NotiRing: A Comparative Study of Notification Channels for Wearable Interactive Rings

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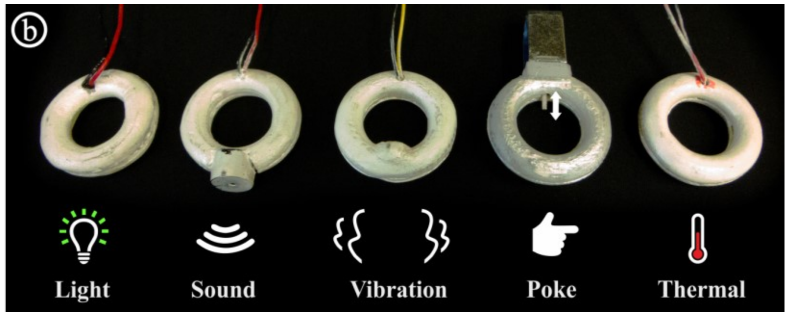

Figure 1: (a) Prototype connected to light ring; (b) Each ring supports a channel: light, sound, vibration, poke and thermal.

ABSTRACT
We conducted an empirical investigation of wearable interactive rings on the noticeability of four instantaneous notification channels (*light*, *vibration*, *sound*, *poke*) and a channel with gradually increased temperature (*thermal*) during five levels of physical activity (laying down, sitting, standing, walking, and running). Results showed that *vibration* was the most reliable and fastest channel to convey notification, followed by *poke* and *sound* which shared similar noticeability. The noticeability of these three channels was not affected by the level of physical activity. The other two channels, *light* and *thermal*, were less noticeable and were affected by the level of physical activity. Our post-experimental survey indicates that while noticeability has a significant influence on user preference, each channel has its own unique advantages that make it suitable for different notification scenarios.

Author Keywords
Notification; Wearable Computing; Poke; Vibration; Light; Sound; Heat; Ring; Activity.

ACM Classification Keywords
H.5.m. HCI: Miscellaneous.

INTRODUCTION
Wearable interactive devices have started to enter the consumer market, bringing new opportunities and challenges for notification design. While there are many issues surrounding user interaction with these devices, we chose to focus on the efficacy of different notification channels. Specifically, we evaluated the effectiveness of four notification channels with instantaneous feedback (light, sound, vibration, and poke) plus a thermal channel with gradually increased temperature. We were interested in how channel noticeability is affected by different levels of physical activity that users inevitably experience in mobile contexts (i.e., lying down, sitting, standing, walking, and running). We also explored how these channels can be mapped to real world notifications with different levels of urgency.

Each of the mentioned individual channels has been investigated separately [2,3,7,9,11]. Some researchers have also performed comparative studies with multiple channels under other interesting settings such as desktop and smart home scenarios [10]. However, we are not aware of any comparative study on all five channels for wearable notifications under varying physical activities.

In this paper, we present an empirical investigation on the noticeability of five notification channels for interactive rings during five levels of physical activity. Our findings contribute to the understanding of notification performance of these channels and user preference for notification scenarios with different levels of urgency.

RELATED WORK
Interactive rings [2,5] have the advantage of being easily accessible and generally visible to the user. Fingers are sensitive areas for haptic (cutaneous) sensation [1], and the wrist (hand) is the most visible body part [6]. Thus, these devices are well suited to convey notifications on the move, even if the user is engaged in an activity [3].

CHI 2015, April 18 - 23 2015, Seoul, Republic of Korea

ACM 978-1-4503-3145-6/15/04…$15.00
http://dx.doi.org/10.1145/2702123.2702350

Numerous works have separately studied existing notification channels such as light [3,6], sound [5], vibration [9], or thermal [4,11] notifications. These papers generally explored the expressivity of each channel but did not compare them with other channels. A poke gesture is a common way for a person to attract attention from another person, which makes it a potential mechanism for notification. However, besides being used to simulate physical effects (e.g., bump in a car race [7]), it has yet to be explored as a notification channel.

