback for human-computer interaction (HCI). Thermal feedback is usually silent and effective in noisy environments [40]. The characteristics of single-spot and multi-spots thermal feedback have been investigated for mobile devices [13, 14, 39, 41] and smart wearable accessories (e.g., ear hook [24], headband [25], bracelet [26], and finger ring [42]), with a reliable recognition accuracy for general purposes. In addition, the thermal feedback can be integrated on the steering wheel for notifying lane changes and directions in driving simulation [9, 10]. The spatial thermal feedback has also been used in the assistive device to provide navigation cues for visually-impaired people, showing the advantages of localization over the vibrotactile feedback [5, 23, 40].

Ear, as one of the body parts that are more sensitive to tactile feedback, has motivated the emerging research of earable haptic devices[11]. With the recent advancements in the hearable technologies that focuses on the auditory output, many HCI researchers and analysts proposed 'ear as the new wrist', and started the research of earable devices which could be worn on and around the ear and head [1]. Research [20] show that the multi-point spatial vibrotactile feedback could be reliably perceived on the ear with the average accuracy over 80%. On the other hand, the on/around-ear (i.e. auricular) spatial thermal haptics for earables is less explored when compared to the vibrotactile feedback. While thermal feedback has shown great potential in facilitating information representation, it is still unclear how it could be perceived as an earable form factor as ear is one of the body parts that are very sensitive to temperature change.

In this paper, we focus on integrating thermal haptic feedback in an earhook form factor for designing the wearable device. More specifically, we designed ThermEarhook as shown in Fig. 1, a wearable device that can provide hot and cold stimuli at multiple points on the auricular skin area. To investigate users' thermal perception around the auricular area, we developed three ThermEarhook prototypes with 3, 4, and 5 Peltier modules respectively. Difference from most existing research that adopted the constant level of haptic signal for different users, our pilot study shows that the auricular thermohaptic threshold varies across the feedback locations and the users. With the user-customized thermohaptic signals around the ear, our first study suggested the selection of the ThermEarhook with four TEC modules on each side for further investigation, considering the users' identification accuracy (averagely 99.3%). We then conduct three follow-up studies to further evaluate users' perception of spatial thermal patterns with ThermEarhook, and finalize a set of multi-points auricular thermal patterns that can be reliably perceived by the users with the average accuracy of 85.3%. Lastly, we discuss the user-proposed potential applications of the thermal haptic feedback with ThermEarhook, such gaming, music, navigation, mobile notifications, therapeutics, and so on.

The contributions of this paper are three-fold:

- We designed and developed ThermEarhook, a earable prototype that provides spatial thermal haptic feedback around the ear.
- We conducted a series of user studies with a total of 58 participants (i.e., 10 in the pilot study, and 12 in each of the four following studies), to thoroughly investigate the auricular thermal feedback with ThermEarhook. Based on the results, we proposed a set of fourteen multi-points thermal icons on the auricular skin area with the average accuracy of 85.3%.
- We revealed a set of user-proposed applications that can leverage the ThermEarhook design with the thermal icons.

2 RELATED WORK

Our research is inspired by two emerging topics in HCI: thermal feedback, and multimodal haptic feedback in the earable devices. We also discuss ear sensitivity to thermal stimuli.

2.1 Thermal Feedback in HCI

As one early study on thermal feedback, Jones and Berris [17] suggested a list of design recommendations for the thermal display based on psychological evidence. Some comprehensive research on thermal feedback in HCI has provided important insights such as: 1) hand is a body part with high thermal sensitivity [14]; 2) the perception of thermal feedback could be strongly affected by clothes [14] and the environment [13]; 3) a set of thermal icons with an overall recognition accuracy of 83% can be designed using the rate and the direction of temperature change [39]. Following Wilson et al.'s insights, Tewell et al. showed that thermal feedback could enhance the emotional perception of text-based information [35] and could be used to support on-screen navigation [36] for sighted users. Singhal and Jones [33] evaluated thermal pattern recognition on the hand and arm with single thermoelectric module, and proposed the model-based approach for designing thermal icons. More recently, researchers started investigating the spatial thermal feedback in wearable accessories and wide variety of applications, such as finger ring [42], bracelet [26], headband [25], earhook [24], cane grip [23], etc. ThermOn [2] was designed for users to feel dynamic hot and cold sensations on their body corresponding to the sound of music. Motivated by these emerging thermohaptic-related research, we propose ThermEarhook, to further study the user perception of auricular spatial thermal feedback and its potential application.

2.2 Multimodal Haptic Feedback on Earable Devices

There are several earable form factors that fit on, in or around the ear, providing audio playback, soundscape augmentation, or even integrate biometric sensors. However, haptic devices designed for the ear are relatively less explored. Kojima et al. leveraged the viscoelastic characteristics of human ears to present navigational information, by applying the pulling forces on the ears to notify a particular direction. Orecchio [16] earable device has experimented various static and dynamic auricular postures for extending the body-language, but with a focus on onlookers' perception of ear movement. Emoti-chair [18] and the use of a vibratory earphone [3] on the pinna used the vibratory sense to enhance the emotion of sound. Narumi et al. [32] has explored change the perception of the direction of sound by deforming the pinna. Recently, Lee et al. developed ActivEarring to provide the spatial vibrotactile feedback on the ear [20]. Their studies showed that the users can perceive a set of sequential vibrotactile patterns with an average accuracy over 80%. While the force-based and the vibrotactile feedback for earable devices have started gaining more and more research interest, the thermal earable is still under-explored. Recently, Nasser et al. presented the design of thermohaptic Earable display for the hearing and visually impaired users [24], by installing two miniature Peltier modules on each side of the earhooks. However, how users may perceive such auricular spatial thermal feedback is still unknown. With ThermEarhoook in this paper, we thoroughly investigated the affordance of auricular spatial thermohaptic patterns, including the user perception and the suitable thermal icons.

2.3 Thermal Sensitivity around the Auricular Area

Early research on the temperature sensitivity of the body surface showed that the forehead and the cheek have the lowest hot and cold threshold [6]. Recently, it is reported that the ear and the surrounding areas also possess a low thermal threshold, indicating high sensitivity to the thermal variations [21]. Treede et al. found that the hairy skin is more heat sensitive than the glabrous part [37]. Recent research on the on-finger thermal feedback supported this finding of the difference on the thermal sensitivity between the hairy and the glabrous skins [42]. As the hair and the skin thickness vary around the ear, it is reasonable to hypothesize that different areas around the ear may yield different thermal sensitivity, making it non-trival for designing auricular thermal patterns.

