RingIO: An Eyes-Free Smart Ring with Inputs via Touch and Outputs via Touch

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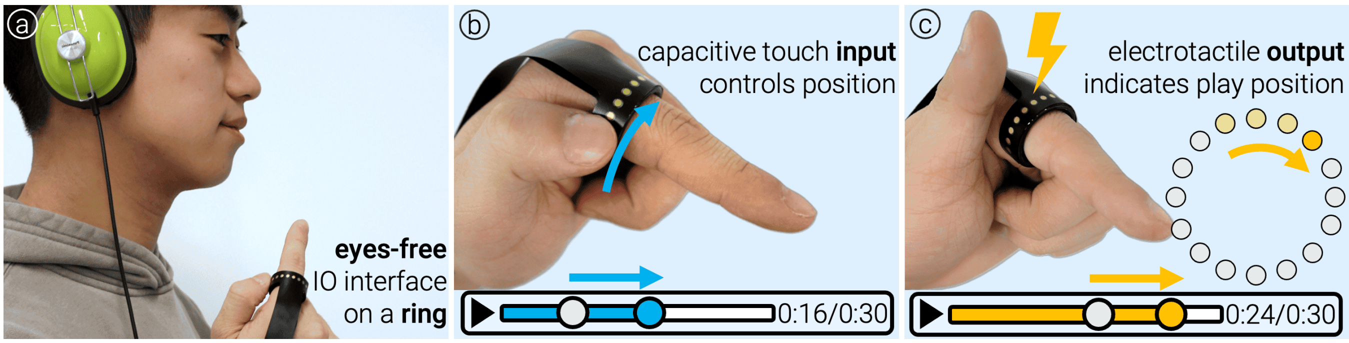

Figure 1: (a) This user wears our smart ring prototype, which enables *eyes-free* interaction with their podcast playback. The ring's input and output (IO) is *collocated*: (b) it detects inputs via capacitive touch on the outer surface, and (c) outputs via electrotactile stimulation on the inner surface. In this interaction, a user scrubs on the ring to skip ahead in the podcast, and collocated electrotactile stimulation conveys the playback position via a spatially symmetric mapping.

Abstract

In many interactive domains, output modalities are added to assist users with their inputs (e.g., gestural animations or vibrations to confirm inputs on touchscreens). While smart rings gained immense popularity for their wearable form factor, their compact size and constrained power budget limit the use of traditional output modalities (e.g., displays or large vibration motors). In this paper, we explore how an extremely low-powered form of haptic feedback—electrotactile stimulation—can be applied to smart rings to enable eyes-free IO. To explore and validate this, we devised a smart ring prototype incorporating an array of double-sided electrodes for collocated capacitive touch input and electrotactile output, enabling a variety of electrotactile animations—given its unique input & output (IO) capabilities, we refer to it as RingIO. In a user study, we found that users recognize ring-based electrotactile animations with up to 89% accuracy and with average localization errors less than 30 degrees. We demonstrate how haptics can support eyes-free interaction on smart rings in a series of applications.

CCS Concepts

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

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Keywords

Electrical Stimulation, Electrotactile, Haptics, Embodied Interaction

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1 Introduction

Many argue that smart rings are the next promising form factor for wearables, after smart watches. Smart rings offer a socially discreet alternative to watches and can be interacted with on a single hand [9, 46]. In fact, the finger is superior to the wrist as a site for tracking certain vital signs (e.g., blood pressure, heart rate) due to its increased capillary density [31, 50, 54]. This has proliferated a range of commercially available smart rings, most prominently, the *Oura* ring [23, 33], having sold more than 5.5 million rings as of 2026 [10] (alongside many others [51]). However, despite being one of the latest developments in new mainstream interfaces, smart rings fundamentally lack expressive haptic capabilities.

