PokeRing: Notifications by Poking Around the Finger

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ABSTRACT
Smart-rings are ideal for subtle and always-available haptic notifications due to their direct contact with the skin. Previous researchers have highlighted the feasibility of haptic technology in smart-rings and their promise in delivering noticeable stimulations by poking a limited set of planar locations on the finger. However, the full potential of poking as a mechanism to deliver richer and more expressive information on the finger is overlooked. With three studies and a total of 76 participants, we informed the design of PokeRing, a smart-ring capable of delivering information via stimulating eight different locations around the index finger's proximal phalanx. We report our evaluation of the performance of PokeRing in semi-realistic wearable conditions, (standing and walking), and its effective usage for information transfer with twenty-one spatio-temporal patterns designed by six interaction designers in a workshop. Finally, we present three applications that exploit PokeRing's notification usages.

AUTHOR KEYWORDS
Haptics; wearable; poke; ring; notification.

ACM Classification Keywords
H.5.2. [Information interfaces and presentation]: User Interfaces – Haptic I/O

INTRODUCTION
Smart-rings are an increasingly popular research topic in the field of Human-Computer Interaction (HCI). In fact, the wearable form factor of rings make them an ideal candidate for both always-available input interactions, [e.g., 11, 21, 24, 33], and subtle notifications through numerous output modalities, [e.g., 21, 25, 32]. Common notification modalities include the usage of light from LEDs [21] or screens [25], sound, thermal [32] and tactile feedback [30, 32]. While light and thermal feedback are not ideal for realistic wearable conditions [32], sound leads to fast and accurate stimuli recognition but is not apt to many social situations. On the other hand, tactile stimuli, such as vibrations and poking, offer discreet notifications without impacting recognition performance.

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For this reason, haptics researchers in recent years have proposed several rings and finger-augmentation devices with tactile notifications. These includes rings that use vibrations to notify users about incoming messages or phone calls [21, 24], nail augmentation through an array of vibration motors [13], and a ring that can drag a tactor on the skin around the finger [15]. Poking is another tactile modality, usually achieved by stimulating the skin with the vertical motion of a solenoid valve [32], linear actuators [7] or an array of custom bidirectional tactile pixels [30]. However, previous research about poking was limited to explorations with one or few actuators located only on a single side of the finger (e.g., the volar side). Considering that the human spatial resolution on the proximal phalanx, (the part of the finger closest to the metacarpus, where usually rings are worn), is 5 mm [17], we see an opportunity for leveraging on this accuracy by increasing the number of actuators and displacing them in a non-planar arrangement around the finger. With these enhancements we are ultimately interested in knowing the perception limits of poking, so as to be able to design and test more expressive and accurate haptic notifications.

Therefore, this paper aims to contribute to the field of HCI in the following four ways: 1) we evaluate human perception limits for poking recognition with different configurations of actuators placed around the finger, and we suggest an optimal layout. 2) We present PokeRing, a smart-ring capable of poking in eight distinct locations, and evaluate its performance in semi-realistic wearable conditions (walking vs. standing). 3) Based on these results, we generate three sets of notification patterns through a design workshop with interaction designers. We then use them to evaluate recognition performance with users. 4) Finally, we present few demo applications that showcase potential usage scenarios of PokeRing for notification.

RELATED WORK
The related work is organized in two sections. In the first section we discuss smart-rings as output modalities and notifications, with an emphasis on haptic solutions. In the second section we discuss poking as a haptic modality, with an emphasis on wearable devices.

Smart-ring output modalities

Output through the finger has been widely developed for desktop and Virtual Reality applications using a variety of finger-augmentation devices [4, 5, 10, 19, 13, 23, 27, 39]. A comprehensive review can be found in [33]. In contrast, in mobile situations, the output capabilities of smart-rings are far more limited due to their small size. Within existing research, a common method is to use an LED [6, 21, 25, 31]. For example, Ketabdar et al. [21] suggested using an RGB LED to visualize mid-air finger gestures. Ring*U [6] employed both LED and vibrotactile feedback to allow remote couples to feel connected. Miner et al. [25]'s work integrated a colored LED into a ring to alert the wearer about email notifications. Rings with touchscreens have also been considered to provide a much higher bandwidth for complex visual information [1]. A general limitation of visual output is that the ring has to be visible to the wearer, which cannot always be guaranteed in a mobile context.

Haptic feedback does not have this limitation and has been used with smart-rings to communicate low bandwidth messages to their users [6 , 9, 11, 21, 24, 31, 40]. For example, Pingu [21] alerts the wearer about important messages from a coupled smartphone using vibrotactile feedback. Marti et al. [24] used vibrotactile feedback on a smart-ring to inform the wearers of an incoming call. Pradana et al. [31] and Werner et al. [38] used vibrotactile feedback to create a sense of presence for remote couples. Freeman et al. [9] and Yeom et al. [40]'s rings provide vibrotactile feedback in response to the wearer's mid-air hand gestures. Frictio [11] took a different approach by allowing the wearer to feel different patterns of resistance force when rotating the ring. tactoRing [15] delivers notifications by dragging a tactor against the skin of the finger. A study showed that with this technique, users could distinguish eight different dragging motions. Of most relevance to the present exploration, NotiRing [32] provided light, sound, vibration, poking, and temperature feedback on a ring. The authors found that vibration and poking were among the most noticeable channels for notification. Building upon this work, we systemically explore and design location-based poking as a notification mechanism on a smart-ring.