3 THERMAL EARHOOK DESIGN

We adopt the form factor of earhook over the circular ear pad, as earhook is used as a common form of not only audio and verbal communication, but also assistive device for people with hearing impairment. In the prototype of ThermEarhook, we use the 10×6 mm thermoelectric modules (i.e., Peltier modules) with the thickness of 1.4 mm (Model No.: TES1-03103), as shown in Fig. 2. The

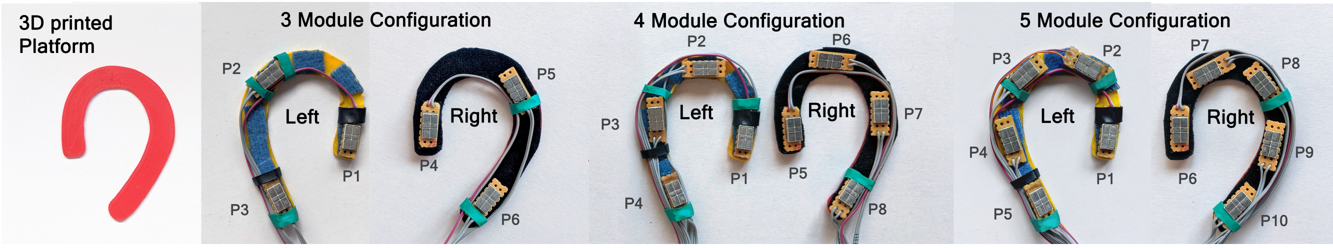

Figure 1: ThermEarhook prototypes with 3, 4, and 5 Peltier modules

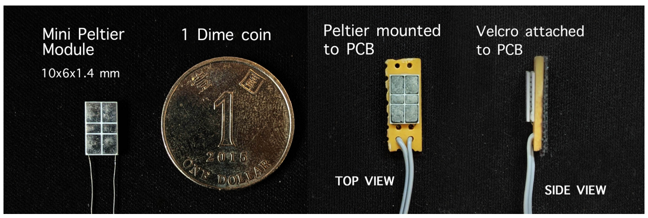

Figure 2: Mini Peltier modules used on the ThermEarhook

thermoelectric element consists of a matrix of micro Peltier elements with a metallized surface. We selected these modules because of their thinness, light weight, and the manufacturing process that offers a high thermal efficiency (maximum refrigerating capacity $Q_{max} = 7.51W$) even without the heat sink.

The earhook frame used in the prototype (Fig. 1) is 3D printed with PLA (Polylactic Acid) in the thickness of 1.2 mm. This allows slight flexibility to fit the uneven surface around the back of the ear. The miniature size of the used thermoelectric module also facilitate the fitting of the ThermEarhook prototype on the skin around the auricular area.

The setup of ThermEarhook is as shown in the Fig. 1. All the Peltier modules are driven using an custom designed H-bridge driver module (Model No.: L298N) shield and an Arduino Mega micro-controller, with an external switching mode power supply. Each Peltier module draws a maximum of 400mA at 6V during the stimulation. The system was controlled by the Arduino Mega connected to a laptop through USB, to ensure the fine control of the temperature through Pulse Width Modulation (PWM). Following the recent related research on thermal devices [23], we activated the thermal stimuli for 1.5s (on for 1.5s and then switched off), for a comfortable yet perceivable temperature feedback. With the full duty cycle of PWM (255), the Peltier module can change its surface temperature with the temperature-changing rate of 3.5°C/s, increase/reduce 5.25°C within 1.5s.

4 PILOT STUDY

While existing thermal HCI research usually adopted the same thermal signals for all the Peltier modules and all the participants in the settings of multi-spot feedback, psycho-physical research shows that different skin parts have different thermal threshold [21], so do different people [12]. To the end, we conducted a pilot study before the formal experiments of multi-spots thermal feedback, to understand the thermal threshold of various points around the auricular skin area for different persons. The results of the pilot study will provide the practical guidance for the following experiments.

4.1 Participants

10 participants (5 male and 5 female) aging from 25 to 35 years old (Mean = 31.5, SD = 4.42) were recruited for the study. The average skin temperature on the auricular area was 33.2°C and the average room temperature was 27.3°C.

4.2 Apparatus

We used the 3D-printed earhook frame with five Peltier modules for the pilot study. The Arduino-based thermal control system for the earhook was connected to a Surface Pro laptop through a USB cable. We designed a Processing-based graphical user interface (GUI), as shown in Fig. 3 to let the participant adjust the hot and the cold stimuli to a perceivable and comfortable level for each of the five points on the earhook. This information is then stored as a text file in the laptop.

Figure 3: Testing setup with the participant wearing the ThermEarhook

4.3 Procedure and Task

There is one experimenter and one participant in each experiment session. Upon the arrival of the participant, the experimenter briefly introduces the purpose and the flow of the study. The experiment first measured the participant's skin temperature around the auricular areaand collected biographic information. He then demonstrated how to wear the earhook on the left ear and then assisted the participant to wear it. The experimenter verbally explained the nature of each stimulation to familiarize the participant with the stimuli. During the explanation, the experimenter numbered the position of the stimulus corresponding to the GUI shown on the screen Fig. 3. With each thermal stimulus(hot and cold) lasting for 1.5s, they were presented in a clock-wise order with the front position (P1 in Fig. 1 F) of the earhook as the start. The slider on the GUI allows the participant to select the PWM values, ranging from 0 to 255, to control the intensity of the thermal stimulus. The participant could slide it freely and repeat the current stimulus until satisfied and then move to the next position. For the PWM adjustment, the participant is instructed to find the intensity that he/she feels the most comfortable and perceivable.

4.4 Results and Analysis

We took the PWM values adjusted by the participants as the dependent variable, the location of the Peltier module and the direction of temperature change as the within-subjects independent variables, and the gender as the between-subjects variable. The repeated-measures ANOVA showed that in our data, the user-defined PWM values were significantly affected by the location of the Peltier module (F(4,32) = 6.07, p < 0.005, η_p^2 = 0.431) and the direction of temperature change (F(4,32) = 6.07, p < 0.005, η_p^2 = 0.431). There is no interaction effect between the location of the Peltier module and the direction of temperature change. Fig. 4 shows the PWM values chosen by the participants for five points on the earhook, with the location P1 yielding the lowest average PWM value chosen by the participants. Post-hoc pairwise comparison showed that the PWM values for P5 was significantly higher than those for P1 (p < 0.005), P2 (p < 0.05), and P4 (p < 0.05). In addition, the PWM values for the cold stimuli were significantly higher than those for the hot stimuli (p < 0.0005), echoing with the existing research results of humans having lower thermal threshold for the heat than the cold [8]. Gender-wise, there was a significant difference between the PWM values chosen by the female and the male participants (F(1,8) = 8.39, p < 0.05, η_p^2 = 0.521. Female Average: 170.15 (SD = 45.74); Male Average: 196.77 (SD = 43.46)).

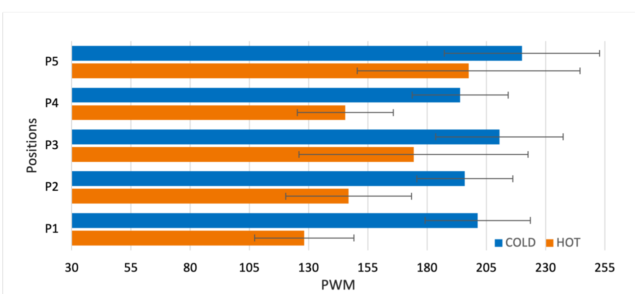

Figure 4: PWM values for Hot and Cold feedback for various positions on the earhook. The error bars indicate the standard deviations.

Based on the pilot-study results, it is reasonable to assume that different users will prefer different levels of thermal intensity for

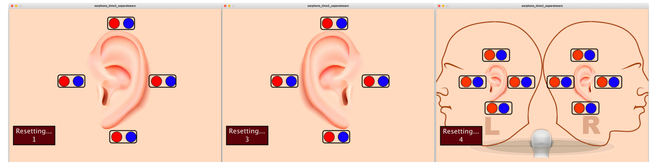

Figure 5: GUIs for the Study 1 (a) Left ear and (b) Right ear, and for Study 2, 3, & 4 (c) multi-points thermal patterns

different spots around the auricular area. This further indicates a need to allow the users to customize the thermal signals in the following experiments.

5 STUDY 1: SINGLE-POINT THERMAL PERCEPTION AROUND THE AURICULAR AREA

To investigate the spatial acuity of perceiving single-point stimuli and determine the optimal multi-point layout, We first investigate how users would perceive the single-point thermal feedback around the left and right ears.

