ActivEarring: Spatiotemporal Haptic Cues on the Ears

Minkyeong Lee, *Student Member, IEEE,* Seungwoo Je, Woojin Lee, Daniel Ashbrook and Andrea Bianchi

Abstract—The symmetric configuration and the sensitivity of ears in addition to the long tradition of earrings as adornment open up the possibility for smart ear-worn devices. Taking advantage of these attributes, past research mostly focused on creating novel unobtrusive sensing input devices and auditory displays placed on the ear. Meanwhile, the tactile sensitivity of the ear has long been overshadowed by its auditory capacity, presenting the opportunity to investigate how ears can be exploited for unobtrusive tactile information transfer. With three studies and a total of 38 participants, we suggest the design of ActivEarring, a ear-worn device capable of imparting information by stimulating six different locations on both ears. We evaluated the performance of ActivEarring in a semi-realistic mobile condition and its practical use for information transfer with spatiotemporal patterns. Finally, we demonstrate that ActivEarring can be incorporated in common jewelry design, and present three applications that illustrate promising usage scenarios.

Index Terms—Ear, haptics, wearable, digital jewelry, spatiotemporal patterns, smart earring.

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1 INTRODUCTION

THE emergence of augmented and virtual reality has brought about a proliferation of head-worn devices that communicate information to the wearer. While many head-mounted displays have been developed, they largely utilize visual and audio channels for communication, leaving the tactile modality under-explored. At the same time, a smaller, more-subtle form-factor is desirable. In this context, the ears attract our attention as a potential location for tactile output. Their symmetric location on the head suggest a possibility for communicating spatially arranged haptic cues; presenting such stimuli on symmetrically arranged areas may lessen the cognitive load necessary for interpretation [1], [2]. Dim and Ren identified the ear as a highly promising location for vibrotactile stimuli in various situations [3], and Sinclair et al. showed that the auricle—the portion of the ear external to the body—demonstrates sensitivity similar to the fingers [4]. This natural sensitivity of the ear suggests that it can offer a communication channel that, while lower in bandwidth than the auditory channel, is also more subtle and potentially less distracting to the wearer.

The ear also has a number of natural advantages from a social standpoint. It is very common to augment the auricle with small objects due to the ancient tradition of ornamenting the ear with earrings and other jewelry. Meanwhile, some research has been conducted on digital jewelry [5] which emphasizes social, emotional, and aesthetic needs in addition to functional requirements. Haptics have been added to other wearable ornaments such as smart watches [6], [7], [8], [9] and rings [10], [11], [12], [13], while little attention has been paid to the potential of haptic feedback on earrings [14].

Our goal with the research presented in this paper is to understand the human perception of tactile stimuli presented on the ears, and based on these findings develop and test the prototype of a ear-worn haptic display, named *ActivEarring*. We then aim to test the feasibility of using such prototypes for haptic information transfer in semi-realistic conditions involving walking on a treadmill. The paper presents specifically four contributions to the field of HCI. First, we investigated the human perception of tactile cues of various frequencies at several locations on the ears and suggest the preferable frequency of the stimuli. Second, we explore how multiple stimuli are perceived depending on their relative positions and temporal variations. Third, we designed and evaluated spatiotemporal patterns representing letters, numbers, and icons, and propose design guidelines for information transfer based on the evaluation results. Finally, we present a practical form factor for haptic earrings and discuss several applications that showcase potential use scenarios.

2 RELATED WORK

2.1 Non-auditory ear interfaces

While the most popular ear-worn device is the earphone, many researchers have also explored soundless wearable interfaces. Some have exploited the form of conventional earphones by making them touch-sensitive [15] or enabling them to detect facial movement [16], [17] or ear deformation [18]. Lissermann et al., on the other hand, utilized a different form factor that can be worn behind the ear [19]; they placed a series of touch-sensitive conductors on the back of the ear, claiming that natural body landmarks enable intuitive and easy input [20]. A health-tracking wearable in the form of an earring has been commercialized [21], but lacks the output functionality.

Output devices designed for the ear are relatively uncommon. Kojima et al. [22] made use of the viscoelastic

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characteristics of human ears to convey navigational information, by pulling gently on the ears to indicate a particular direction. Huang et al. utilized a similar technique to deform the ears, but with a focus on observer perception of ear movement [23]. The goal of our research is to communicate more than simple directional information to the wearer of the device with a simple form factor.

2.2 Near-ear haptic modalities

While little research has been conducted on ear-worn haptic interfaces, there are multiple examples of haptic interfaces for the head and face. For example, some researchers have added vibration motors to VR headsets to give navigational cues in 3D space [24], [25], or have used air flow to communicate information [26]. Some researchers have augmented glasses for haptic feedback. Rantala et al. augmented glasses with vibration motors to give haptic feedback in connection with gaze gestures [27], and others have added thermal stimulation to glasses [28], [29]. Gil et al. investigated ultrasonic cues on the face, but avoided the ears to prevent potential hearing damage [30]. In contrast to these approaches, our compact haptic earrings, are able to communicate more information more quickly than air- and thermal-based approaches, and do not present the risk of damaging hearing as the ultrasonic approaches.

3 DESIGNING ACTIVEARRING

To understand the requirements and opportunities around feedback mechanisms for haptic earrings, we decided to compare the technical feasibility of different ear-mounted transducers through empirical vibration measurements and a pilot study with three participants.