Poke interfaces

For a long time, poking has been used by neuroscientists as a method to assess the skin spatial resolution [17, 18, 37]. The two-point discrimination method involves the usage of a mechanical device with two tips, (e.g., a Venier caliper [37]), manually placed on the skin of different body parts and used to measure the minimum recognizable gap. Recently this method became more controversial [18], with researchers suggesting an alternative method based on identifying whether two consecutive stimuli separated by a short pause happen in the same place (point localization [17]).

In the past years, HCI researchers became interested in using poking for novel haptic feedback. Researchers used poking as an intimate communication modality in remote interactions through shape-changing mobile devices [29] or a haptic jacket [8]. Poking has also been used for subtle notifications on wearable devices [7, 30], as for the NotiRing project described in the previous section [32]. Pece et al. [30] introduced MagTics, a novel wearable and flexible haptic interface capable of poking with custom-designed actuators. The authors also demonstrated with a study that accurate notifications are possible on different body parts. However, this experiment used a limited number of actuators collinear on a planar surface, (e.g., the volar part of the finger). In our paper we see the opportunity to explore the feasibility and the limits of arranging a larger number of poking actuators around the finger, in the form factor of a ring. We then instantiate this knowledge in creating and testing a rich set of notifications presented exclusively on the finger.

STUDY 1: POKING AROUND THE FINGER

While poking has been primarily used in the past to study the cutaneous spatial and temporal resolution of fingertips [17, 18], no prior work studied the feasibility and performance of poking for the non-planar skin surface around the finger. Our first study aims to understand the feasibility of non-planar poking, and discusses the limits of perception with different numbers of actuators.

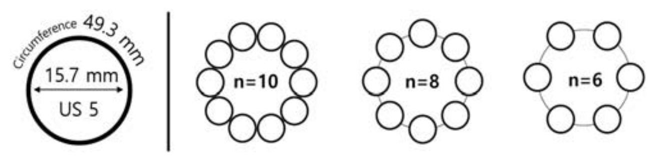

Figure 1. Measures for woman's average finger size (left) and configurations with 10, 8 and 6 actuators for the study.

Specifically, we selected three configurations with ten, eight and six equidistant poking actuators (Figure 1). To allow inclusion in the study of a large pool of participants, we determined these configurations by taking the average size of a woman's finger as base case. We then divided the corresponding ring circumference by 5 mm, which is the minimum spatial resolution on the proximal phalanx [17]. According to Blue Nile [2], the largest online retailers of diamonds specialized in fine jewelry, the most common women's ring sizes in the USA range between US-size 5 and 7, resulting in an inner circumference between 49.3 and 54.4 mm. Hence the maximum number of equidistant poking locations is ten (36° apart). The eight (45° apart) and six (60° apart) configurations were obtained as the next smaller layout with actuators placed symmetrically around the horizontal axis.

We designed a between-subjects study with 30 participants, where we tested the three configurations using a custom non-wearable hardware prototype (described below). By measuring input time, errors and cognitive load we extracted guidelines for designing a wearable poking ring

PokeBox

To test the three different poking conditions, we built a device shaped as a 20x20x20 cm box, referred to in this paper

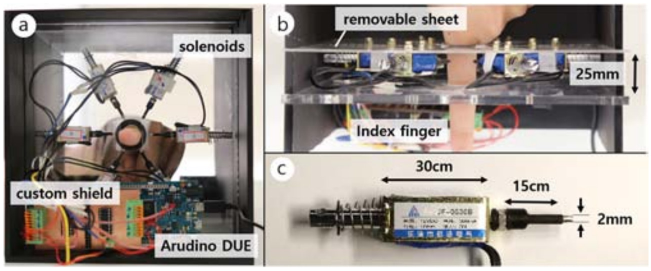

Figure 2. PokeBox front view (a), and top view (b). Detailed view of the modified solenoid valve used in the study (c).

as PokeBox (Figure 2), with a customizable number of poking actuators, and capable of adapting to finger sizes in the range between 3 and 13 (inner circumference: 44.2-69.7 mm). PokeBox is made of several 5 mm laser-cut acrylic sheets glued together that compose a box structure. It is painted black to hide the inner mechanisms, which can be accessed through a cover. A removable 1.5 mm thick acrylic sheet is mounted parallel to the back surface at a distance of 25 mm (Figure 2.b). This sheet and the back side of the box have two collinear 25 mm diameter holes, through which the user can insert an index finger. By forcing the finger through two parallel holes, we effectively constrain the finger motion and isolate the area of the finger subjected to poking. To account for different finger sizes, we use 3D printed attachable adapters with PolyLactic Acid (PLA).