5.1 Participants

Twelve participants participants (10 male and 2 female) aging from 23 to 30 years old (Mean = 26.5, SD = 42.42) were recruited. None of them participated in the pilot study. The average room temperature was 30.3°C. Average skin temperature around the auricular area was 33.6°C

5.2 Apparatus

We used three pairs of 3D-printed earhooks (for left and right ears) which have three configurations of three, four, and five Peltier modules respectively, as shown in Fig 2. The Arduino-based thermal control system for the earhook was connected to a Surface Pro laptop through a USB cable. We developed the Processing-based graphical user interface (GUI) as shown in Fig. 5, for triggering the stimuli and registering the participants' responses. The GUI was ran on a Microsoft Surface Pro with the touch screen.

5.3 Study Design

We designed a within-subject study with the configuration (i.e. the number) of the Peltier modules (3, 4, and 5), the side of ear (left and right) and the directions of temperature change (hot and cold) as the independent variables. The dependent variables included the accuracy and the response time of stimuli perception. Here we define the response time as the time duration between the end of the stimulus and the timestamp when the participant makes his/her choice on the touch screen. Since the GUI pops up after the 1.5s stimuli, the participant could be notified when one stimulus ends as the selection buttons show up. For each combination of the module configuration and the side of ear, the participants were instructed to choose a just noticeable yet comfortable thermal intensity by adjusting the PWM value for each of the Peltier modules before starting the experiment. The order of the module configuration and the ear side were counter-balanced using the Latin Square method, splitting into 2 ears × 3 configurations = 6 sessions, for each participant. The locations and the directions (hot/cold) of the stimuli were randomly presented within each combination of the module configuration and the side of ear. Each stimulus is repeated thrice, resulting in 2 ears (left and right) × (3+4+5) module positions × 2 directions of temperature change × 3 repetitions = 144 trials for each participant.

5.4 Procedure and Task

Each session experiment involved one participant and one experimenter at a time, and consisted of one training block and one testing block. Upon the arrival of the participant, the experimenter introduced the procedure of the experiment, collected the participant's biographical information, and demonstrated the ThermEarhook prototype. In each session, the participant was first assisted to wear the pair of ThermEarhook prototypes on both his/her ears. The thermal stimuli were then activated, starting from P1 to P3/4/5 on the same side, with the corresponding point highlighted in GUI. Each stimulus lasted for 1.5s. Meanwhile, the experimenter verbally explained the position of the stimulus and the nature of each stimulation to familiarize the participant with the stimuli. The participant could choose to repeat the current stimulus for training or move to the next one by verbally reporting to the experimenter.

After training, the participant started the testing block, where the stimuli were presented in a randomized order. The selection interface was displayed after each stimulation. The participant was also instructed to make a respective selection on the touch screen as fast as possible once he/she felt and confirmed the stimulus. The timestamp of the participant making the selection on the screen was used to calculate the response time. There was a 7s break between two consecutive stimuli. Between two experiment sessions, a temperature-resetting and resting period of 5 minutes was given to the participant. A short semi-structured interview was conducted in the end of the experiment to collect the participant's subjective comments on his/her experience of ThermEarhook. The overall experiment duration per participant was approximately one hour.

5.5 Results

5.5.1 Accuracy. The repeated-measures ANOVA (RM-ANOVA) shows that the accuracy of element identification was significantly affected by the number of Peltier modules ($F(2,22) = 81.83$, $p < 0.0005$, $\eta_p^2 = 0.882$), while there is no significant effect of the side of ear ($p = 0.817$), nor the direction of temperature change on the accuracy ($p = 0.670$). The post-hoc pairwise comparison reveals that the five-module configuration yielded significantly lower accuracy than the three- and the four-module configurations (3 vs 5: 99.1% vs 86.0%, $p < 0.0005$, 4 vs 5: 99.1% vs 86.0%, $p < 0.0005$), with no significant difference between the three- and the four-module configurations ($p = 0.923$). Fig. 6 shows the accuracy of individual stimuli identification, and Fig. 7 shows the confusion tables in different module configurations.

5.5.2 Response Time. The multi-factorial repeated measures ANOVA revealed the significant effect of the configuration on the participants' response time to the stimuli ($F(2,22) = 11.53$, $p < 0.005$, $\eta_p^2 = 0.512$). Post-hoc Boferroni test showed that the 5-modules configuration yielded significantly longer response time than the 3-modules configuration ($p < 0.005$) and the 4-modules configuration ($p < 0.05$), and there was no significant difference between the response time for the 3-modules and the 4-modules configurations. Fig. 8 illustrates the descriptive results of the response time for different temperature-change direction and configurations.

5.6 Discussion on Study 1

In general, Study 1 showed that the user performance of locating auricular thermal feedback was affected negatively by the number of the Peltier modules in the ThermEarhook prototype. This is aligned with the existing research results that the spatial acuity reduces with the reduction on the distance between two thermal stimuli [34]. While the three-modules configuration resulted in the best performance of locating the single-point thermal feedback, we decided to use the four-modules configuration, the accuracy and the response time of which have minor difference with the three-module configuration, for further study. This was mainly due to the higher expressiveness for communication with more Peltier modules. With the selection of the four-module ThermEarhook, the multi-factorial RM-ANOVA showed that there is no significant effect of the location of the thermal stimulus or the direction of the temperature change on the accuracy and the response time of identifying the feedback location.

6 DESIGNING SPATIAL THERMAL HAPTIC PATTERNS AROUND THE AURICULAR AREA

Our Study 1 confirmed that users can reliably perceive the individual thermal stimulation with the 4-modules 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 single-point thermal stimuli on the same ear and two different ears. Inspired by the existing work on designing thermal icons on wearable and handheld devices [23, 42], we considered the following dimensions for the auricular spatial thermal patterns design:

- Temperature Direction {Hot - h, Cold - c}
- Location {Front: P1 & P5, Top: P2 & P6, Back: P3 & P7, Bottom: P4 & P8}
- Grouping Strategy {Different locations around the left ear, Different locations around the right ear, Same location on two different ears} (for patterns involving two Peltier modules)
- Temporality {Simultaneous} (for patterns involving two stimuli, controlled)

The aforementioned design dimensions result in three groups of spatial thermal patterns: left-ear patterns (Fig. 9a), right-ear patterns (Fig. 9b), and two-ears patterns (Fig. 9c). Each group could be further divided into two groups: hot and cold, according to the direction of temperature change. To facilitate the data analysis, we coded the thermal pattern based on the locations of the individual stimuli and the direction of temperature change. For example, the pattern 1h2h indicates the pattern that the front and the top modules on the left side are triggered with the hot stimuli, while 5h6h indicates the similar pattern but on the right side. The pattern 1c5c indicates

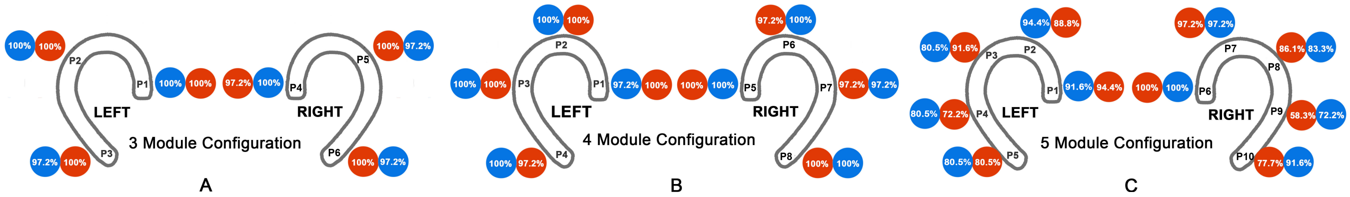

Figure 6: Accuracy for Study 1

Left

3 TEC Configuration(LEFT)	1C	2C	3C	1H	2H	3H
1C	**96.3%**			3.7%		
2C		**100.0%**				
3C			**96.3%**		3.7%	
1H				**100.0%**		
2H		6.9%			**93.1%**	
3H			3.7%			**96.3%**