While a variety of output modalities have been applied to smart watches (e.g., vibrations [25, 35], screens [4, 32], and even force feedback [43]) to enable closed-loop IO, porting these modalities from smart watches to smart rings poses significant challenges given their extremely reduced size and surface area [33, 39]—making smart rings much less accommodating to visuals/displays, and critically, other eyes-free modalities, such as traditional haptics via power-hungry vibration motors. Unfortunately, a striking asymmetry exists in research on interactive rings: while input is emerging quickly, output is lacking significantly. Exploring suitable input techniques (e.g., gestures [6], twisting [2], touch [9, 46]) for rings has become an active research area, with 100+ explorations in HCI alone [51]. Conversely, output for rings remains heavily underexplored (<30 works [51]) with many still not proposing techniques suited to the low-powered nature of smart rings (e.g., high-power actuators which are not feasible in rings [13, 17]).

In this paper, we propose *RingIO* to bridge the gap between input and haptic output on rings by enabling a symmetric interaction paradigm [37] in which multi-touch input *and* output occur simultaneously. To enable eyes-free, collocated IO and address the difficulty of compacting haptics into smart rings, we turn to *electrotactile* as a low-power and ultra-thin alternative to mechanical vibrations [5, 41, 53]. In our study, we show techniques for rings leveraging this form of IO for improving accuracy on eyes-free interactions. We demonstrate how collocated output can support eyes-free interaction on rings in three applications.

2 Related Work

Our work builds on input and output interfaces on rings.

2.1 Input techniques for smart rings

The vast majority of research into user interfaces for smart rings primarily focuses on input—with 100+ explorations in HCI alone [51]. While commercially available smart watches primarily rely on touchscreens and mechanical buttons/dials, these input techniques are more challenging on rings due to their limited surface area.

Research in gestural input (i.e., by moving one's limbs) has recently extended to smart rings. These works use rings as wearable platforms for accelerometers [7], IMUs [26], or even electric field sensors [6, 52] to detect in-air gestures (e.g., by drawing shapes in the air or posing the hands). Similarly, *ThumbRing* [47] and *FingOrbits* [57] detect interface selections by tracking thumb movements, but both rely on a head-mounted display to provide visual feedback.

Manual inputs on the ring itself inherently provide tactile feedback by touching and manipulating the surface of the ring. *Nenya* [2] and *FrictIO* [13] achieve eyes-free input by directly manipulating the ring, twisting it around the finger like a dial. *Ringteraction* [9] and *TouchRing* [46] allow users to perform touch-based gestures (e.g., swiping, pinching, or tapping) on one (e.g., thumb and index) or two hands via capacitive sensing. However, touch-based input constitutes only one side of the IO equation. Interactive output remains heavily underexplored (with <30 explorations in HCI [51]).

2.2 Haptic output on rings

Display-augmented smart rings such as *VisRing* [28] can visualize complex data, but do not enable eyes-free interaction. Vibration remains the most common modality for eyes-free haptic feedback on smart rings [51]. *NotiRing* [38] found faster notification response times for vibration than other haptic modalities, such as poking or thermal. Vibrations can also provide spatial or directional feedback [1, 42]. However, these solutions are difficult to miniaturize (e.g., [1] created a device that was 47 mm thick and 30 mm wide). Due to the size constraints of rings [33, 39] coupled with the demanding power requirements of vibration motors [40, 49], commercially available smart rings have not readily adopted vibration as a haptic feedback modality. Microfluidic devices enable thin, flexible displays [11, 12], but fluidic latency limits expressivity, and external valves and pumps are difficult to miniaturize to fit in a ring. Other mechanical actuation techniques, such as skin dragging [15, 17], magnetic [29], air pressure [44], and poking [16], are also too large to meet the minimal form factor of smart rings.

Electrotactile provides a promising haptic output modality. The relaxed power demands of electrotactile [19, 24] enable it to be compacted into smaller wearable devices such as smart rings. *TactileWear* [41] also showed that electrotactile patterns were more localized and recognizable than vibration patterns; however, patterns were restricted to a low-resolution display of only four electrodes, and input was not explored. In contrast, high-resolution electrotactile displays have been used to render dense information and textures on the hands [22, 45, 56], feet [48], and face [18, 21].