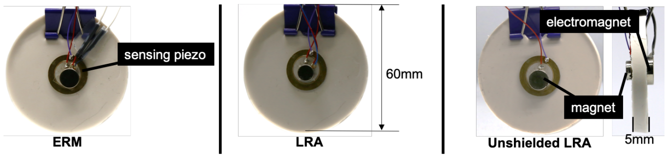

Fig. 1. The measurement setup of each transducer.

We considered two types of conventional vibration motors—a linear resonant actuator (LRA, C08-001, ⌀8×3.5mm) and an eccentric rotating mass (ERM, MSD0827, ⌀10×2.7mm) motor—and a custom-made unshielded LRA system. The unshielded LRA system consists of an electromagnet (⌀15×5mm, 6V, 0.04A) and a neodymium magnet (⌀10×3mm) like a conventional LRA, while using an auricle as a spring. We connected each transducer to an audio amplifier (PAM8302A) connected to a function generator (Siglent SDG805) and a DC power supply. To avoid making audible sounds that might irritate users, we tested actuation of the three transducers at 15 and 30 Hz, frequencies under the lower threshold of human hearing (16–32 Hz [31]). We stimulated the transducers with square waves ($V_{pp} = 3V$, duty cycle = 50%, offset = 1.5V) using the function generator.

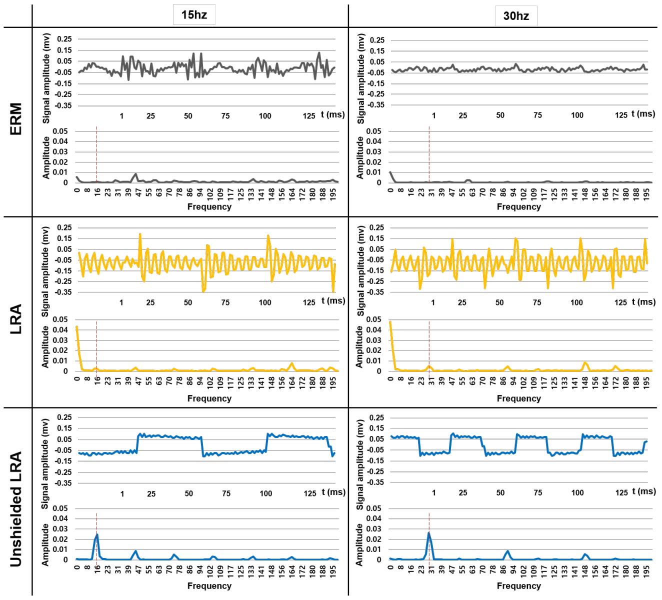

Fig. 2. The measured amplitude of each transducer regarding the time and frequency.

To measure the vibration properties of the transducers, we placed a piezoelectric element in the center of a 5 mm-thick silicon pad (EcoFlex 0020) simulating an auricle. It was linked to an oscilloscope (Rigol DS1052E) to record the vibration of each transducer. We placed the permanent magnet and electromagnet on opposite sides of the pad with the permanent magnet resting on the piezoelectric disc, while we used double-sided tape to affix the ERM and LRA to the disc. Figure 1 shows the setup for each transducer and frequency.

Our pilot setup was similar to the measurement setup, but with the transducers connected to the ear of the participants (one male, two female, ages 21–37). As the anatomical structure of the ear is not uniform, we exploited two planar parts of the ear with different structures—the lobule (earlobe, tender without cartilage), and the superior crus (upper part of the outer ear, firm with cartilage)—as they might affect the actuation sensation.

Interestingly, participants perceived buzzing sounds generated by the LRA and ERM due to their mechanical structures regardless of the actuation frequency and location. Our measurements support this finding by revealing unintended high-frequency vibrations with short bursts (Figure 2). These vibrations hinder the delivery of the pulsing sensation at the desired frequencies, instead conveying a feeling of continuous vibration. The ERM could not correctly generate pulses at 30 Hz as the minimum activation time for the motor is 40 ms; a figure larger than 33ms is required for a single activation cycle. On the other hand, the unshielded LRA transmitted pulses at low frequencies, minimizing audible sound (participants reported either not hearing the sound or that it was not distracting), and imparting the intended pulsing sensation. The displacement of the unshielded LRA is 7 micron at 15 Hz and 10 micron at 30 Hz. The acceleration time of the unshielded LRA is 1 ms and the average duration is 32.71 ms (SD: 0.76 ms) at 15 Hz and 15.8 ms (SD: 1.09 ms) at 30 Hz. For these reasons, we decided to use the unshielded LRA as the transducer for the rest of our research.

Using these findings, we developed ActivEarring—a haptic earring made of an electromagnet, a neodymium magnet, and a case 3D-printed with flexible PolyLactic Acid filament (Figure 3a). To control ActivEarring, we used an external board with three motor drivers (L293B) controlled by an Arduino Mega that communicates with a touchscreen PC (Microsoft Surface 2) via USB. The prototype works with 6V, supplied by an external power supply.

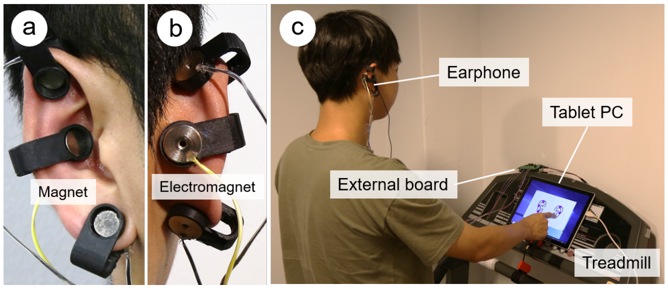

Fig. 3. Setup for studies. a) ActivEarring front view, b) back view, c) study setup.