4 TEC Configuration (LEFT)	1C	2C	3C	4C	1H	2H	3H	4H
1C	**87.1%**		3.2%		9.7%			
2C		**91.3%**				8.7%		
3C			**66.7%**				33.3%	
4C				**81.5%**				18.5%
1H				3.0%	**97.0%**			
2H		9.5%				**90.5%**		
3H			3.7%				**96.3%**	
4H				7.4%				**92.6%**

5 TEC Configuration(LEFT)	1C	2C	3C	4C	5C	1H	2H	3H	4H	5H
1C	**91.7%**	4.2%				4.2%				
2C		**87.5%**		4.2%			8.3%			
3C			**83.3%**	12.5%				4.2%		
4C				**80.0%**	20.0%					
5C				20.8%	66.7%			4.2%	4.2%	4.2%
1H						**87.5%**	4.2%		8.3%	
2H				4.2%			**95.8%**			
3H								**91.7%**	8.3%	
4H								4.2%	66.7%	29.2%
5H									20.8%	79.2%

Right

3 TEC Configuration(RIGHT)	1C	2C	3C	1H	2H	3H
1C	**92.6%**			7.4%		
2C	2.0%	**98.0%**				
3C		3.7%	**88.9%**			7.4%
1H				**96.3%**	3.7%	
2H					**100.0%**	
3H			3.7%			**96.3%**

(a)

4 TEC Configuration (RIGHT)	1C	2C	3C	4C	1H	2H	3H	4H
1C	**96.6%**				3.4%			
2C		**88.0%**				12.0%		
3C			**92.6%**				7.4%	
4C				**88.9%**				11.1%
1H					**100.0%**			
2H		4.2%				**95.8%**		
3H			7.4%		3.7%		**88.9%**	
4H				7.4%				**92.6%**

(b)

5 TEC Configuration(RIGHT)	1C	2C	3C	4C	5C	1H	2H	3H	4H	5H
1C	**100.0%**									
2C		**100.0%**								
3C			**83.3%**	16.7%						
4C			4.2%	62.5%	20.8%				12.5%	
5C				12.5%	75.0%	4.2%		4.2%	4.2%	
1H						**100.0%**				
2H							**100.0%**			
3H								**87.5%**	12.5%	
4H				4.3%				17.4%	47.8%	30.4%
5H									25.0%	75.0%

(c)

Figure 7: Confusion tables of Study 1: (a) 3 TEC configuration (b) 4 TEC Configuration 3: (c) 5 TEC Configuration. Rows represent stimulated pattern and columns the participants' input.

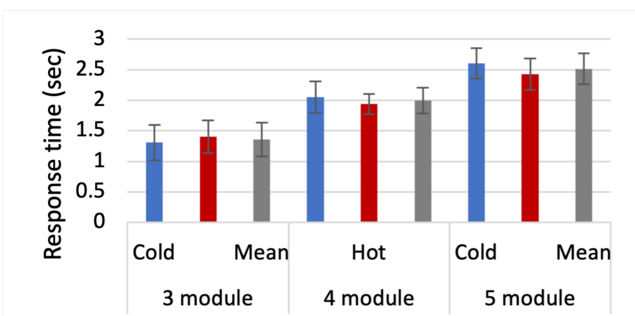

Figure 8: Response time for Study 1. The error bars indicate the standard deviations.

that the front modules on both left and right sides are triggered with the cold stimuli.

7 STUDY 2: MULTI-POINT THERMAL PATTERNS WITH ONE EAR

With the multi-spot auricular thermal patterns in Fig. 9a and b, we then conducted Study 2 to study how accurately and fast the users could recognize these spatial thermal patterns that only involve the spots around the same ear.

7.1 Participants

We recruited 12 participants (3 female and 9 male, averagely aging 25 years old) from a local university where none of the participants had previous experience with thermal haptics. The average auricular skin temperature was 32.3°C (SD = 1.8). The room temperature was controlled as 24°C.

7.2 Apparatus

Based on the design of the auricular thermal icons, we used the four-Peltier ThermEarHook prototype for the study, and used the same temperature control mechanism and hardware as those used in Study 1.

7.3 Study Design

We designed a within-subjects evaluation with the side of ear, the direction of temperature changing, and the type of pattern as the independent variables. The dependent variables were the accuracy and the response time of the stimulus. The order of the two stimuli sets (i.e. left ear, and right ear) was presented in the Latin-Square counter-balanced order, resulting in two sessions for each participant. The stimuli within each set were presented thrice in a randomized order, so there were (12 on the left ear +12 on the right ear) patterns × 3 repetitions = 72 trials for each participant. There was a 7-second gap between two consecutive cues, and a 5-minute break after one set of stimuli. Each participant went through the procedure of training and testing similar to Study 1.

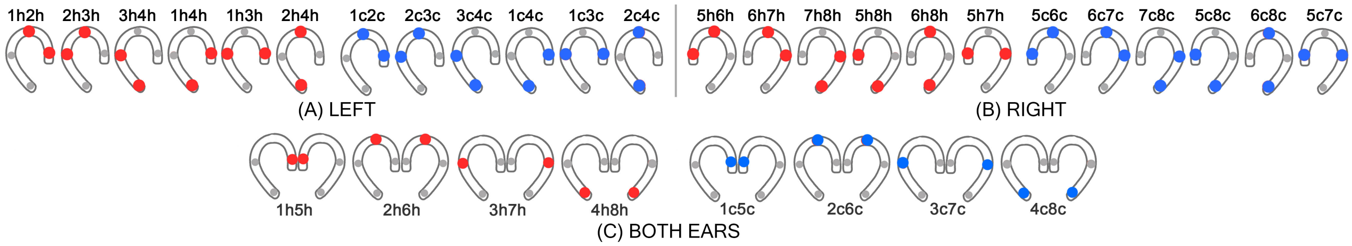

Figure 9: Thermal icons for Study 2: (a) Left ear and (b) Right ear, and Study 3: (c) Both ears. The icons in red represent the hot stimuli and the one in blue denotes cold stimuli

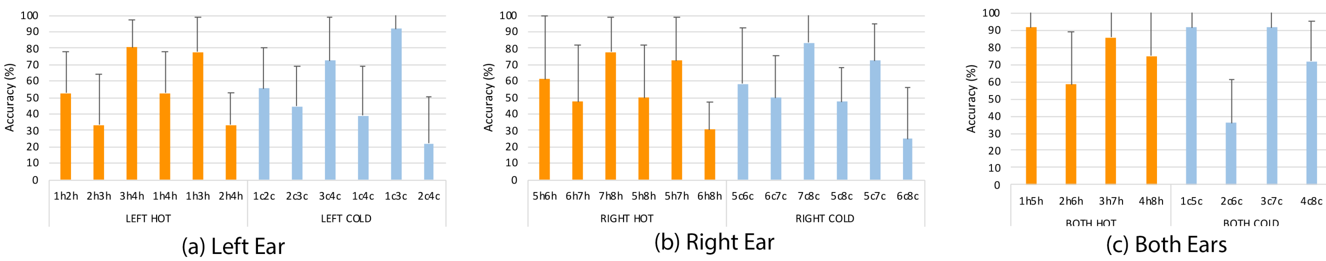

Figure 10: Descriptive results of the identification accuracy of Study 2: (a) Left ear and (b) Right ear, and Study 3: (c) Both ears.