2.3 Challenges in enabling multi-touch output on rings

The haptic multi-touch output techniques above are challenging to implement in smart rings because smart rings impose extremely stringent constraints on both space for multiple actuators and power consumption. Commercially available smart rings such as the *Oura Ring* [33] and the *Samsung Galaxy Ring* [39] are less than 3 mm thick to ensure wearability and comfort, and currently accommodate space for batteries and health sensors without any haptics. Even the smallest vibrational actuators, which are typically 3 mm thick [34], would consume most of the ring's available internal depth on their own. Integrating an array of vibration motors to support spatial, multi-touch output is therefore challenging. Moreover, the high power consumption of vibration actuators [40] (even using power-saving techniques such as short pulses) would strain smart ring battery capacities which are limited to less than 20 mAh [39].

3 Contribution, Benefits, and Limitations

The key contribution of our work is to enable closed-loop, *eyes-free interactions* on smart rings with symmetric input *and* output via collocated touch—research on the latter is significantly lagging in rings. We address this gap by proposing and validating the coupling of multi-touch input with electrotactile output.

Our approach has several key benefits, as leveraging electrotactile for eyes-free output on rings addresses the challenges of compacting haptic actuators into smart rings: (1) more power-efficient output, i.e., our output draws less than 1 mA, making it, in theory, an order of magnitude more efficient than vibration motors [49]; (2) electrotactile can be implemented in thin actuators (e.g., our 0.08 mm flexible PCB or even thinner substrates[53]), easily fitting inside a smart ring (between the ring and skin) compared to ultra-small vibration motors (e.g., [34] is 3 mm and [49] is 4.7 mm); and (3) ours is the first symmetric interaction for smart rings—a type of interaction where the same modality and mapping are used for input and output, resulting in a particularly intuitive interaction that even allows users to learn input based on output [8, 27, 37].

Finally, as the first exploration of this novel eyes-free IO method for smart rings, our investigation is not without limitations, which reveal future research directions: (1) while we opted for a large multiplexer and versatile stimulator to explore this design space, miniaturization via smaller stimulators is possible [5, 55]; (2) this study was limited to a lab setting, which may not generalize to everyday/highly-mobile applications; (3) electrotactile stimulation is sensitive to sweat/skin impedance [20, 24] and habituation due to repeated stimulation [24], and therefore requires calibration.

4 Implementation

At its core, our prototype requires thin electrodes suitable for the extremely narrow gap between smart rings and skin, an electrotactile stimulator, a capacitive sensor, and multiplexers (Figure 2). In principle, this can be realized with via different hardware variations (from extremely small electrotactile stimulators such as [5, 55] to larger stimulators such as [36]). As the first exploration in this territory of eyes-free rings with co-located IO, we opted for flexibility (i.e., a larger multiplexer and a versatile stimulator with strong current output) rather than focusing only on miniaturization. We mounted a flexible PCB on a *COLMI R02 Smart Ring*. Figure 3 depicts the high-level circuit implementation and Figure 4 depicts the whole prototype on a user's arm.

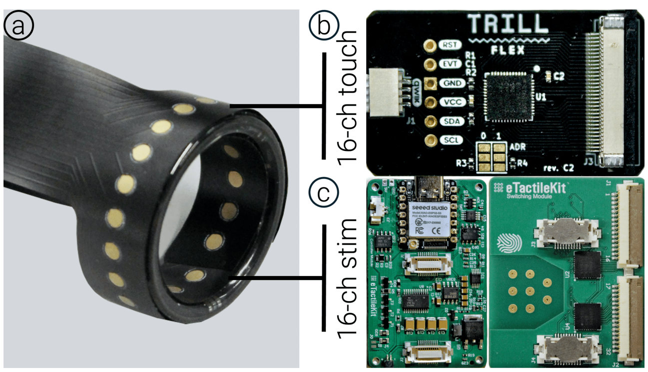

Figure 2: Key components of our smart ring prototype including: (a) our flexible PCBs mounted on a *COLMI R02* totaling 3.16 mm thickness; (b) external capacitive sensing circuit from [3]; (c) open-source electrotactile stimulation from [36].