Studies have also been conducted to compare multiple channels of notifications (visual, audio, vibration). Warnock et al. [10] found that each channel used for notifications disrupts primary tasks, with no significant differences between channels. However, their study focused on contexts such as desktop or smart home.

While these studies provide important insights into each channel, a comparative study is needed to better understand their relative strengths and weaknesses, especially for interactive rings during varying levels of physical activity.

NOTIRING HARDWARE PROTOTYPE

To investigate the effect of physical activity on the five channels of notification, we created a hardware prototype for <u>noti</u>fication <u>ring</u>s (NotiRing) with two components: a central processing unit and a set of rings equipped with different types of actuators.

Central Processing Unit

The physical dimension of the central processing unit was 100 × 60 × 25 mm, comparable to the size of a cigarette case. Inside the case, there was an Arduino Nano microcontroller and a Bluetooth module for wireless communication. It also had a connection module consisting of a PCB that allowed for easy plug and play of the five types of rings described later. It also contained two batteries (5 and 12V). A button (dimensions 12 × 12 × 20 mm) was attached to the front face of the box for user interaction. The prototype is presented in Figure 1-a.

Rings

The rings (Figure 1-b) were 3D printed using PLA. Table 1 shows the actuators used to produce the feedback. Poke and thermal feedback required additional voltage and thus had to be powered using the 12V battery instead of the 5V battery. To test a particular type of ring, the connector of the ring was inserted into the outlets of the processing unit. The poke ring was bulky because the solenoid measured 11 × 10 × 20 mm. All rings provide almost instantaneous feedback except the thermal ring. Our hardware setup requires 6 seconds to warm up before the heat became noticeable. Note that due to the differences in feedback speed, the result of thermal ring should be considered separately from the other four channels.

The experimental software was written in Java 7 and run on a MacBook Air 13". It sent different types of notifications to the prototype for execution and recorded the button presses by users. The communication between the prototype and computer can either be done via Bluetooth or a USB cable. The entire prototype is lightweight enough for portability (150g for the case and an attached ring).

Channel	Light	Sound	Vibration	Poke	Thermal
Actuator	2×ultra bright green LEDs	Piezo buzzer, up to 75 dB sound	Coin-like motor 1.3g amplitude	Pull-type solenoid	4×25Ω resistors, *6 secs to heat up*
Actuator Ref.	COM-08285	PKM17EPP-4001-B0	310-103	ZHO-0420L	
Power by	5V	5V	5V	12V	12V

Table 1: Actuators used to build the interactive rings.

USER STUDY

Participants and Apparatus

25 participants (9 female, 18 male) ranging from 20-35 years old (*M*=23.8, *SD*=3.1) volunteered for the study. The experiment was conducted in a well-lit gym close to the university with a constant (air-conditioned) temperature of 23°C. For walking and running tasks, we used a FreeMotion Reflex t 11.8 Treadmill. The hardware and software used were described in previous section.

Task and Stimuli

Primary task: we chose 5 common physical activities as the primary tasks. A previous study [8] used three types of activity for evaluating mobile navigation techniques: sitting, standing and walking. We included two additional activities: lying down and running, as they are also commonly experienced in everyday life situations. The movement speed of walking and running was set to 2.5 and 7.5 km/h respectively. The 7.5 km/h speed ensured participants actually ran instead of just walking fast.

Secondary task: we chose a simple *on and off* notification as the secondary task. The durations for the on and off patterns were 500 ms each and the notification lasted 20 seconds, except for thermal, which was on for 26 seconds (including 6 seconds to warm up, see the supplementary appendix) resulting in a gradual temperature increase. Twenty seconds is the standard time a phone will ring for an incoming voice call in many countries[1]. Participants had to hit the button on the box (CPU) whenever they noticed stimulation from the ring to end the notification.

To facilitate fair comparison, we choose a notification intensity that was comfortable and safe for each of the channels in an indoor environment with constant room temperature. Our post-experimental results indicated that participants found four of the five channels highly comfortable (scores > 4/5 on a Likert scale). Thermal had a slightly lower than average comfort score of 3.2/5.