	HOT						COLD					
	1h2h	2h3h	3h4h	1h4h	1h3h	2h4h	1c2c	2c3c	3c4c	1c4c	1c3c	2c4c
1h2h	**44.4%**	5.6%	5.6%	5.6%	27.8%	11.1%						
2h3h	8.3%	**36.1%**	22.2%	2.8%	19.4%	11.1%						
3h4h	5.6%	2.8%	**80.6%**	2.8%	2.8%	5.5%						
1h4h	2.8%		16.7%	**55.6%**	13.9%	11.1%						
1h3h	2.8%	2.8%	5.6%	5.6%	**77.8%**	5.5%						
2h4h	8.3%	22.2%	30.6%	11.1%	5.6%	**22.2%**						
1c2c							**52.8%**	2.8%		16.7%	27.8%	
2c3c	2.8%		5.6%		2.8%		5.6%	**33.3%**	22.2%		22.2%	5.6%
3c4c						2.8%		11.1%	**72.2%**	2.8%	5.6%	5.6%
1c4c		2.8%	2.8%				16.7%	2.8%	11.1%	**41.7%**	19.4%	2.8%
1c3c								2.8%	2.8%	2.8%	**91.7%**	
2c4c			5.6%		2.8%		2.8%	25.0%	38.9%	2.8%	5.6%	**16.7%**

(a) Left Ear

	HOT						COLD					
	5h6h	6h7h	7h8h	5h8h	5h7h	6h8h	5c6c	6c7c	7c8c	5c8c	5c7c	6c8c
5h6h	**52.8%**	8.3%	5.6%	8.3%	22.2%	2.8%						
6h7h	8.3%	**41.7%**	13.9%	5.6%	8.3%	22.2%						
7h8h		5.6%	**77.8%**	8.3%	8.3%							
5h8h	5.6%	2.8%	25.0%	**58.3%**	8.3%							
5h7h		5.6%	2.8%	13.9%	**72.2%**	8.3%			2.8%			
6h8h	2.8%	13.9%	33.3%	19.4%	2.8%	**25.0%**						2.8%
5c6c				2.8%			**38.9%**	5.6%	5.6%	22.2%	25.0%	
6c7c		5.6%	5.6%		2.8%		8.3%	**41.7%**	27.8%	2.8%	5.6%	
7c8c		2.8%			2.8%				**83.3%**	2.8%	2.8%	5.6%
5c8c							13.9%		5.6%	**47.2%**	30.6%	2.8%
5c7c							8.3%		2.8%	11.1%	**77.8%**	
6c8c			8.3%				2.8%	13.9%	38.9%	11.1%	5.6%	**19.4%**

(b) Right Ear

	HOT				COLD			
	1h5h	2h6h	3h7h	4h8h	1c5c	2c6c	3c7c	4c8c
1h5h	**94.4%**	2.8%			2.8%			
2h6h		**55.6%**	27.8%	2.8%		2.8%	11.1%	
3h7h		5.6%	**94.4%**					
4h8h		2.8%	16.7%	**80.6%**				
1c5c					**97.2%**	2.8%		
2c6c		5.6%	11.1%			**33.3%**	41.7%	8.3%
3c7c							**88.9%**	11.1%
4c8c		5.6%					19.4%	**75.0%**

(c) Both Ears

Figure 11: Confusion tables of Study 2: (a) Left ear and (b) Right ear, and Study 3: (c) Both ears. Rows represent stimulated pattern and columns the participants' input. The error bars indicate the standard deviations.

7.4 Results: Accuracy & Response Time

7.4.1 Accuracy. We performed a multi-factorial repeated measures ANOVA on the accuracy of recognizing the one-ear thermal patterns. The results showed that there was a significant effect of the type of pattern ($F(5,55) = 16.19$, $p < 0.0005$, $\eta_p^2 = 0.595$), but no significant effect of the ear side or the direction of temperature changing. Post-hoc pairwise comparison showed that 1h3h and 3h4h yielded significantly higher accuracy than the other hot patterns on the left side ($p <= 0.0045$), and so did 5h7h and 7h8h on the right side ($p <= 0.032$). Similar results were found in the cold stimuli, with 1c3c and 3c4c being significantly more accurate on the left side, and 5c7c and 7c8c yielding significantly higher accuracy on the right side. Fig.10a and b depict the average accuracy of stimuli identification for each pattern on the left and the right ears. Fig.11a and b show the confusion tables for the left and the right sides respectively.

7.4.2 Response Time. The overall average response time for the multi-point thermal patterns around one ear is 2.30 seconds (SD = 0.72). A repeated measures ANOVA revealed there is no significant effect of the side of ear on the participants' response time. Also, there was no significant effect of the direction of temperature change on the response time, nor the pattern type. Fig. 12 illustrates the response time for different temperature-change directions and different sides of ear.

7.5 Discussion on Study 2

We found six same-ear spatial patterns with over 70% accuracy: 1h3h, 3h4h, 1c3c, 3c4c, 5h7h, 7h8h, 5c7c, and 7c8c. All these patterns involve the back location in the ThermEarhook prototype. This could be due to the thin skin at the back around the ear leading to a high thermal sensitivity, as existing psycho-physical research shows that the thickness of the skin is negatively co-related to the thermal sensitivity [7]. In addition, half of these more accurate

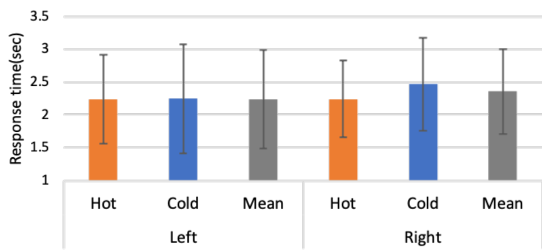

Figure 12: Response time for Study 2. The error bars indicate the standard deviations.

patterns involves the front location (i.e. 1h3h, 1c3c, 5h7h, and 5c7c). This could be because of the high thermal sensitivity of the hairy skin in this area [37]. However, as the thickness of the hairy layer increases at the top location of the ThermEarhook prototype, the thermal stimuli were mostly blocked by the hair, resulting in the lower accuracy (averagely 35.4%) for the patterns involving the stimuli in this area (i.e., 1h2h, 2h3h, 2h4h, 1c2c, 2c3c, and 2c4c on the left; 5h6h, 6h7h, 6h8h, 5c6c, 6c7c, and 6c8c on the right).

8 STUDY 3: MULTI-POINT THERMAL PATTERNS WITH BOTH EARS

Besides the spatial thermal patterns around one ear only, it is also possible to design the patterns by combining the spots on both ears. To this end, we conducted the third study to investigate how accurately and fast users may recognize the two-ears spatial thermal patterns as shown in Fig.9c.

8.1 Participants

We recruited 12 participants (6 female and 6 male, averagely aging 25.2 years old) from a local university where none of the participants had previous experience with thermal haptics. The average skin temperature was 32.4°C (SD = 1.2). The room temperature was controlled as 25°C.

8.2 Apparatus

We used the same apparatus as those used in Study 2.

8.3 Study Design and Procedure

Similar to Study 2, we designed a within-subjects study, taking the direction of temperature change and the type of pattern as the independent variables, and the recognition accuracy and the response time as the dependent variables. For each participant, the order of the both-ears thermal patterns was randomized, and each pattern was repeated thrice. There was 4 patterns × 2 directions of temperature change × 3 repetitions = 24 trials for each participant. In addition, each participant went through the similar procedure of training and testing as the ones in Study 2.