The inner acrylic sheet also serves also a purpose: ten, eight or six actuators are directly screwed onto it, allowing the operator to easily swap among poking configurations. For actuators we used linear solenoid valves (30x13x15 mm) with a shaft of 55 mm length x 3 mm diameter and capable of generating a force of 5N at 9V (660 mA). The shaft, which is retracted with a spring when the solenoid is unpowered, was modified by mounting a 3D printed 15 mm PLA protrusion terminating with a metallic 2 mm wide flat tip (Figure 2.c). This tip is the only part of the shaft in contact with the skin during actuation, and its diameter was selected to conform to prior experiments about skin spatial resolution [37]. The solenoid valves are wired to a controlling board consisting of an Arduino DUE and a custom shield for driving the solenoids. The shield board contains two motor drivers (ULN2803) and diodes for back-EMF protection. The Arduino DUE is connected to a PC running a controlling software written in Java.

Study design

We recruited 30 volunteers (15 female) from the authors' affiliated institution (KAIST, South Korea), aged 19-31 (M: 22.7, SD: 3.0) with finger sizes between 5 and 11, (average finger circumference of 57.2 mm, sd: 5.4). Participants were randomly distributed in three groups with homogeneous gender distribution, and assigned to one of the three experimental conditions: ten, eight and six configurations. They were compensated with 5 USD in local currency for their time.

After the initial debriefing, participants inserted the left index finger in the PokeBox. They were then prompted with ten sets of *n* stimuli in random order, (n=10, n=8 or n=6 depending on condition), with the first two sets considered as training and removed from the analysis of the results. Each stimulus consisted of a single poking (500 ms duration) on one of the *n* locations around the finger, and the participant had to identify it by making a selection using the other hand with a mouse cursor on a graphical user interface, displayed on a PC monitor. In case of a mistake, the trial had to be repeated again after a random reshuffling.

With this method, we collected exactly eight correct input trials for each of the n locations, allowing us to compare the input time for different configurations without incurring time artifacts that could invalidate the results, (e.g., usually wrong trials lead to faster input times). Therefore, for each user we collected a total of 800, 640 and 480 data points for the ten, eight and six configurations. We used a software written in Java for visualizing the three configurations, for logging all the participants' answers (errors and response times), and for providing an auditory feedback to users during the training phase, using beeps and buzzes for successful and failed trials. At the end of each condition, participants filled a NASA TLX questionnaire [12]. Earmuffs were used during the testing to limit auditory distractions. The experiment took approximatively 20 minutes per participant.

Results and guidelines for ring design

Results were analyzed using one-way ANOVA tests followed by Bonferroni correction post-hoc analysis with $\alpha=0.05$. Levene's test was used to assess homogeneity of variance. Input time for the ten, eight and six conditions were 3.83s (sd: 0.5), 3.72s (sd: 0.3) and 3.84s (sd: 0.2) respectively. No statistical differences were found. The average success rates for each poking locations are presented

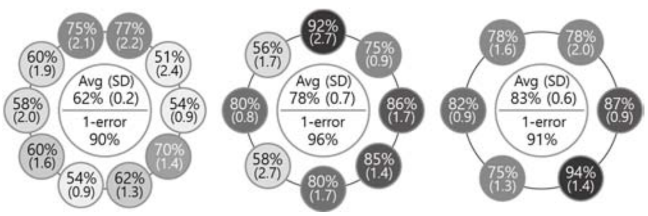

Figure 3. Accuracy thresholds and normalized standard deviation for the three configurations.

in Figure 3. Error rates were found statistically different across conditions ($F_{(2,27)}=7.9$, $p<0.01$, $\eta_p^2=0.37$) with the ten condition performing worse (38% errors) than both the eight (22%, $p<0.05$) and six (17%, $p<0.01$) conditions. A deeper analysis of the errors reveals that 90% or more of errors in all conditions were 1-errors (i.e., selections one location away from the correct point where the stimulus happened). However, a subsequent ANOVA test revealed no significantly different distribution of errors across poking locations. Finally, the cognitive workload measures from the TLX (Figure 4) were statistically different ($F_{(2,27)}=8.2$,

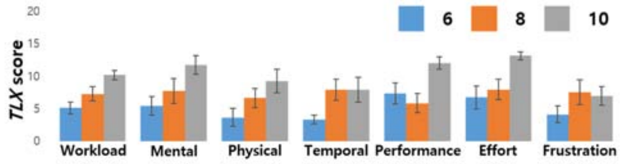

Figure 4. Cognitive load results from TLX.

$p<0.05$, $\eta_p^2=0.37$) with the six configuration significantly better than the ten layout ($p<0.01$).