[1] http://optus.custhelp.com/app/answers/detail/a_id/34/~/missed-call-service%3A-add-%2F-remove,-faq

Channel	Reaction time (s)						Error rate (%)					
	Lying	Sitting	Standing	Walking	Running	Overall	Lying	Sitting	Standing	Walking	Running	Overall
Light	2.45	3.22	2.87	2.93	2.86	2.87	8%	1.6%	3.2%	4.8%	10.4%	5.6%
Sound	1.79	1.54	1.63	1.85	1.58	1.68	0.8%	**0%**	**0%**	**0.8%**	**0%**	**0.3%**
Vibration	**1.58**	**1.48**	**1.47**	**1.44**	**1.31**	**1.46**	**0%**	**0%**	**0%**	1.6%	2.4%	0.8%
Poke	1.86	1.83	1.65	1.59	1.61	1.71	2.4%	**0%**	**0%**	3.2%	4%	1.9%
Thermal	14.79	13.94	13.93	14.91	13.66	14.23	32%	28.8%	25.6%	24%	16%	25.2%

Table 2. Summary of experimental results. Bold values are the best values (lowest reaction time/error rate) for each activity level.

Matching task between channels and common notification scenarios. The post-experimental survey contained nine common notification scenarios, grouped in three levels of urgency. The first group contained *urgent notifications* that typically require immediate response from a user, including phone calls and immediate alarm.

The second group contained a spectrum of *moderate urgent notifications* that most likely do not require an immediate response, but to which the user may still need to react to fairly quickly, such as SMS, instant message, email, and social media notifications. The third group was more *information updates* that may or may not require a response, such as low battery status or the update for an application. Participants were asked to pick suitable channels for each scenario. Multiple channels were allowed to be mapped to a single scenario. For each scenario, we calculated the percentage of participants who picked a channel (Table 2). For example, if 19/20 participants picked vibration for phone call, the user preference is 95%. 20 of our participants answered the survey.

Procedure
The experiment was divided into five sections, one for each ring. Participants were asked to wear the ring on either their middle or ring finger of their dominant hand, depending on which finger provided the better fit. During each section, participants underwent trials for all five levels of physical activity. After a new physical activity was started, we allowed 30 seconds of warm-up time before starting a trial. Each trial lasted for up to 50 seconds, during which a notification would randomly occur. Participants were allowed to take breaks before or after completing an activity or when switching rings.

Design
The experiment was a 5×5 within-subject design with two independent variables: *channel* (light, sound, vibration, poke, thermal) and *activity level* (lying down, sitting, standing, walking, running). The orders of *channel* and *activity level* were counter-balanced with Latin Square.

We considered two dependent variables (DV): *reaction time* (from presentation of the stimuli on the ring to the participants hitting the button), *error rate* (percentage of time they did not perceive notifications out of all notifications). We also collected user preferences via the post-experiment survey that mapped channels to notification scenarios.

In summary, each participant performed 125 trials (5 *channels* × 5 *activity levels* × 5 *repetitions*). The experiment lasted approximately 2 hours and 15 minutes.

Results and Discussion
We performed two-way repeated-measure ANOVA on both factors for each DV. Pairwise comparisons were run using paired sample *t*-tests with Bonferroni correction.

Error Rate
We found no significant main effect on *activity level* (p=.33), indicating that the error rate does not change much with different physical activities; however, *channel* did have a significant effect ($F_{4,96}$=28.72; p<.001). Among the 4 instantaneous channels, *light* has the highest error rate (5.6%), which is significantly different from sound and vibration (all p<.01). Poke (1.9%), sound (0.3%) and vibration (0.8%) had the lowest error rates, with no significance (p>.05) between them. Thermal also had high error rate (25.2%), significantly greater than all other channels (all p<.01). Table 2 summarizes the results.