8.4 Results: Accuracy & Response Time

A multi-factorial repeated measures ANOVA showed that there was a significant effect of the type of pattern ($F(3,33) = 13.28$, $p < 0.005$, $\eta_p^2 = 0.547$), but no significant effect of the direction of temperature changing. Post-hoc pairwise comparison showed that within the hot stimuli, 2h6h yielded significantly lower accuracy (55.6%) than the other three hot stimuli (i.e. 1h5h: 94.4%, 3h7h: 94.4%, 4h8h: 80.6%. $p <= 0.0023$). Similar results were found in the cold stimuli, with 2c6c resulting in significantly lower accuracy (33.3%) than the others (i.e. 1c5c: 97.2%, 3c7c: 88.9%, 4c8c: 75.0%. $p <= 0.00042$). For the response time, there is no significant effect of the type of pattern or the direction of temperature change, with an overall average value of 2.6 seconds (SD = 0.71).

8.5 Discussion on Study 3

We observed a similar trend of user performance in Study 3 as the one in Study 2. The two-ears patterns with the front locations (with thin hair) and the back locations (with thin skin) yielded higher accuracy than the rest of the patterns did. These results echo with the existing psychophysical studies on the thermal sensitivity of human beings as mentioned in Section 7.5.

According to the results of Study 2 and 3, we selected in total fourteen spatial thermal patterns as shown in Fig. 13, as the set of spatial thermal icons for ThermEarhook. The average accuracy for the users recognizing the chosen one-ear multi-points thermal patterns was 80.2%, and 88.4% for the two-ears patterns. Overall, the two-ears patterns are more accurate than the one-ear ones, as the increased distance between the two individual stimuli for the two-ears patterns improve the spatial acuity for thermal perception [34].

9 STUDY 4: EVALUATING THE CHOSEN SET OF SPATIAL THERMAL PATTERNS

While Study 2 and 3 found a set of hot and cold thermal patterns/icons with considerable identification accuracy, they are tested in separated sessions. It is still unknown how accurate humans can perceive them when testing them all together. In Study 4, we tested these two-point simultaneous thermal patterns together, to investigate the feasibility of using them together as a set of thermal icons.

9.1 Participants

We recruited another 12 university students who didn't have any prior experience with thermal haptics (4 female and 8 male, averagely aging 26.7 years old). The average skin temperature was 32.2°C (SD = 1.5).The ambient indoor temperature was controlled to be 25°C.

9.2 Apparatus

We used the same apparatus as those used in Study 2 and 3.

9.3 Study Design

We designed a within-subjects evaluation with the direction of thermal change and the pair of spots involved in the spatial thermal patterns as the independent variables. The dependent variables were the accuracy and the response time of users perceiving the thermal patterns. All the patterns were repeated thrice and presented in a randomized order, resulting in 7 pairs of spots × 2 directions of temperature change × 3 repetitions = 42 trials for each participant.

There was a 7-second gap between two consecutive cues. Each participant went through the similar procedure of training and testing as the ones in Study 2 and 3.

9.4 Results: Accuracy & Response Time

9.4.1 Accuracy. The repeated-measured ANOVA (RM-ANOVA) shows that the accuracy of thermal pattern identification was significantly affected by the pair of spots involved in the pattern (F(6,66) = 7.75, $p < 0.0005$, $\eta_p^2 = 0.413$), but not the direction of temperature change. The post-hoc pair-wise comparison reveals that the patterns involving the front spots around both ears were perceived significantly more accurately than the others ($p < 0.05$). The patterns with the back spots and the bottom spots of both ears yielded significantly lower accuracy than the others ($p < 0.05$).

Considering the patterns that involve the spots around the same ear, we perform the repeated-measured ANOVA with the side of ear, the pair of spots, and the direction of temperature change as the independent variables. The results show that the perception accuracy was not significantly affected by any of these factors. Fig 14 shows the average accuracy of the thermal pattern identification in Study 4, and Fig. 15 depicts the confusion table.

9.4.2 Response Time. Similar to previous studies, our analysis with a multi-factorial repeated measures ANOVA showed no significant effect of the type of pattern or the direction of temperature change on the response time, with the average value of 2.3 seconds (SD = 0.72). Fig. 16 illustrates the descriptive results of the response time in Study 4.

9.5 Discussion on Study 4

The set of fourteen spatial thermal patterns achieved an average accuracy of 85.3% in overall. The lowest accuracy was found for the pattern 4h8h, 63.8%, and its cold counterpart, 4c8c, also yielded a relatively low accuracy of 75.0% . Both of these patterns involve the the area below the ear, which may have thicker skin and less hair than the other around-ear areas, leading to a lower therm sensitivity as shown in Study 2 & 3. Different from these previous studies in which the area behind the ear yielded a high accuracy, the patterns with two stimuli behind the ear, 3h7h and 3c7c, resulted in relatively lower accuracy (3h7h: 77.8%, and 3c7c: 72.2%). Although both accuracy are above 70%, there is a large drop from their accuracy in Study 3. We suspect that this could be because there were more confusion options against these two patterns in Study 4, where as in Study 3 3h7h and 3c7c were the only patterns with the area behind the ear. Excluding the four aforementioned patterns with lower accuracy, the remaining 10 patterns achieved an average accuracy of 90.6%

10 USER-PROPOSED APPLICATIONS OF THERMEARHOOK

The participants during the post-study interview proposed a wide range of prospective areas where the ThermEarhook could be used. Two participants who had experience in using VR games stated that the ThermEarhook could be used along with VR headset for an immersive experience. One participant said, " It would be nice to feel the heat from an bomb blast or the cold feeling of the water splashing during a VR game". Another participant said " I could feel an enemy approaching me from the back with the help of the thermal pattern on the back of the earhook". Thermal haptic has been already explored in the domain of virtual reality for enhancing the experience of the user in the virtual environment,game play, movie watching,etc[4, 27]

During our subjective feedback interview, 2 of our participants preferred using single point thermal haptic feedback for a variety of mobile notifications which includes incoming messages and calls. One of them said "I could use this in a meeting room or in a movie theater to let me know if someone important is calling without others letting know about the call". Thermal feedback being a discrete modality could be used as a substitute for vibrohaptic feedback to be used as mobile notifications[26, 42].

Thermal sense plays a significant role in the human recognition of environments and influences human emotions. To support this, one participant said " I feel that I am in danger when some hot feedback suddenly strikes". Another participant reported that " I could use mild hot and cold feedback for a therapeutic effect which could help me relax or with my sleep". ThermEarhook could be used to create a new emotional compatibility by combining auditory and thermal senses with its enhanced multipoint thermal feedback patterns.

Two of the participants reported that they could use this while cycling which can help them in navigation without looking at the screen or relying on the audio feedback from the google maps. Researchers have already used thermal feedback[23, 26, 28, 35, 42] for navigation. Hence, ThermEarhook could also have a potential application as it relatively keeps the users' hands free.

11 LIMITATIONS AND FUTURE WORKS

We identified few limitation with the studies conducted with the ThermEarhook. Firstly, gender balance wasn't maintained over the entire studies conducted with the the ThermEarhook. Hence, it is still unclear that if there is a significant effect of the accuracy and response time when using the ThermEarhook patterns with respect to the gender. It may also be likely that the ThermEarhook accuracy may vary in a different environment with a different weather/temperature conditions. The results may also vary if tested with people from different continents/regions as the research shows that the temperature perception varies from people to people across various regions.