These numbers tell a simple story: unsurprisingly, the greater the number of poking locations the harder was the recognition task, as clearly shown by the increasing error rates and cognitive workload results. However, the six configuration was only marginally better than the eight configuration (5% improvement), as no statistical differences were found for the reported cognitive load, time and error rates. This suggests that the eight layout, compared to the ten and six, is the best trade-off between accuracy of stimuli recognition and potential output expressiveness. Moreover, because no specific actuation point was perceived particularly better or worse than the others, we conclude that our initial choice for using equidistant locations around the finger was a correct design decision. Comparing these results with prior research that measured spatial accuracy around the finger using a skin-dragging ring [15], poking (78% accuracy) improves accuracy of 14% (skin-dragging accuracy for eight discreet equidistant locations around the finger is 64%). Therefore, in this paper we consider eight equidistant poking locations.

POKERING PROTOTYPE

We designed the PokeRing prototype based on the results of the previous study. PokeRing (Figure 5) is a smart-ring haptic interface capable to poke around the finger in eight distinct 45° equidistant locations. PokeRing was printed with PolyLactic Acid (PLA), has an outer diameter of 47.8 mm and a thickness of 11 mm. Poking is achieved with eight micro solenoid valves (measured force of 0.08N at DC 5V and 330mA), which are wired to an external amplification board and power supply. Each solenoid has a retractable magnetic shaft of 9 mm length and 2 mm diameter (as in study 1), and was modified with a back metal plate (5x5 mm, 0.5T) to allow latching of the magnetic shaft to the retracted state when power is not supplied. The external board contains four push-pull and four-channel H-bridge chips (L293B) to drive the solenoids and an Arduino Mega interfaced through USB with a controlling PC. The host PC runs a Java application that controls the state of the solenoids (push, pull or off, when latched). Power is supplied using an external DC power supply set at 5V.

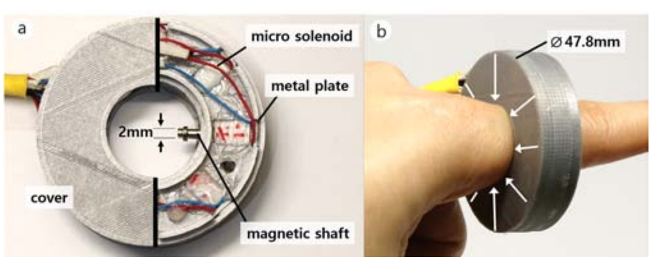

Figure 5. PokeRing hardware with external and internal views (a). The eight poking regions are highlighted in (b).

STUDY 2: POKING ON A WEARABLE RING

We designed the second user study with two objectives. We aimed to investigate whether the PokeRing prototype works in a semi-realistic mobile condition, with participants wearing the ring while standing or walking. Secondly, we wanted to verify whether temporal variations of poking stimuli, (i.e., a double-poke in the same spot), would improve spatial accuracy, a method known in haptics literature as point-localization [37]. Because some researchers argue that this technique offers more precise localization than single-time stimulation, (e.g., like in two-point discrimination) [18], we hypothesize that double poking leads to higher accuracy than single poking. We therefore designed a within-measure experiment with two factors, *posture* (standing vs walking) and *poking-type* (single- vs double-poking), resulting in a 2x2 fully factorial experiment.

The study was conducted in a temperature-controlled room (26 °C) using a Health Park HP-6000 treadmill (Figure 6). In the standing conditions the treadmill was off, while in the walking conditions it was set to a speed of 2.5km/h, as in closely related prior work [32]. The single-poke condition consisted of a single 500 ms actuation, like in study 1, while the double-poke condition consisted of two 200ms actuation separated by a 100ms pause for a total of 500 ms (note that the threshold for judging successive mechanical pulses is a much lower 5 ms [15]). For the experiment we fabricated two identical PokeRings of different sizes (US-sizes 8 and 11). Earmuffs were used to limit external noise.

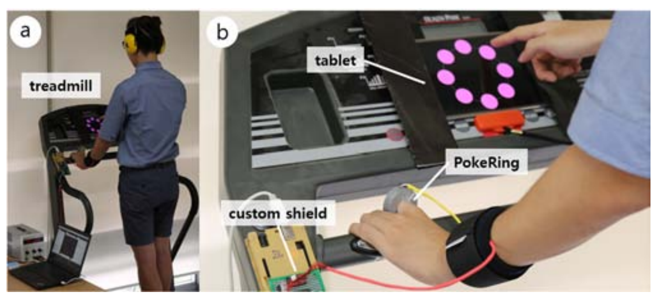

Figure 6. Study setup for testing PokeRing in semi-realistic settings (walking vs standing).

We recruited 16 participants (5 female) aged 19-30 (m: 23.3, sd: 2.75) with finger sizes 8 and 11. Seven participants reported to be familiar with haptics, eight commonly use wearable devices and eleven wear rings. All participants received a compensation of 15 USD in local currency.