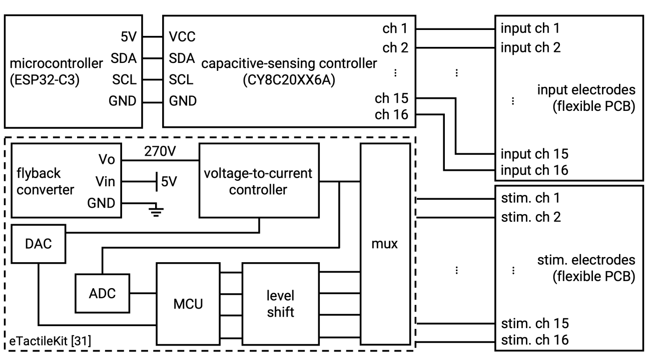

Figure 3: High-level circuit implementation schematic.

Figure 4: A user wearing RingIO.

4.1 Input module: multiplexed capacitive sensing

The input module captures capacitive touch input around the outer surface of the ring. It is driven by a *CY8C206X6A* capacitive multi-touch sensor (*Trill Flex* board [3]). We utilized a US 9.5 reference ring size and a two-point discrimination for electrotactile of 2–4 mm at 200 and 400 Hz respectively [14] to inform our custom flexible PCB design[1], which is 0.08 mm thick and spaces 2 mm diameter electrodes every 4 mm (i.e., electrode center-to-center) yielding 16 electrodes. The input location is determined by tracking the centroid of the capacitive touch array across all electrodes [18, 46].

4.2 Output module: multiplexed electrotactile stimulation

The output module controls electrotactile stimulation on the ring's inner surface (i.e., in contact with the skin). Stimulation electrodes are arranged around the finger in the same manner as the input module. We utilized the open-source *eTactileKit* [36] to enable rapid multiplexing of the stimulation electrodes on our flexible PCB. This could be substituted for smaller stimulation devices, e.g., [5, 55].

4.3 Hardware power breakdown

The complete power breakdown for all prototype components is provided in Table 1. While the maximum voltage of electrotactile is 270 V, it relies on pulse widths with a duty cycle of 1% at 50 Hz. We estimate an approximately 1 mA peak output current, at a 1% duty cycle, resulting in an upper bound of 2.7 mW on the average power delivered to the electrode load. This estimate excludes stimulation-control and conversion losses and is therefore not a measure of full-system efficiency. For comparison, the vibration motor cited in [49] has a rated electrical input of 27 mW. The employed stimulator-control electronics draw an additional 25 mW and were selected for prototyping flexibility rather than power optimization.

Table 1: Power breakdown of all prototype components.

Component	Current Draw	Power Draw
Electrotactile Stimulation	**1 mA**	**2.7 mW**
Stimulator Control (*eTactileKit*)	5 mA	25 mW
Capacitive Input (*Trill Flex*)	4 mA	20 mW
Microcontroller (*ESP32-C3*)	12 mA	60 mW

[1] fPCBs are accessible at: https://lab.plopes.org/#RingIO

5 User Study

Our user study tested how well users could input with a touch ring that featured our electrotactile output. Participants experienced a series of *eyes-free* touch-based interactions on our interface. This study was approved by our Institutional Review Board (IRB21-1229).

Apparatus. Participants sat with their non-dominant index finger supported on a rest and wore our ring by wrapping the flexible PCB tightly around their finger, minimizing gaps between the electrodes and skin. Since participants' fingers were not all the same size, excess electrodes that did not directly touch the participant's finger were deactivated, i.e., participants with thinner fingers used fewer electrodes than those with thicker fingers (participants used between 11–15 electrodes; M=13.62; SD=1.31). Participants wore the device for one hour.

Calibration. We calibrated each electrode per participant to a comfortable intensity that robustly elicited touch sensations by pulsing stimulation on/off every 200 ms and increasing the stimulation intensity in steps of 0.01 mA until the participant could clearly distinguish individual pulses.

Electrotactile animations. To test RingIO's unique output capabilities (e.g., localization of simple/complex patterns, multi-touch sensations, and dynamic trajectories), the four animations in Figure 5 were inspired by previous studies of haptic animations [30, 41]: (1) *pulse*: stimulates the target location; (2) *pinch*: simultaneously stimulates two locations each 90° from the target in both directions that converge to the target; (3) *sweep*: stimulates the location directly 180° away from the target and rotates clockwise through electrodes until reaching the target; and (4) *wobble*: oscillates between the target and each immediately adjacent electrode (on both sides) twice. Each animation lasted exactly 800 ms.