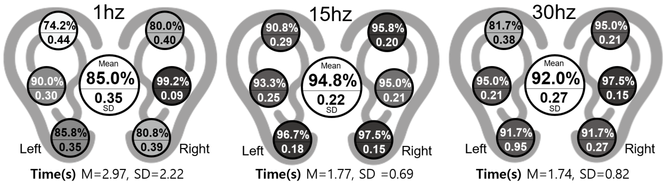

Fig. 4. The mean accuracy of each location, across locations, and the response time for each frequency. a) 1 Hz, b) 15 Hz, and c) 30 Hz.

4 SINGLE STIMULUS ON EARS: PREFERABLE FREQUENCY AND LOCATION

Although there is some work discussing the sensitivity of the skin on the ears [3], [4], no research has presented the properties for a suitable haptic stimulus delivered on the ear. In this study we aimed to understand the ears' capability to perceive tactile stimuli at different frequencies on different locations on the auricle. We added 1 Hz to emulate a single tap in addition to the 15 and 30 Hz that we tested in the preliminary study. Thus, the duration of the stimuli were 16 ms for 30 Hz, 33 ms for 15 Hz and 50 ms for 1 Hz, followed by a fixed pause of 666 ms plus the time needed for the user's input.

Then, we placed the stimuli on three vertical points—Superior curs, Concha, and Lobule—on each ear as illustrated in Figure 3a, regarding the mean height of ears ($M = 59.6$ [32]) and the size of ActivEarring (⌀17mm including the case). Specifically, the Concha was chosen as the central position since the shape of the antihelix substantially varies across participants and does not provide a planar surface for firmly attaching the earring. To validate these locations, we empirically tested the ActivEarring at frequencies lower than 30 Hz, while users wore earphones. No user reported audible sound leakage in any of the locations. We tested a total of 18 conditions (3 frequencies × 6 locations); to be as ecologically valid as possible, we ran the test solely with participants walking.

We recruited 12 participants (6 male, 6 female) from our institution, aged 22–32 ($M = 25.58$, $SD = 2.64$). The mean height of participant ears was 66.37 mm ($SD = 3.33$), and the mean width was 34.27 mm ($SD = 2.97$). All participants independently performed a pure tone audiometer test as a part of regular medical check-up required by our institute and self-reported as having normal hearing capabilities. Eight participants reported having experience with wearing earrings or piercings, while ten participants had tried wearable haptic devices before participating in the study. We compensated participants with $9 USD in local currency for their participation.

The study was conducted in a temperature-controlled room (23C) using a Health Park HP-6000 treadmill with the speed set at 2.7 km/h like previous walking-based studies [10]. After initial debriefing, we equipped each participant with ActivEarrings and headphones playing white noise to limit auditory distraction. Then, 14 sets of 18 conditions were presented in random order (within each set) to the participants while they walked. Participants were asked to state the location of each given stimulus via a touch-sensitive graphical interface on the PC while each stimulus lasted until they responded (Figure 3 c). The first four sets are treated as training and removed from the analysis. During the training period, we informed participants if their response was correct or not via beeping sounds. With this method, we collected 2,160 data points for response time and errors. A brief interview about the experience and participants' preferences followed the main experiment. Each study took approximately 45 minutes.

4.1 Results and Discussion

We conducted a two-way ANOVA test with posthoc analyses with Bonferroni corrections regarding the accuracy, finding an interaction effect between the frequency and location ($F(7.12, 847.23) = 5.32, p < 0.001, \eta_p^2 = 0.043$). Subsequently, we performed one-way ANOVA tests for each location and frequency. We adopt the Greenhouse-Geisser value when the Mauchly's sphericity value is smaller than 0.05. The 1 Hz stimulus required notably longer time than other frequencies ($p < 0.05$) as in Figure 4. Concerning accuracy, 15 Hz stimuli render no significant difference between transducer locations, while there are statistically significant differences for 1 Hz ($F(3.78, 449.23) = 14.76, p < 0.001$) and 30 Hz stimuli ($F(2.73, 324.81) = 9.94, p < 0.001$). The analyses regarding locations reveal that 15 Hz stimuli yielded distinctly higher accuracy than 1 Hz and 30 Hz on the top and bottom locations on both ears ($p < 0.02$). No significant difference between frequencies exists on central locations; the accuracy on central locations was equally high ($> 90\%$) as shown in Figure 4.

These results illustrate that 15 Hz stimuli render consistently high accuracy on all the six locations, while other frequencies do not. 1 and 30 Hz stimuli render lower accuracy on the top and bottom locations, yielding the accuracy as high as the 15 Hz stimuli only on the central locations. WE conclude that a 15 Hz stimulus enables the use of all the six locations, leaving larger space for more complex haptic cues. The response time of 15 Hz stimuli is also much shorter than that of 1 Hz stimuli. Besides the numerical values, participants coherently preferred 15 Hz stimuli for being clear and unobtrusive. Thus, we decided to continue further studies on multiple stimuli with 15 Hz in preference to other frequencies and to exploit all six locations.

5 TWO STIMULI ON EARS: TEMPORAL AND SPATIAL VARIATIONS

After verifying the feasibility of a single stimulus on a location, we moved on to investigate how users perceive stimuli on two different locations on the ears. In addition to changing the location on the ears, we added temporal variation; we therefore have simultaneous stimuli and sequential stimuli. To avoid order effects, we present the sequential stimulus for a given location twice, switching which transducer is activated first. We therefore have $\binom{6}{2} = 15$ combinations of locations, and three types of activation(two sequential sets, a simultaneous set), for a total of 45 tests.