After the initial debriefing and an informal demonstration of PokeRing, the four experimental conditions were presented in a balanced Latin-square order, each followed by a NASA TLX questionnaire [12]. The experiment took approximatively one hour to complete. In each of the four conditions, participants were prompted with a sequence of randomized stimuli that they had to identify using a graphical interface. Each condition consisted of 15 sets of eight random locations. The first 5 sets were considered as training data and were not included in the results analysis. If recognition failed, the same trial was randomly repeated at a later time. In total each condition consisted of 10 sets by 8 correct trials by 16 participants—for a total of 1280 data points.

During the experiment, participants wore PokeRing on the left hand index, while resting the hand on the front-facing foam handle. Using their right hand, they directly selected on a touchscreen (Samsung Galaxy Tab S2) the location of the stimulus around the finger using a graphical interface, like in study 1. The application running on the tablet logged the input responses and transmitted them via Open Sound Control protocol (OSC) to the PC controlling PokeRing.

Results and findings

Results were analyzed using two-way ANOVA tests followed by Bonferroni correction post-hoc tests with $\alpha=0.05$. Sphericity was assessed with Mauchley's test, and, if violated, Greenhouse-Geisser corrections were employed. Average input time ranged between 3.4s and 3.5s. No statistical differences were found for posture, poking type, or their interaction. Average error rates ranged between 23% and 29%, again with 94%-98% of errors being 1-errors. Errors are shown in Figure 7-top. No statistical difference was found for error rates across conditions. Finally, a posture effect was found for the cognitive workload ($F_{(1,15)}=19.6$, $p<0.01$, $\eta_p^2=0.56$), but no statistical effect was found for poking type or variables' interaction.

Task \ Location										Average (SD)	1-error
Stand	Single	68% 8(13.2)	69% 7(12.2)	78% 5(8.2)	70% 7(15.1)	66% 8(15.8)	81% 4(7.6)	80% 4(9.4)	77% 5(11.9)	75% (0.1)	96%
	Double	48% 17(32.5)	67% 8(17.3)	86% 2(5.3)	72% 6(13.1)	80% 4(7.4)	87% 2(4.6)	90% 2(3.4)	58% 11(29)	74% (0.1)	94%
Walk	Single	52% 15(31.7)	70% 7(12.2)	70% 7(12.9)	74% 6(9.7)	65% 9(16)	79% 4(9.8)	81% 4(10.2)	69% 7(17.8)	71% (0.1)	94%
	Double	63% 10(20.6)	77% 5(8.5)	74% 6(11.4)	74% 6(11.4)	68% 7(13.9)	82% 4(7.3)	91% 2(4.2)	84% 3(8)	77% (0.1)	98%

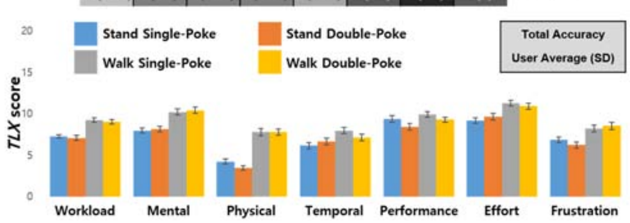

Figure 7. Accuracy results for each condition (top): each cell contains the total accuracy, and the average number of errors across users. Cognitive load results for each condition (bottom).

From these results we conclude that participants did not find any of the conditions easier or harder, and performed equally well throughout the experiment, with an average success rate of 74% (sd: 0.12)—a slightly lower figure than the accuracy achieved in the same configuration with the PokeBox in study 1 (78%). This difference can be explained by considering the physical demand required by walking on a treadmill for half the duration of the experiment and the smaller force (~60 times less) exerted by the tiny solenoids used in PokeRing. We also can conclude that double-poking, compared to a single-poke, does not improve (nor deteriorate) spatial accuracy in our hardware. The lack of statistical evidence across conditions is a strong endorsement that PokeRing would perform well in a realistic wearable condition (e.g., walking or standing), and that a single actuation would be sufficiently distinguishable. Finally, the great majority of errors across conditions are due to the misrecognition of a point for its adjacent locations (1-errors): this finding suggests that the successful encoding of information could benefit from both temporal and spatial encoding, rather than resorting to spatial encoding alone. The next study will ascertain this hypothesis.

STUDY 3: SPATIO-TEMPORAL PATTERNS AND INFORMATION TRANSFER

We designed a third study to understand the human capabilities of recognizing complex spatio-temporal poking patterns, associated to predefined information. Specifically, we varied the number of actuators (and hence increased the distance between them) to evaluate the effect of 1-errors, resulting again in three possible configurations: PokeRing with eight actuators (45° gap, as in study 2), four actuators (90° gap) and two actuators (180° gap). We however note that the meaning of these configurations is different than that in study 1. In fact, while in the former study we aimed to understand the spatial resolution of single pokes, in this study we aim to understand the maximum gap-size (45, 90 or 180 degrees) that still allows the user to recognize sequences of pokes. This allows us to systematically conclude in which degree users can recognize "locations jumps"of different sizes around the finger. We then designed a study composed of two parts: in the first part we recruited a team of interaction designers and asked them to generate seven poking patterns representing information states for typical mobile scenarios through a workshop [34]. The chosen number of patterns is motivated by considering that the average number of information chunks stored in the short-term memory is seven, according's to Miller's law [26]. Each pattern was adjusted by the designers to work in all three actuator configurations.