We also observed a *channel* × *activity level* interaction ($F_{16,384}$=2.07; p<.01). This interaction was mainly apparent with two channels: the error rate of the thermal channel decreased as the intensity of activity increased, while light exhibited the opposite trend. These results show that our sensitivity to thermal stimuli increases with physical activity. On the contrary, our ability to notice visual notifications decreases during increased activity.

Reaction Time
We found no significant main effect, nor any interactions, for *activity level* (all p>.4). However, we found a significant effect for *channel* ($F_{4,96}$=431.74; p<.001). As expected, the additional heating time causes thermal to be significantly slower (14.25s) than every other channel (all p<.01), followed by light (2.87s), which is slower than vibration, sound and poke (all p<.01). Poke and sound come next with 1.71s and 1.68s, respectively, and not significantly different from each other (p>.05). The fastest channel was vibration (1.46s), which was significantly faster than all other channels (all p<.01). Table 3 shows the result of the post-experimental survey.

Based on the performance results, We found that vibration, sound, and poke all have faster reaction time and are not affected by levels of physical activity. Among them, vibration stands out as being slightly more effective as it has the shortest reaction time and a very low error rate comparable to sound and poke; however, the speed advantage is not large (~200 ms).

Scenario	Light	Sound	Vibration	Poke	Thermal
Phone call	20%	<u>80%</u>	**95%**	10%	0%
Immediate alarm	15%	**70%**	<u>65%</u>	40%	10%
SMS	55%	<u>60%</u>	**70%**	15%	0%
Instant Message	45%	<u>50%</u>	**70%**	25%	5%
Event in 30 mins	20%	30%	**65%**	<u>40%</u>	10%
Email	<u>55%</u>	**65%**	35%	20%	0%
Social Media	**65%**	25%	<u>35%</u>	20%	0%
Low battery	**50%**	30%	30%	25%	<u>35%</u>
App Update	**55%**	20%	15%	20%	<u>25%</u>

Table 3: User preference of channels per scenario (see explanation in *Task and Stimuli* for details). The most preferred channels are marked bold and the second most preferred channels are underlined for each scenario.

Light and the thermal channel with gradually increased temperature are less effective with much higher error rates and longer reaction times. In addition, their notification performance is highly affected by the level of physical activity: skin sensitivity to heat increases with the level of activity [1], whereas light becomes less noticeable.

The notification performance results can help to explain the preference choices made by users for different notification scenarios. As indicated by Table 3, most users preferred vibration and sound for urgent and moderately urgent notifications. On the other hand, light was preferred for less urgent notifications.

Since poke is less familiar to users, it may reduce its preference score among the participants. However, still 40% of participants choose it for immediate alarm and calendar events, indicating the potential of poke as an emerging notification. In addition, as pointed out by our participants, poke carries an affective human touch, suggesting its potential to be used for notifications coming from family and close friends.

Our thermal ring has a number of technical limitations: not only does it have delayed feedback; only a fourth of the ring was heated up, resulting in less effective notification performance. Despite its limitations, thermal was chosen as the second preferred channel for non-urgent information updates. In addition, our experimental results showed a high variation among participants for thermal perception: some perceived it 100% of the time (*P17*, *P19*), while others found it difficult to notice and only perceived it 44% of the time (*P14*). Consistent and accurate thermal perception by some participants indicates that even thermal with a gradually increased temperature has the potential to be used by some users as a channel for moderately urgent messages. With improved thermal devices that have more immediate feedback, thermal's potential as a notification channel can be further explored.

CONCLUSION AND FUTURE WORK

We conducted the first comparative study of five notification channels for wearable interactive rings under different levels of physical activity. We found that the level of physical activity affects the noticeability performance of light and thermal, but not vibration, sound, and poke. Vibration was proven to provide the fastest response time, followed by sound and poke. These three channels are better suited for urgent notifications and work well under varying levels of physical activity. On the other hand, light and thermal with gradually increasing temperature are suited for less urgent notifications, and designers should consider their noticeability/activity level trade-off. We plan to extend our studies to more channels and other possible external factors in the future.

ACKNOWLEDGEMENT

This project was funded by 2013 Microsoft Research Asia Collaborative Research Program.

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