We recruited 12 new participants (6 male, 6 female) aged between 20–27 ($M = 24.00, SD = 2.86$) via an advertisement on an online community website at our university. The mean height of participant's ears was 64.92 mm ($SD = 5.08$), and the mean width was 34.33 mm ($SD = 3.05$). All participants again independently performed a pure tone audiometer test as a part of regular medical check-up required by our institute and self-reported to have normal hearing capabilities. Eight participants reported having experiences of wearing earrings or piercings, while five participants had tried wearable haptic devices before this study. They were compensated with $9 USD in local currency.

The study setting and procedure were similar to that of the first study, including the treadmill. To determine the length of the stimulus, we conducted a brief pilot study with two participants, both male, aged 24 and 25, testing stimuli lengths between 500–1700 ms, and choosing 700 ms as the optimal length. The simultaneous stimuli were thus 700 ms long and the sequential stimuli were 1400 ms long, without a pause in between. We replaced the touchscreen from the first study with a handheld game controller, in order to better assist participants in performing simultaneous input of multiple locations.

We asked participants to indicate the location of a given stimulus by pressing a button corresponding to the ear location on the handheld controller. We also asked them to specify whether the stimulus was simultaneous or sequential by holding one of the gamepad's trigger button while responding if they thought it was simultaneous.

We presented six sets of the 45 tests, with the first two sets treated as training and removed from the analysis. Within each set, we presented the tests in random order. We collected 2,160 valid data points, comprised of the response time (from the end of the stimulus to the first input) and the errors. Each study took approximately 45 minutes.

5.1 Result and discussion

We first conducted multiple two-way ANOVA tests to clarify the effect of the order and the relative locations of stimuli with two sequential activation results. As no statistically significant difference has been found, we conducted two-way ANOVA tests simply with two temporal variations (simultaneous vs. sequential); the means of the two sequential activation sets were used to maintain the equal sample size. We adopt the Greenhouse-Geisser value when Mauchly's sphericity value is smaller than 0.05. Regarding the response time, the simultaneous stimuli took mean 1838.86 ms ($SD = 384.39$) while the sequential stimuli required mean 768.75 ms ($SD = 228.92$), showing a significant difference ($F(1.13,\ 12.24) = 119.39, p < 0.001$). The sequential stimuli ($M = 82.36\%, SD = 0.12$) coherently yielded higher accuracy than the simultaneous stimuli ($M = 54.58\%, SD = 0.24$), while posthoc paired t-tests show few location sets render no statistically significant difference in accuracy between temporal variations (Figure 5). There was no statistically significant difference between spatial locations.

A deeper analysis elicits that 79.5% of the errors were due to one wrong location perception between the two stimuli, and that only 1.2% failed to specify any correct locations. The other 19.3% were wrong sequence errors, which mean participants distinguished both locations adequately but could not state the sequence properly.

These results imply that sequential stimuli are easier to perceive and distinguish than simultaneous stimuli considering the higher accuracy and shorter response time. Furthermore, sequential stimuli show the potential for longer patterns as at least one of the two stimuli is perceivable with high accuracy (98.8%). The lack of difference in spatial variations also supports the broad expressiveness of multiple stimuli presented via ActivEarrings. We thus hypothesized the potential of spatiotemporal patterns composed of more stimuli points using six locations.

6 SPATIOTEMPORAL PATTERNS AND INFORMATION TRANSFER

The high accuracy of sequential ActivEarring stimuli revealed in the second study inspired us to investigate whether users can map information to complex patterns of stimuli. As the transducer locations draw a 2×3 array, we tested using ActivEarrings as a virtual display, similar to previous haptic devices on the fingernails [33] or distributed across the body [34]. We tested conveying letters, numbers, and icons in patterns similar to previous work [6], [35] and investigated how much information can be communicated via our system.

We designed a total of 25 patterns using several criteria: semantic categories, design factors, and similarities between the patterns, summarized in Figure 7. Firstly, there are three semantic categories of patterns: 1) ten letters; 2) ten numbers; and 3) five icons. We selected letters and numbers based on natural order starting with "a" and "0", while we selected icons similar to those found in musical interfaces. Secondly, the design factors include the length (the number of stimuli composing a pattern) and the intersection (a location stimulated twice). Each pattern consists of a single stroke comprised of three to six stimuli points with maximum one intersection. Last, the similarity of each pattern is evaluated by the number of other patterns that are 1) congruent or axial symmetric, or partially congruent by, 2) having fewer than two disparate stimuli, or 3) sharing the first or last three stimuli locations.

We recruited 14 new participants (7 female) aged between 19–26 ($M = 22.50,\ SD = 2.44$) via an open call in