In the second part of the study, we presented these patterns to users, and assessed their recognition accuracy. As posture was not found to effect recognition in study 2, here patterns were tested with users in a sitting condition. Based on the results, we computed the information transfer for each of the tested configurations, and extracted generalizable knowledge about which layout is most suitable for notifications. In the next two sections we describe in detail the design workshop and the pattern recognition study.

Pattern design workshop

We recruited six graduate students (1 PhD and 5 master's) aged 23-31 (m: 25.3, sd:2.9) from the industrial design department of *KAIST*. All designers completed a degree in design and took coursework in motion graphics, interface

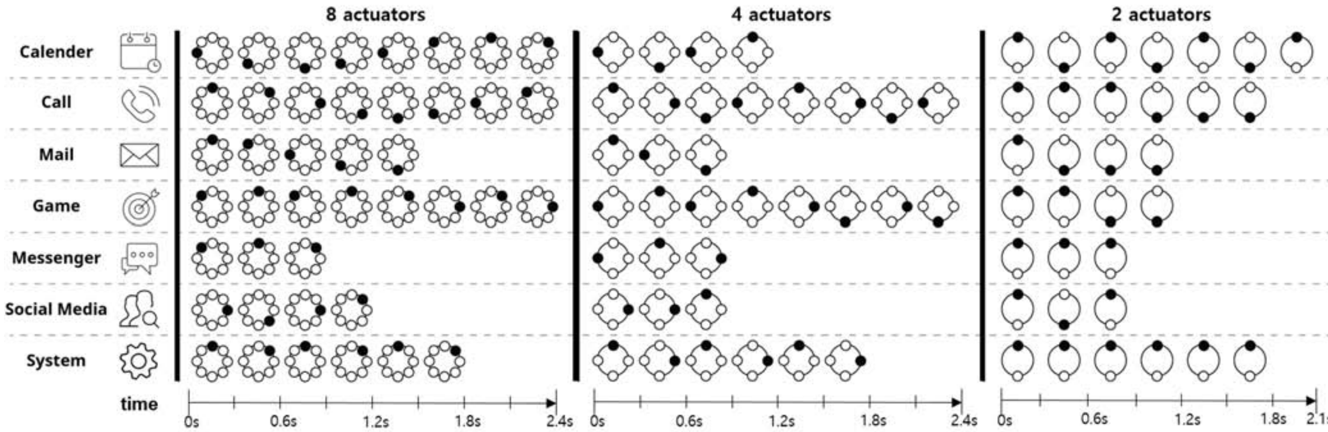

Figure 8. Patterns generated in the design workshop using 8, 4 or 2 actuators, for each of the selected seven information states.

design and interaction design. Three of them had prior professional experience in companies as interaction designers, and one designed haptic motions for a commercially available haptic device. They were compensated with 40 USD in local currency for their time.

After an initial ice-breaking session and introduction of PokeRing (10 minutes), we grouped designers in three random teams of two. We then asked them to create as many poking patterns as possible for seven common information states of mobile applications that were presented in prior work [34]: incoming text message, call, email, social media notification, calendar's appointment, system alert, and game. Initially we asked designers to create patterns for the eight-points configuration, using pens and paper. We also asked them to follow these design rules1) only one poke at time is possible; 2) each poke location must be adjacent to the previous, without any gap, so as to convey the sense of motion; 3) a pattern can at most contain eight pokes, for a total of 2.4 seconds (0.3 seconds per poke).

This design process lasted 40 minutes. After this phase, all of the designers gathered together and shared and discussed their patterns for each information state in random order. Using a whiteboard and post-it notes, they created an affinity diagram and used it to reach a consensus about how each information state should be represented (30 minutes). Finally, they were asked to translate the patterns for the eight configuration into the four-point and two-point configurations (30 minutes). At any point of the process, designers were free to revise previously defined patterns. The overall workshop took about two hours.

The primary result of this workshop are three sets of patterns representing seven information states, visualized in Figure 8. In total, designers generated 134 patterns, with a team average of 44.6 patterns (sd: 9.8). The final patterns for each configuration were implemented for PokeRing. The design rationales for patterns were collected in a post-hoc interview. Similarly to previous work [16], designers used the length of the motion to indicate importance (e.g., "calendar" notifications are more important than "game"), and directional changes to indicate emotional arousal (e.g., "system" alerts are "tense", and "game" alerts are "fun").