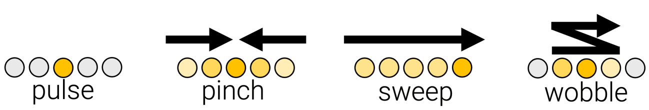

Figure 5: The four electrotactile animations used in the study.

Trial design. In each trial, participants experienced one of the four electrotactile animations and used their dominant index finger to touch the ring where they thought the target was. The capacitive touch sensor reading was recorded upon releasing the touch, so participants could slide their finger around the ring before confirming their inputs. Each trial was either *collocated* or *non-collocated* for response collection. When participants touched the ring during *collocated* trials, stimulation was delivered at the location of the input (i.e., pulse). In *non-collocated* trials, no stimulation was delivered during the input. After confirming their guess, participants used the computer to select which of the four animation types (multiple choice) they thought they felt. Participants performed three trials per combination of condition/animation at each active electrode location in a fully randomized order. We ran 4,248 trials in total.

Metrics. Our key metrics were: (1) the angular error between the target and participant's input; and (2) the accuracy of their classification of trials into the correct animation types.

Participants. We recruited 13 right-handed participants (average age=25.5 years, SD=8.7; 7 female and 6 male). Participants provided consent and received $20 USD as compensation.

5.1 Results

Localization accuracy. We analyze the average localization error for each participant (i.e., the arc between the target electrode and the centroid of the participant's capacitive touch). Figure 6 (a) shows the error results for inputs without collocated stimulation. *Wobble* produced the lowest localization error (M=32.2°; SD=5.3°), while *sweep* produced the highest error (M=41.7°; SD=13.2°). A Shapiro-Wilk test confirmed normality of the distributions of errors for non-collocated inputs. A one-way repeated measures ANOVA revealed significant differences between animation types (F=5.74; p<0.01). Post-hoc analyses with Bonferroni corrections found that *pulse* (M=33.1°; SD=5.8°) was significantly more accurate than *pinch* (M=40.1°; SD=8.5°; p<0.05), and that *wobble* was significantly more accurate than *pinch* (p<0.05).

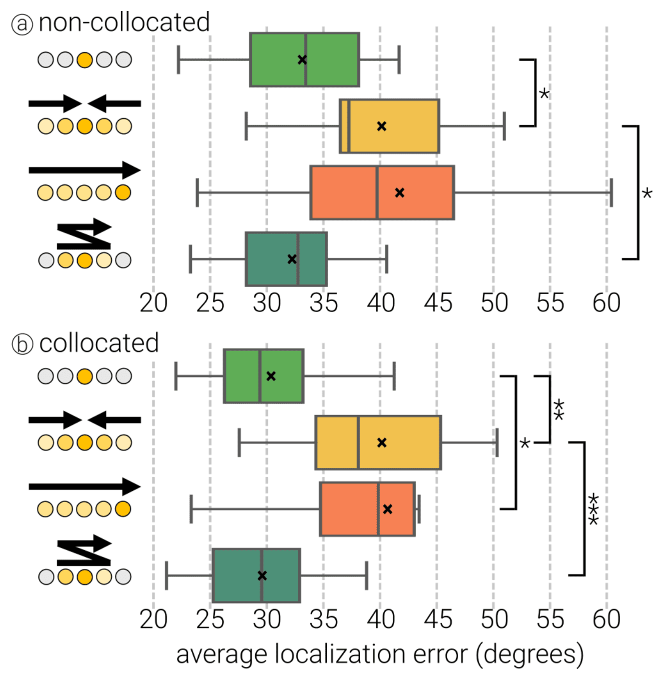

Figure 6: Average localization errors for (a) non-collocated trials and (b) collocated trials. Boxplot bars from left to right denote Q1, median, and Q3. Whiskers denote range. x denotes mean. * denotes p<0.05, ** denotes p<0.01, and * denotes p<0.001. All non-annotated comparisons are non-significant.**