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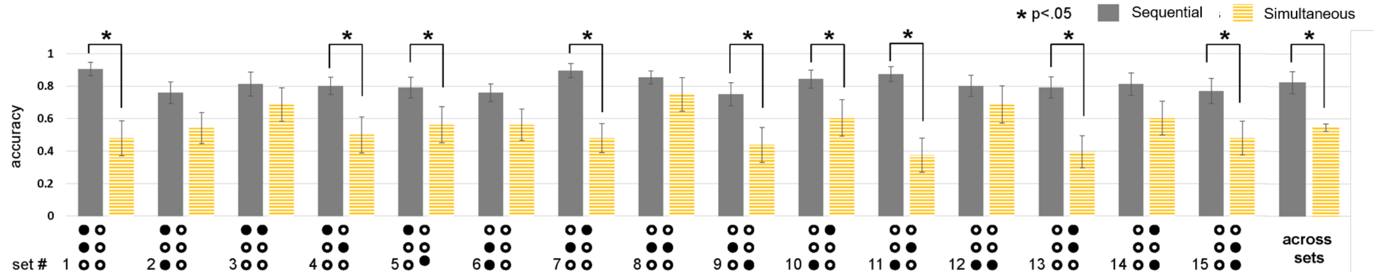
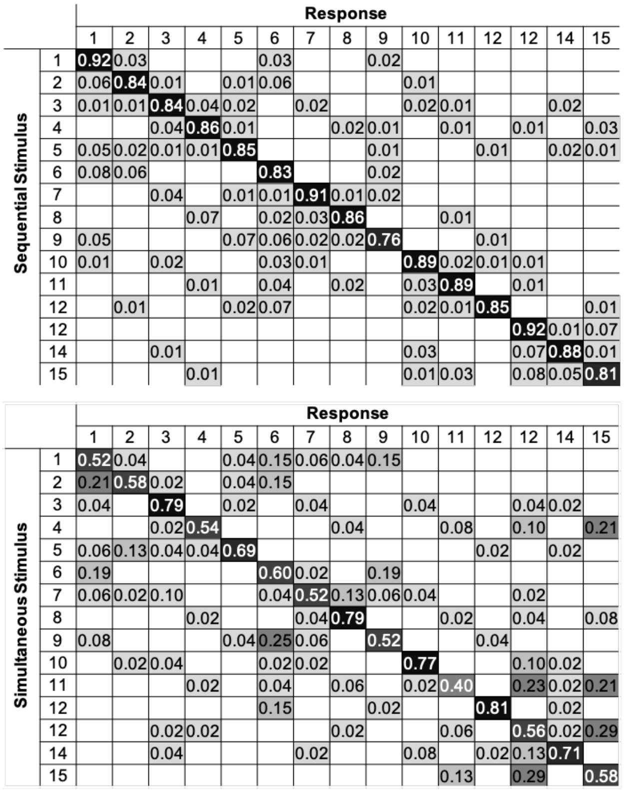


Fig. 5. The accuracy of each set of locations regarding temporal variations



		Response														
		1	2	3	4	5	6	7	8	9	10	11	12	12	14	15
Sequential Stimulus	1	0.92	0.03				0.03			0.02						
	2	0.06	0.84	0.01		0.01	0.06				0.01					
	3	0.01	0.01	0.84	0.04	0.02		0.02			0.02	0.01			0.02	
	4			0.04	0.86	0.01			0.02	0.01		0.01		0.01		0.03
	5	0.05	0.02	0.01	0.01	0.85				0.01			0.01		0.02	0.01
	6	0.08	0.06				0.83			0.02						
	7			0.04		0.01	0.01	0.91	0.01	0.02						
	8				0.07		0.02	0.03	0.86			0.01				
	9	0.05				0.07	0.06	0.02	0.02	0.76			0.01			
	10	0.01		0.02			0.03	0.01			0.89	0.02	0.01	0.01		
	11				0.01		0.04		0.02		0.03	0.89		0.01		
	12		0.01			0.02	0.07				0.02	0.01	0.85			0.01
	12													0.92	0.01	0.07
	14			0.01							0.03			0.07	0.88	0.01
	15				0.01						0.01	0.03		0.08	0.05	0.81

		Response														
		1	2	3	4	5	6	7	8	9	10	11	12	12	14	15
Simultaneous Stimulus	1	0.52	0.04			0.04	0.15	0.06	0.04	0.15						
	2	0.21	0.58	0.02		0.04	0.15									
	3	0.04		0.79		0.02		0.04			0.04			0.04	0.02	
	4			0.02	0.54				0.04			0.08		0.10		0.21
	5	0.06	0.13	0.04	0.04	0.69							0.02		0.02	
	6	0.19					0.60	0.02		0.19						
	7	0.06	0.02	0.10			0.04	0.52	0.13	0.06	0.04			0.02		
	8				0.02			0.04	0.79			0.02		0.04		0.08
	9	0.08				0.04	0.25	0.06		0.52			0.04			
	10		0.02	0.04			0.02	0.02			0.77			0.10	0.02	
	11				0.02		0.04		0.06		0.02	0.40		0.23	0.02	0.21
	12						0.15			0.02			0.81		0.02	
	12			0.02	0.02				0.02			0.06		0.56	0.02	0.29
	14			0.04				0.02			0.08		0.02	0.13	0.71	
	15											0.13		0.29		0.58

Fig. 6. The normalized confusion matrix of sequential and simultaneous stimuli.

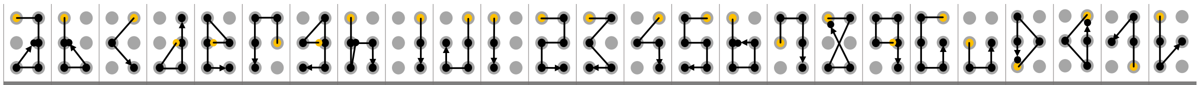
an online community website for our institute. The mean height of the participants' ears was 62.71 mm ($SD = 4.59$), and the mean width was 33.25 mm ($SD = 1.96$). All participants independently performed a pure tone audiometer test as a part of regular medical check-up required by our institute and self-reported to have normal hearing capabilities. Six participants reported having experiences of wearing earrings or piercings, while only one participant has tried wearable haptic devices before this study. They were compensated with $9 USD in local currency.