Pattern recognition study

We recruited 30 participants (9 female) aged 19-30 (m: 21.7, sd:2.8). Four participants reported to be familiar with haptics. Thirteen use wearable devices, and five wear a ring. Participants were compensated with 8 USD in local currency. Following a between-study design, they were split in three random groups and assigned to the eight-, four- and two-points conditions. Participants wore the ring on the index finger of the left hand, and sat on a chair with arms resting on a table. They faced a numeric keypad on which we applied seven stickers with icons representing each information state. This was used for input. After an introductory demonstration and a free training session offered to learn the patterns' meanings, the experiment started. Each of the seven patterns was repeated 15 times in random order (the first 5 repetitions were considered as

Stimulus	Response							Accuracy (%)	
								Mean	SD
	98	0	0	2	0	0	0	0.98	0.03
	0	100	0	0	0	0	0	IT (bits)	
	0	0	99	0	0	0	1	Mean	SD
	1	0	0	99	0	0	0	2.73	0.11
	0	0	0	0	98	2	0	RT (ms)	
	0	0	0	0	1	99	0	Mean	SD
	0	0	0	4	1	0	95	612.95	184.20

Stimulus	Response							Accuracy (%)	
								Mean	SD
	100	0	0	0	0	0	0	0.98	0.03
	0	98	0	2	0	0	0	IT (bits)	
	1	0	94	0	3	1	1	Mean	SD
	0	0	0	99	0	0	1	2.73	0.14
	1	0	1	0	97	1	0	RT (ms)	
	0	0	0	0	0	100	0	Mean	SD
	0	0	0	0	0	0	100	545.03	101.92

Stimulus	Response							Accuracy (%)	
								Mean	SD
	98	1	0	0	0	0	1	0.97	0.06
	1	96	0	3	0	0	0	IT (bits)	
	0	0	93	0	1	6	0	Mean	SD
	0	0	1	96	0	3	0	2.67	0.22
	0	1	0	0	97	2	0	RT (ms)	
	0	0	0	0	0	100	0	Mean	SD
	0	3	1	0	0	0	96	517.16	149.79

Figure 9. Confusion matrices, accuracy, information transfer (IT), and response time (RT) for all actuators' configurations.

training and removed from the analysis of results), for a total of 700 valid data points (7 patterns x 10 trials x 10 participants) per condition. Failed trials were not repeated, but the users received an auditory feedback for successes (beeps) and failures (buzzes). Finally, we collected a NASA TLX questionnaire [12]. The experiment took approximatively 30 minutes.

Results

Results were analyzed using one-way ANOVA tests with Bonferroni correction post-hoc analysis at $\alpha=0.05$. The input time in the three conditions ranged between 0.5 and 0.6 seconds and were not significantly different ($p>.5$). Similarly, accuracy in the three conditions was between 96.6% and 98.3%, with no differences across configurations ($p>.5$). Confusion matrices, accuracy rate, reaction times (RT), and information transfer (IT) computed as in [22, 36] are reported in Figure 9. We also tested whether differences were recorded for the error rates across patterns in each of the configurations, but no statistical difference was found. Finally, we also found no differences in the cognitive workload measured with the TLX. These results, in view of the previous two studies, are discussed in the next section.

DISCUSSION AND EXAMPLE APPLICATIONS

This paper aims to understand the human perception thresholds of poking around the non-planar surface of the proximal phalanx, and to explore the feasibility of using a poking smart-ring for notifications. The first study assessed spatial resolution thresholds using ten, eight and six locations. The results show that the configuration with eight equidistant poking areas is the optimal trade-off between accuracy and expressiveness. It achieves an accuracy of 78%, which is about 14% higher than that found in previous similar work [15]. In the second study we introduced a wearable ring device (PokeRing), and attempted to verify perception threshold in semi-realistic conditions (walking vs standing), and with different methods of actuations (single-poke vs double-poke). The results reveal the feasibility of PokeRing, with an average accuracy of 74% across conditions, despite the reduced form factor of the hardware. These results suggest that PokeRing is a viable method for notifications in real wearable scenarios. However, the large number of 1-errors, (errors one location away from the intended one), implies that spatial localization alone remains challenging. Thus, we hypothesized that spatio-temporal patterns might improve the recognition performance. In the last study, we aimed to test the notification capabilities of PokeRing with spatio-temporal patterns based on different numbers of actuators (eight, four or two). Before running the study, we organized a workshop with interaction designers in order to generate seven distinct notification patterns for each of the three ring configurations. We then assessed user performance. The results reveal an average recognition rate of ~97% across conditions and no differences for other performance parameters (time or cognitive load).

These results strongly support the feasibility and performance claims of PokeRing. While prior work demonstrated the viability of notifications with one or few poking actuators [30, 32], in our paper we show that it is possible to achieve accurate notifications by poking up to eight distinct points around the finger. In fact, our experimental results clearly indicate that the eight-actuator configuration did not perform any worse than the configuration with two actuators. What this means in practice is that PokeRing is capable of rendering more information per unit time than past poking devices. For instance, a device with a single poking actuator, such as NotiRing [32], could theoretically generate $2^4 = 16$ patterns with a duration of 1.2 seconds if each actuation took 300 ms. For the same amount of time, PokeRing can generate up to $8^4 = 4096$ patterns, or, alternatively, 64 patterns in half the time. By showing these numbers we are not suggesting that designers should attempt to create thousands of patterns for different notifications; instead, we want to highlight the potential output expressiveness of PokeRing.