Next, we analyze the effect of animation types on localization error for collocated trials, as shown in Figure 6 (b). For collocated trials, the most accurate animation was still *wobble* (M=29.6°; SD=4.8°) and *sweep* (M=40.7°; SD=12.4°) again produced the highest error. A Shapiro-Wilk test confirmed normality of participants' average errors for each animation type on trials with collocated stimulation. A one-way repeated measures ANOVA revealed significant differences between animation types (F=10.08; p<0.001). Post-hoc analyses with Bonferroni corrections found that *pulse* (M=30.4°; SD=5.4°) was significantly more accurate than both *sweep* (p<0.05) and *pinch* (M=40.2°; SD=9.9°; p<0.01), and that *wobble* was significantly more accurate than *pinch* (p<0.001).

Animation recognition. Figure 7 shows the confusion matrix for the recognition of each animation. The overall animation recognition accuracy was 79.8±0.6% SE. Paired t-tests found no effects of collocation on animation recognition.

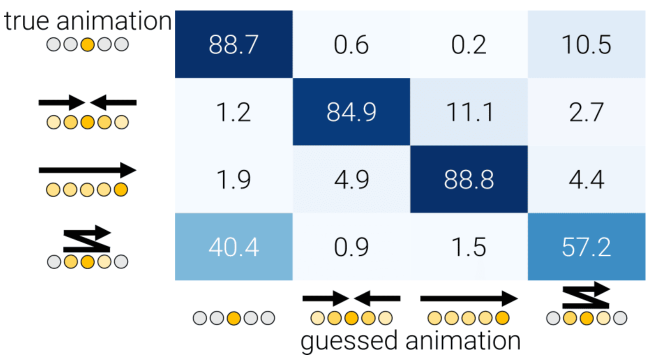

Figure 7: Confusion matrix for recognition of animations.

The most recognizable animation was *sweep* (88.8±1.0%), while *wobble* (57.2±1.5%) was least recognizable. A Friedman test revealed significant differences between the recognition rates of animations ($Q=19.61$, $p<0.001$). Post-hoc pairwise comparisons with Bonferroni correction found that *pulse* (88.7±1.0%), *pinch* (84.9±1.1%), and *sweep* were all more recognizable than *wobble* ($p<0.01$). Notably, participants frequently misinterpreted *wobble* as *pulse* (40.4±1.5%).

5.2 Discussion

These results inform the complexity smart ring interfaces may support. The lowest error tolerance of 30° via *wobble* with collocated stimulation conservatively affords six spatial targets for touch-based interfaces on smart rings—higher than previous smart ring explorations (e.g., three targets of [9] or four targets of [41]). Our localization accuracy is in line with *PokeRing*'s highest accuracy, which was precisely when six large (i.e., 55 mm in height) solenoids were aimed at the finger [16].

The recognition results inform task-specific design choices. The highly recognizable sweep (~89%) and pinch (~85%), both depict circular motion around the finger—in line with [41], which also found clockwise (~70%) and counterclockwise (~82%) circles to be most recognizable. However, we observed higher recognizability with our denser array of electrodes than [41] with their four electrodes, suggesting that high-resolution tactile displays on smart rings improve the accuracy of notifications.

The results also indicate a tradeoff between localization and recognizability. The most localized animations were less recognizable (e.g., *wobble* & *pulse*), and highly recognizable animations were less localized (e.g., *sweep*). Designers of smart ring interfaces should therefore use animations with larger movements for notifications while reserving localized stimulation patterns for spatial tasks, which aligns with research on recognizability of tactile animations [30, 41]. However, *wobble* was often mistaken for *pulse* and treating them as a single class may yield high recognition accuracy.

6 Applications

To demonstrate how RingIO supports eyes-free interactions, we implemented three applications.

6.1 Application 1: eyes-free authentication

We implemented a simple user authentication system based on gestures and localization. In Figure 8 (a), the use locks the smart ring for security by performing a pinch gesture. Likewise, an electrotactile pinch animation confirms the action. In (b), the user unlocks the ring by providing a series of touch inputs (which are met with collocated stimulation) that constitute a touch-based passcode. The smart ring unlocks if and only if the correct passcode is entered. In (c), the smart ring notifies the user that it has been unlocked with a ripple-open animation (i.e., the reverse of pinching closed).