The physical setting was similar to the first study with a slightly different graphical interface: buttons of 25 information patterns rather than 6 locations. After an initial briefing, we equipped each participant with ActivEarrings and earphones for white noise. Participants then acquainted themselves with patterns for 10 minutes, by looking at a schematic of the patterns (as in Figure 7) and activating patterns by pressing buttons on the touchscreen. Then, while the participants walked on the treadmill, we presented 6 sets of the 25 patterns, with the first two sets treated as training and removed from the analysis. Within each set, we presented the patterns in random order. After the experiment, participants filled out a NASA TLX [36] questionnaire to assess the cognitive load of the task. Each study took approximately 45 minutes. We collected 1,400 valid data points across all users and sets.

6.1 Result and Discussion

The mean accuracy across the 25 patterns is 58.2% ($SD = 0.25$), and the average response time is 4.86 s ($SD = 1.49$). The confusion matrix reporting details for all the stimuli is presented in Figure 6. The mean workload reported from NASA TLX is 62.20 and the standard deviation is 12.84. The Pearsons correlation coefficient between the workload the accuracy of each participant yields -0.62 ($p < 0.05$). We calculated the information transfer using the confusion matrix (Figure 8) as in previous work [26], [37]. It yields 3.51 bits, indicating approximately 11.4 patterns can be successfully conveyed via ActivEarrings. We then analyzed the accuracy using one-way ANOVA tests followed by Bonferroni correction posthoc tests with alpha value 0.05. The accuracy significantly differs depending on the patterns ($F(24,\ 222) = 222, p < 0.001$).The letter "i" and number "2" yields very high accuracy (91.1% and 94.6%), while the icon "+" renders the lowest accuracy of 41.1%. We then attempted to clarify the cause of the difference regarding the criteria used to design the patterns: semantic categories, design factors, and reciprocal similarities of patterns. As the semantic category yields no significant difference in the accuracy, the design factors and the reciprocal similarity were normalized and analyzed collectively using correlation analyses and regression analyses. However, no significant correlation between any subcriteria (Length, Intersection point, Congruence/Symmetry, Partial congruence) and the accuracy was found. Moreover, simple regression analyses and multiple regression analysis with the accuracy as the dependent variable and the subcriteria as the independent variables failed to render any statistically significant result.

Surprisingly, the performance of the ActivEarring as a low-resolution tactile display failed to mirror its very high accuracy in the two previous studies (94.9% and 82.6%). None of the criteria could explain the accuracy discrepancy between patterns, implying the existence of other variables that lead to the low accuracy. One possibility is the excessive number of patterns far exceeding short term memory

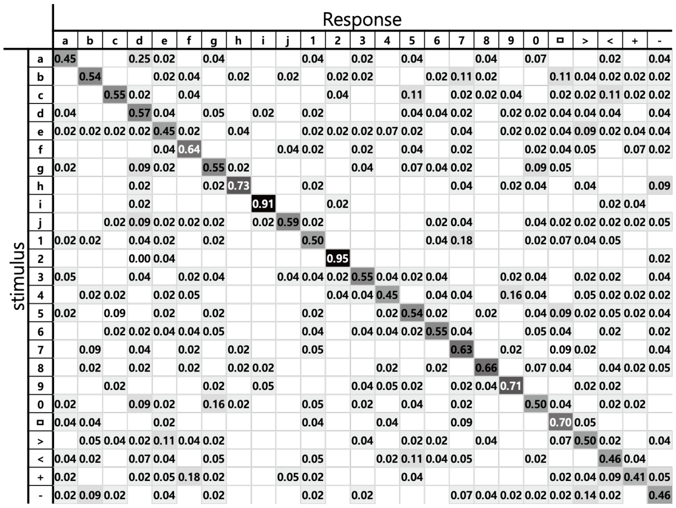


	a	b	c	d	e	f	g	h	i	j	1	2	3	4	5	6	7	8	9	0	□	>	<	+	-
Length	6	5	3	5	6	5	6	6	3	5	3	6	5	4	6	6	5	4	6	6	4	5	5	4	4
Intersection	·	·		·	·		·	·								·		·	·			·	·		
1 point	1	0	0	0	0	0	0	0	0	1	0	0	0	2	0	1	1	0	1	0	0	0	0	1	1
2 point	0	2	0	2	0	1	2	1	0	2	0	0	1	0	2	2	2	0	2	4	0	1	1	0	0
First three	1	4	1	0	0	0	0	4	1	1	4	1	0	0	1	4	0	0	0	1	0	0	1	4	0
Last three	0	0	0	1	1	2	1	0	2	0	2	1	0	0	1	0	2	0	2	1	1	2	1	0	0
Congruent · Symmetric	0	1	0	1	1	2	1	0	1	2	1	1	0	0	1	1	2	0	1	0	0	1	1	1	1

Fig. 7. Stimuli patterns and their criteria properties: design factors and reciprocal similarity

capacity [38] considering the information transfer value we calculated. We thus speculate that the training session was insufficient for participants to familiarize themselves with the given setting. While the given stimuli were more complex and a cognitive process of mapping information was required, the training session was not different from the first two studies. Structured learning and training sessions as in similar work on the wrist [35] might contribute to higher accuracy; we would like to see how performance evolves over time with more training in future work.