Another interesting aspect comes from comparing poking with other notification modalities, such as sound, light, thermal feedback and vibration. While light and thermal feedback are usually less suitable for wearable notifications [32], and sound is potentially intrusive, vibrations are a suitable channels for notifications (binary notifications or structured in tactons [3]). However, binary notifications, like single poking, incur the same limitations of expressiveness describe above. Complex vibration patterns on fingers [13], on the other hand, require a longer time and present a lower accuracy rate, (a 2x2 tactor array gives an average accuracy of 82% for ten spatio-temporal patterns rendered in 1s-3.4s). Finally, skin-dragging can also be used to convey complex patterns with accuracy up to 94% (*tactoRing*'s VirtualPoint method [15])—but at the cost of longer input times and a higher cognitive load demanded to decode the patterns. We conclude that poking around the finger is suitable for expressive notifications, and we propose some application examples in the next section.

Applications

To exemplify the potential of PokeRing for notifications, we developed three proof-of-concept applications for Android devices, using Java and the Processing framework. The applications run on an Asus Zenfone and a Samsung Galaxy Tab S2 devices, and wirelessly communicate through OSC with a PC software that controls the PokeRing motions. They aim to explore scenarios for eyes-free notifications, affective communication and spatial cues.

The first application shows a phone simulator that triggers a poking motion pattern depending on the caller ID or in case of missed or urgent phone calls (Figure 10.a). For example, the phone's user can assign specific poking patterns to favorite contacts, so as to be aware of who made an incoming call without looking at the phone display. The second application is an effective communication messaging system

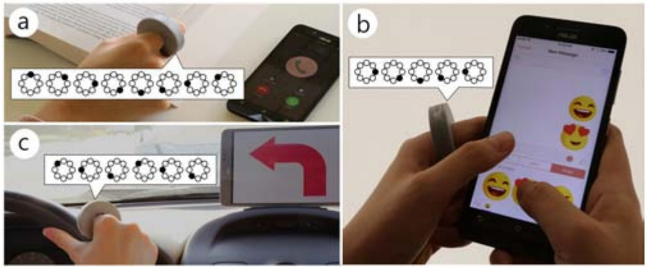

Figure 10. Three demo notification applications. Eyes-free notification of phone calls (a); affective communication with emoji and poking (b); spatial cues for car navigation (c).

(Figure 10.b). When a user sends an emoji using a chat application, the receiver of the message feels the emoji's corresponding poking pattern on the finger. This system not only allows users to receive eyes-free notification messages, but also to experience emotions associated to emoticons through the sense of touch. The last application is a car navigation system, similar to tactoRing [15], that leverages on the users' ability to recognize spatial poking cues with great accuracy (Figure 10.c). Users can interpret poking in the left, right and top and bottom locations as driving directions (left/right, U-turn or straight) without incurring visual distractions from navigation displays.

LIMITATIONS AND FUTURE WORK

The PokeRing hardware is sufficient for evaluations with a semi-realistic wearable scenario, but the current device is technically limited and not fully wearable: in fact, the prototype works with an external control board and power supply. Although technical improvements are beyond the scope of this paper, future work will attempt to miniaturize the ring and accommodate both batteries and a controller board on the ring itself, perhaps by using fewer poking actuators. In the future we also would like to design custom poking actuators, using multi-layered and flexible PCBs to route the turns of small solenoids as in [30, 35]. Another limitation of this work is that we did not individually explore the different properties of the poking feedback, such as the force, speed and durations of the stimuli. Arguably all these properties contribute to a mixture of haptic sensation that might hinder the direct applicability of our results. Future work will aim to ascertain the effects of each individual component, perhaps by contrasting them with vibrations for baseline performance. The different layout configurations (eight-, four- and two- points) explored in this paper also offer the chance to investigate whether poking can generate haptic illusions, (i.e., phantom sensation), as in previous work with vibrations [14, 20, 28]. Furthermore, we also acknowledge the lack of an investigation into multiple simultaneous pokes. Future work will investigate either the usage of PokeRings on different fingers or multiple simultaneous pokes within a single device.

In terms of the applicability of our results, we reckon that the proof-of-concept notification applications presented in this paper are only simple examples of the possible design space. Future work will focus on developing more applications for the effective communication and eyes-free notifications, and test them in realistic settings. Ultimately we acknowledge that the technical contribution of this work is still in a preliminary stage and that further design iterations are needed before the advent of a feasible and commercializable haptic ring based on poking. However, we trust that when future technology matures, researchers interested in this topic will benefit from the findings presented in this paper.

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