Second, while we studied the spatial thermal patterns with 4 module configurations, only 3 points (i.e., front, top, and back) were usable with higher accuracy. This could be due to the thicker skin or due to the hair present in those areas. However, this would not be the same as directly using the layout with three modules in Fig. 1. Our studies showed that the patterns involving the top module in the four-module layout led to low perception accuracy because of the thick hair, and the top module in the three-modules layout also lies around the thick hairy area. Therefore, it is reasonable to assume that the top module in the three-modules layout would result in low accuracy for identifying the multi-point thermal patterns with ThermEarhook.

Third, though the participants have proposed several potential applications with the ThermEarhook, we haven't tested any of the

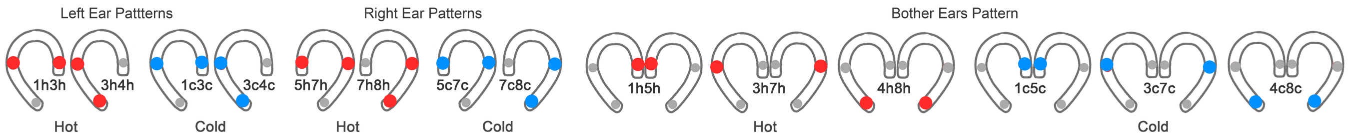

Figure 13: Selected spatial thermal icons (red: hot, blue: cold).

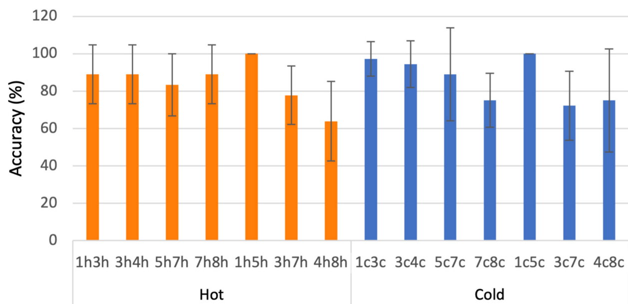

Figure 14: Accuracy of Study 4.

	1h3h	3h4h	5h7h	7h8h	1h5h	3h7h	4h8h	1c3c	3c4c	5c7c	7c8c	1c5c	3c7c	4c8c
1h3h	86.1%	11.1%				2.8%								
3h4h	2.8%	88.9%				2.8%	5.6%							
5h7h			80.6%	5.6%	5.6%	8.3%								
7h8h			5.6%	88.9%		2.8%	2.8%							
1h5h	5.6%				94.4%									
3h7h		8.3%		2.8%		77.8%	8.3%				2.8%			
4h8h		8.3%		13.9%	5.6%	8.3%	63.9%							
1c3c								97.2%	2.8%					
3c4c								2.8%	94.4%			2.8%		
5c7c										88.9%		2.8%	8.3%	
7c8c										13.9%	75.0%		5.6%	5.6%
1c5c												100.0%		
3c7c				2.8%					8.3%	2.8%	2.8%		72.2%	11.1%
4c8c									2.8%	2.8%	2.8%		13.9%	75.0%

Figure 15: Confusion table for Study 4

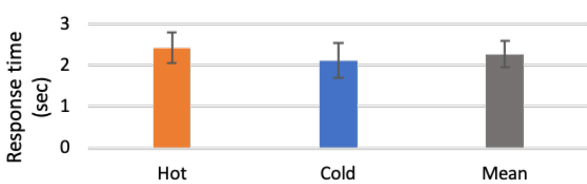

Figure 16: Response time for Study 4. The error bars indicate the standard deviations.

practicality. The results may vary when the system is tested in a real-world environment. In the future, we will integrate ThermEarhook in the real-world application and evaluate the effectiveness of around-ear thermal icons.

12 CONCLUSION

In this paper, we present ThermEarhook, an earable device with multiple (i.e. 3, 4, and 5) thermohaptic modules around the auricular skin area. Our pilot study showed that the thermal threshold varied across different points on the ThermEarhook prototype and across different people, motivating us to adopting the strategy of user customizing the thermal intensity in the following studies. Our first user study suggested the usage of the ThermEarhook prototype with four thermohaptic modules on each side of ear, considering its spatial accuracy of thermal feedback and user preference, for designing the multi-points spatial thermal patterns around the auricular areas. The following three user studies revealed a set of multi-points auricular thermal icons, including the patterns around one ear only and two ears, with an average accuracy of 85.3%. We also received various types of ThermEarhook application proposed by the participants, including gaming, music, navigation, therapeutics, and so on. Taking ThermEarhook as an important step, we aim to investigate future design of multimodal earable devices.

ACKNOWLEDGMENTS

This research was partially supported by the National Natural Science Foundation of China (Project No. 61907037 & 62172346), the Guangdong Basic and Applied Basic Research Foundation (Project No. 2021A1515011893), the Applied Research Grant (Project No. 9667189), and ACIM, School of Creative Media, City University of Hong Kong.

REFERENCES

[1] 2021. From the wrist into the ear – the potential of hearables. https://tectales.com/wearables-sensors/from-the-wrist-into-the-ear-the-potential-of-hearables.html
[2] Shimon Akiyama, Katsunari Sato, Yasutoshi Makino, and Takashi Maeno. 2013. ThermOn: thermo-musical interface for an enhanced emotional experience. In *Proceedings of the 2013 international symposium on wearable computers*. 45–52.
[3] Kanako Aou, Asuka Ishii, Masahiro Furukawa, Shogo Fukushima, and Hiroyuki Kajimoto. 2010. The enhancement of hearing using a combination of sound and skin sensation to the pinna. In *Adjunct proceedings of the 23nd annual ACM symposium on User interface software and technology*. 415–416.
[4] Faisal Arafsha, Kazi Masudul Alam, and Abdulmotaleb El Saddik. 2012. EmoJacket: Consumer centric wearable affective jacket to enhance emotional immersion. In *2012 international conference on innovations in information technology (IIT)*. IEEE, 350–355.
[5] Balata, Jan and Macik, Miroslav and Mikovec, Zdenek. 2014. Heat Map Thermal Display for Visually Impaired. https://www.researchgate.net/publication/264509264_Heat_Map_Thermal_Display_for_Visually_Impaired. CHI 2014 - Assistive Augmentation Workshop. Online; accessed 17-09-2019.
[6] JOSEPH C. STEVENS KENNETH K. CHOO. 1998. Temperature sensitivity of the body surface over the life span. *Somatosensory & motor research* 15, 1 (1998), 13–28.
[7] M Pirtini Çetingül and C Herman. 2010. A heat transfer model of skin tissue for the detection of lesions: sensitivity analysis. *Physics in Medicine & Biology* 55, 19 (2010), 5933.
[8] D Claus, MJ Hilz, I Hummer, and B Neundörfer. 1987. Methods of measurement of thermal thresholds. *Acta neurologica scandinavica* 76, 4 (1987), 288–296.
[9] Patrizia Di Campli San Vito, Stephen Brewster, Frank Pollick, Stuart White, Lee Skrypchuk, and Alexander Mouzakitis. 2018. Investigation of Thermal Stimuli for Lane Changes. In *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Toronto,

ON, Canada) *(AutomotiveUI '18)*. ACM, New York, NY, USA, 43–52. https://doi.org/10.1145/3239060.3239062

[10] Patrizia Di Campli San Vito, Gözel Shakeri, Stephen Brewster, Frank Pollick, Edward Brown, Lee Skrypchuk, and Alexandros Mouzakitis. 2019. Haptic Navigation Cues on the Steering Wheel. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 210.