Another possibility is in the aspect ratio of the ActivEarring system. Although in Figure 7 the patterns are in portrait orientation, in actual use the height of the ears is smaller than the separation between them, lending a landscape aspect ratio. This layout might have increased the cognitive load required to interpret the patterns since letters and numbers usually fit the portrait orientation. This conjecture hints that mapping information that fits better with the landscape orientation or different way of exploiting the ActivEarring may lead to higher accuracy. Nevertheless, the accuracy and information transfer value remain competent compared to previous works considering the intensive training session [35], less demanding condition of sitting [6], [35], and the number of patterns tested [6], [33] of the previous works.



	Response																								
stimulus	a	b	c	d	e	f	g	h	i	j	1	2	3	4	5	6	7	8	9	0	□	>	<	+	-
a	0.45			0.25	0.02		0.04				0.04		0.02		0.04			0.04		0.07			0.02		0.04
b		0.54			0.02	0.04		0.02		0.02		0.02	0.02			0.02	0.11	0.02			0.11	0.04	0.02	0.02	0.02
c			0.55	0.02		0.04						0.04			0.11		0.02	0.02	0.04		0.02	0.02	0.11	0.02	0.02
d	0.04			0.57	0.04		0.05		0.02		0.02				0.04	0.04	0.02		0.02	0.02	0.04	0.04	0.04		0.04
e	0.02	0.02	0.02	0.02	0.45	0.02		0.04			0.02	0.02	0.02	0.07	0.02		0.04		0.02	0.02	0.04	0.09	0.02	0.04	0.04
f					0.04	0.64				0.04	0.02		0.02		0.04		0.02			0.02	0.04	0.05		0.07	0.02
g	0.02			0.09	0.02		0.55	0.02					0.04		0.07	0.04	0.02			0.09	0.05				
h				0.02			0.02	0.73			0.02						0.04		0.02	0.04		0.04			0.09
i				0.02					0.91			0.02											0.02	0.04	
j			0.02	0.09	0.02	0.02	0.02		0.02	0.59	0.02					0.02	0.04			0.04	0.02	0.02	0.02	0.02	0.05
1	0.02	0.02		0.04	0.02		0.02				0.50					0.04	0.18			0.02	0.07	0.04	0.05		
2				0.00	0.04							0.95													0.02
3	0.05			0.04		0.02	0.04			0.04	0.04	0.02	0.55	0.04	0.02	0.04			0.02	0.04		0.02	0.02		0.04
4		0.02	0.02		0.02	0.05						0.04	0.04	0.45		0.04	0.04		0.16	0.04		0.05	0.02	0.02	0.02
5	0.02		0.09		0.02		0.02				0.02			0.02	0.54	0.02		0.02		0.04	0.09	0.02	0.05	0.02	0.04
6			0.02	0.02	0.04	0.04	0.05				0.04		0.04	0.04	0.02	0.55	0.04			0.05	0.04		0.02		0.02
7		0.09		0.04		0.02		0.02			0.05						0.63		0.02		0.09	0.02			0.04
8		0.02		0.02		0.02		0.02	0.02					0.02		0.02		0.66		0.07	0.04		0.04	0.02	0.05
9			0.02				0.02		0.05				0.04	0.05	0.02		0.02	0.04	0.71			0.02	0.02		
0	0.02			0.09	0.02		0.16	0.02			0.05		0.02		0.04		0.02			0.50	0.04		0.02	0.02	
□	0.04	0.04			0.02						0.04			0.04			0.09				0.70	0.05			
>		0.05	0.04	0.02	0.11	0.04	0.02						0.04		0.02	0.02		0.04			0.07	0.50	0.02		0.04
<	0.04	0.02		0.07	0.04		0.05				0.05			0.02	0.11	0.04	0.05			0.02			0.46	0.04	
+	0.02			0.02	0.05	0.18	0.02			0.05	0.02				0.04						0.02	0.04	0.09	0.41	0.05
-	0.02	0.09	0.02		0.04		0.02				0.02		0.02				0.07	0.04	0.02	0.02	0.02	0.14	0.02		0.46

Fig. 8. The normalized confusion matrix of all the patterns.

7 DISCUSSION AND CONCLUSION

Our research aims to understand the human perception of haptic stimuli on the ear, and to explore the feasibility of using a haptic earring for information conveyance. The first study assessed the human perception of a single stimulus from ActivEarrings regarding different locations on the ears and actuation frequencies in the semi-realistic condition. The results show that 15 Hz is a desirable frequency of actuation due to its high accuracy and user preference, while all six locations seem promising. Although further research might be necessary to verify whether differences in ear shape and size may affect these results, our results seem to indicate that perception of stimuli on the ears is relatively homogeneous across participants and mainly depends on their frequency and locations.

In the second study, we endeavored to verify the feasibility of multiple stimuli and the influence of the spatial and temporal variations on it. The results reveal the potential of sequential stimuli for its consistently high accuracy regardless of the relative location of two stimuli. Then, we investigated a viable method for conveying information in a mobile wearable scenario and attempted to use ActivEarrings as a low-resolution tactile display. Although the mean accuracy across patterns is not very high (58.4%), it still remains at a competent level [6], [35] yielding high information transfer value (3.51) exceeding the Miller's magic number [38] and similar haptic devices [7], [10].

Our results from the two previous studies hint at a large design space that simultaneous stimuli and stimuli with differing frequency can be adapted to design haptic patterns beyond our attempt at a low-resolution tactile display. Our findings in the first study, that for central locations 1 and 30 Hz stimuli yielded accuracy as high as 15 Hz, suggest a potential opportunity to adapt stimuli of differing frequencies at different locations. The second study result, that simultaneous stimuli are equally well distinguished in few location sets, suggests using simultaneous stimuli for specific meanings. For example, we might be able to use these factors to design patterns for navigation, mapping speed to stimulus frequency, direction to stimulus location, and simultaneous stimuli to "stop.". We also might dedicate specific kinds of information per ear; a simple example is that stimuli at the top, middle, and bottom locations could indicate incoming communication from three different people, and the left and right ears could indicate the modality (e.g., text vs voice).