[11] Nem Khan Dim and Xiangshi Ren. 2017. Investigation of suitable body parts for wearable vibration feedback in walking navigation. *International Journal of Human-Computer Studies* 97 (2017), 34–44.

[12] MA Farage, KW Miller, AM Wippel, E Berardesca, L Misery, and H Maibach. 2013. Sensitive skin in the United States: survey of regional differences. *Family Med Medical Sci Res* 2, 112 (2013), 2.

[13] Martin Halvey, Graham Wilson, Stephen Brewster, and Stephen Hughes. 2012. Baby it's cold outside: the influence of ambient temperature and humidity on thermal feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 715–724.

[14] Martin Halvey, Graham Wilson, Yolanda Vazquez-Alvarez, Stephen A Brewster, and Stephen A Hughes. 2011. The effect of clothing on thermal feedback perception. In *Proceedings of the 13th international conference on multimodal interfaces*. ACM, 217–220.

[15] Eve Hoggan, Andrew Crossan, Stephen A Brewster, and Topi Kaaresoja. 2009. Audio or tactile feedback: which modality when?. In *Proceedings of the SIGCHI conference on human factors in computing systems*. 2253–2256.

[16] Da-Yuan Huang, Teddy Seyed, Linjun Li, Jun Gong, Zhihao Yao, Yuchen Jiao, Xiang'Anthony' Chen, and Xing-Dong Yang. 2018. Orecchio: Extending body-language through actuated static and dynamic auricular postures. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. 697–710.

[17] Lynette A Jones and Michal Berris. 2002. The psychophysics of temperature perception and thermal-interface design. In *Proceedings 10th symposium on haptic interfaces for virtual environment and teleoperator systems. HAPTICS 2002*. IEEE, 137–142.

[18] Maria Karam, Carmen Branje, Gabe Nespoli, Norma Thompson, Frank A Russo, and Deborah I Fels. 2010. The emoti-chair: an interactive tactile music exhibit. In *CHI'10 Extended Abstracts on Human Factors in Computing Systems*. 3069–3074.

[19] Dagmar Kern, Paul Marshall, Eva Hornecker, Yvonne Rogers, and Albrecht Schmidt. 2009. Enhancing navigation information with tactile output embedded into the steering wheel. In *International Conference on Pervasive Computing*. Springer, 42–58.

[20] Minkyeong Lee, Seungwoo Je, Woojin Lee, Daniel Ashbrook, and Andrea Bianchi. 2019. Activearring: Spatiotemporal haptic cues on the ears. *IEEE transactions on haptics* 12, 4 (2019), 554–562.

[21] Maohui Luo, Zhe Wang, Hui Zhang, Edward Arens, Davide Filingeri, Ling Jin, Ali Ghahramani, Wenhua Chen, Yingdong He, and Binghui Si. 2020. High-density thermal sensitivity maps of the human body. *Building and environment* 167 (2020), 106435.

[22] Anita Meier, Denys JC Matthies, Bodo Urban, and Reto Wettach. 2015. Exploring vibrotactile feedback on the body and foot for the purpose of pedestrian navigation. In *Proceedings of the 2nd international Workshop on Sensor-based Activity Recognition and Interaction*. 1–11.

[23] Arshad Nasser, Kai-Ning Keng, and Kening Zhu. 2020. Thermalcane: Exploring thermotactile directional cues on cane-grip for non-visual navigation. In *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility*. 1–12.

[24] Arshad Nasser, Kening Zhu, and Sarah Wiseman. 2019. Thermo-haptic Earable Display for the People with Hearing and Visual Impairment. In *Proceedings of ACM ASSETS'19*. ACM.

[25] Roshan Lalintha Peiris, Liwei Chan, and Kouta Minamizawa. 2016. Thermocons: Evaluating the thermal haptic perception of the forehead. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 187–188.

[26] Roshan Lalitha Peiris, Yuan-Ling Feng, Liwei Chan, and Kouta Minamizawa. 2019. ThermalBracelet: Exploring Thermal Haptic Feedback Around the Wrist. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 170.

[27] Roshan Lalintha Peiris, Wei Peng, Zikun Chen, Liwei Chan, and Kouta Minamizawa. 2017. Thermovr: Exploring integrated thermal haptic feedback with head mounted displays. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 5452–5456.

[28] Roshan Lalintha Peiris, Wei Peng, Zikun Chen, and Kouta Minamizawa. 2017. Exploration of cuing methods for localization of spatial cues using thermal haptic feedback on the forehead. In *2017 IEEE World Haptics Conference (WHC)*. IEEE, 400–405.

[29] Ioannis Politis, Stephen Brewster, and Frank Pollick. 2013. Evaluating multimodal driver displays of varying urgency. In *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. ACM, 92–99.

[30] Ioannis Politis, Stephen A Brewster, and Frank Pollick. 2014. Evaluating multimodal driver displays under varying situational urgency. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*. ACM, 4067–4076.

[31] Yael Salzer, Tal Oron-Gilad, and Adi Ronen. 2010. Vibrotactor-belt on the thigh–directions in the vertical plane. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 359–364.

[32] Kenichiro Shirota, Roshan Lalintha Peiris, and Kouta Minamizawa. 2019. Altered Pinna: Exploring Shape Change of Pinna for Perception and Illusion of Sound Direction Change. In *Proceedings of the 23rd International Symposium on Wearable Computers* (London, United Kingdom) *(ISWC '19)*. Association for Computing Machinery, New York, NY, USA, 220–224. https://doi.org/10.1145/3341163.3347725

[33] Anshul Singhal and Lynette A Jones. 2018. Creating Thermal Icons: A Model-Based Approach. *ACM Transactions on Applied Perception (TAP)* 15, 2 (2018), 14.

[34] Joseph C Stevens. 1989. Temperature and the two-point threshold. *Somatosensory & motor research* 6, 3 (1989), 275–284.

[35] Jordan Tewell, Jon Bird, and George R Buchanan. 2017. Heat-nav: Using temperature changes as navigation cues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 1131–1135.

[36] Jordan Tewell, Jon Bird, and George R Buchanan. 2017. Heat-nav: Using temperature changes as navigation cues. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 1131–1135.

[37] RD Treede, RA Meyer, Srinivasa Naga Raja, and James N Campbell. 1995. Evidence for two different heat transduction mechanisms in nociceptive primary afferents innervating monkey skin. *The Journal of physiology* 483, 3 (1995), 747–758.

[38] Jan BF Van Erp and Hendrik AHC Van Veen. 2004. Vibrotactile in-vehicle navigation system. *Transportation Research Part F: Traffic Psychology and Behaviour* 7, 4-5 (2004), 247–256.

[39] Graham Wilson, Stephen Brewster, Martin Halvey, and Stephen Hughes. 2012. Thermal icons: evaluating structured thermal feedback for mobile interaction. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*. ACM, 309–312.

[40] Graham Wilson, Stephen Brewster, Martin Halvey, and Stephen Hughes. 2013. Thermal feedback identification in a mobile environment. In *International Workshop on Haptic and Audio Interaction Design*. Springer, 10–19.

[41] Graham Wilson, Martin Halvey, Stephen A Brewster, and Stephen A Hughes. 2011. Some like it hot: thermal feedback for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2555–2564.

[42] Kening Zhu, Simon Perrault, Taizhou Chen, Shaoyu Cai, and Roshan Lalintha Peiris. 2019. A sense of ice and fire: Exploring thermal feedback with multiple thermoelectric-cooling elements on a smart ring. *International Journal of Human-Computer Studies* 130 (2019), 234–247.