While prior research demonstrated the viability of wearable input and sensing on ears, we show that it is possible to provide non-audio *output* via the ears with ActivEarring. Our experimental results indicate that users can easily distinguish both a single stimulus and multiple sequential stimuli among six locations on two ears with very high accuracy (94.8% and 82.4%). In fact, ActivEarrings succeeded in yielding higher information transfer with spatiotemporal patterns compared to other wearable haptic devices, doing so with fewer actuators [7], [10], in less time [28], with a smaller form factor [22], and in more ecologically valid conditions [6], [30], [33], [35]. Moreover, an open design space with diverse promising factors discovered through our study also supports the potential expressiveness of ActivEarrings. We thus highlight that presenting haptic cues on ears via ActivEarrings is promising for information transfer, and propose some application examples in the next section.

8 APPLICATION

To exemplify the potential of our system as haptic jewelry that conveys information, we developed a more pragmatic form factor of our system and suggest proof-of-concept applications that can be easily realized using Java and the Processing framework. Our applications explore scenarios for eyes-free navigational cues, text-to-braille system, and AR notifications.

In our application prototype hardware, shown in Figure 9, the electromagnets are implanted in the temples of glasses, while in the current prototype the batteries and control board remain external. We 3D-printed a casing to fit the size and the shape of the ear so that the auricle can naturally be in touch with the electromagnets. Magnets with the pendants—the earrings—can then be placed on the front side of the ear.

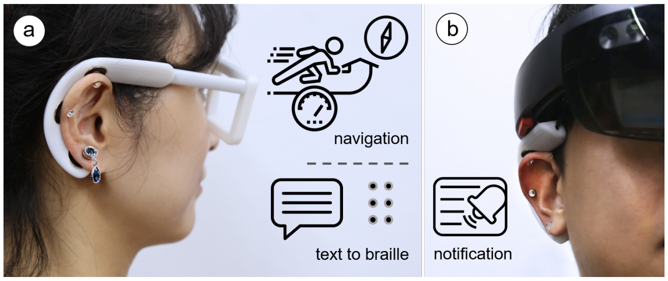


Fig. 9. ActivEarrings applications using different form-factors, like a) glasses, b) and the Microsoft Hololens.

The first application is a navigation system, which gives spatiotemporal haptic cues that leverage the users' ability to recognize navigational information (not only direction but also speed) without visual distractions when jogging or driving (Figure 9a). As the ActivEarrings are spatially distributed around the head, it would be applicable to use spatial variation to provide directional information and map the stimuli frequency to the speed information without visually distracting the wearer. The second application is a mobile simulator that translates the text message into haptic cues using a braille system (Figure 9a), enabling eye-free communication. Although in this paper we attempted a different way of conveying letters, adopting an existing system such as braille might be another promising application especially when it is used by those who are already familiar with the braille system. The final application delivers notifications in an AR environment via ActivEarrings, leaving the audio channel for real-world perception outside the AR environment (Figure 9b). In this case, a spatiotemporal pattern for each notification type such as a calendar or SNS push alarm would be designed through a workshop and implemented in our system.

Although we proposed the use of haptic cues via ActivEarring by itself, we also foresee the presentation of haptic cues in combination with other modalities like visual and auditory feedback. The comments from two participants in the first study that they would like ActivEarrings to be combined with headsets while they do jogging to give navigational information or to augment music experience hints at positive social acceptability and applicability of ActivEarring. We therefore expect the potential of adopting our system with other types of devices such as head-mount displays or sound headsets, providing both navigational information [22], [25] or even augmenting the experience with games and music players with haptic stimuli [29].

9 LIMITATIONS AND FUTURE WORK

Although the current prototype of ActivEarring is sufficient for evaluations with a semi-realistic wearable scenario, the current device is technically limited and not yet entirely wearable due to an external control board and power supply. Technical improvements are beyond the scope of this paper, and future work will attempt to minimize the size of the board, the battery, and the electromagnet. Another limitation of this work is that we did not explore the properties of an electromagnet and the size of the magnet nor did we utilize other mechanisms such as amplitude modulation to convey the signal. Arguably all these properties affect the haptic feedback generated and the perception of it. Other future extensions of this work will focus on implementing and comparing different types of tactile feedback presented on the ears, such as skin stretch, poking, and thermal feedback, as well as using different patterns' duration. Furthermore, we acknowledge that the results presented in this paper are inherently limited by the short duration of the lab studies. Future work will investigate how performance evolves over time and with more training sessions. Finally, we would like the haptic earring to be feasibly incorporated within smart glasses in the future with further development and then explore aesthetic and cultural aspects of ActivEarring to increase the social and cultural acceptability.

Regarding the applicability of our results, we propose that the information mapping method presented in this paper is a simple example of possible design space. Future work will focus on exploring various ways of pattern design and information mapping in addition to the suggestions we made in the discussion such as adopting phonemic coding [39], [40] and testing them in realistic settings without white noise masking the sound generated from the prototype. Ultimately we acknowledge that further design iterations are needed before the advent of a feasible and commercial haptic earring. However, we believe that the findings presented in this paper will benefit researchers interested in this topic in the future.

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