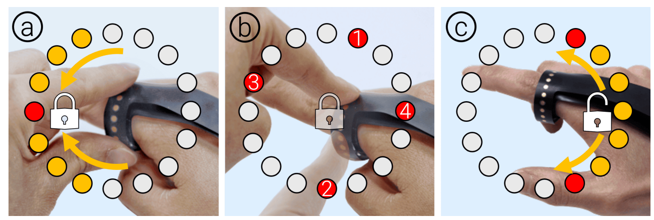

Figure 8: A touch-based user authentication system.

6.2 Application 2: a completely eyes-free game

Our second application delivers an entirely eyes-free gaming experience on a ring. In the classic children's game "Hot Potato", a hot potato ticks for some time before exploding; the objective of the game is to get rid of the potato before it explodes. Figure 9 depicts how the game can be played on RingIO: when the player touches the ring in (a), a collocated pulsing is rendered. The ring modulates the pulse frequency to give clues about the location of the hot potato—slow, gentle pulsing indicates the player's touch is "cold" (i.e., far away from the potato) while fast, intense pulsing indicates "hot" (i.e., close to the potato). When the potato is found, the player swipes as in (b) to throw the potato away. In (c), the player fails to find the potato before time runs out, and the potato "explodes", which is indicated by the rippling-out animation (i.e., the reverse of pinch).

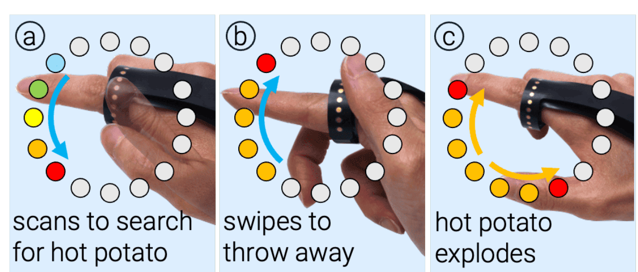

Figure 9: An entirely eyes-free game played solely on RingIO.

6.3 Application 3: eyes-free media controller

Finally, Figure 10 (b) depicts a user playing a podcast with a tap gesture. When they touch and hold in (c), the current playback position is felt by a wobble animation (which had the lowest localization error in our user study), enabling them to feel it without interrupting playback. As they swipe up in (d) to advance playback, the new playback position is felt with pulses. In (e), as the user scrolls through the podcast, the timestamps of important chapters in the media are felt by pinch animations (which participants in our user study found easy to recognize). The user cannot scrub beyond the beginning or end of the podcast—if they attempt to do so, (f) the ring plays sweep animations in the opposite direction of their swipe, indicating that no further input will be accepted.

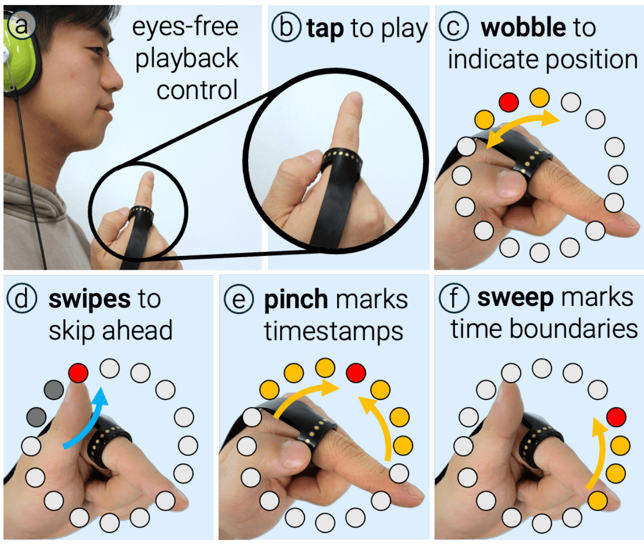

Figure 10: An eyes-free media controller on RingIO.

7 Conclusions & Future Work

In this paper, we presented RingIO, a device we used to propose eyes-free touch-based IO interactions on a smart ring. For multi-touch output, RingIO utilizes thin, low-powered, and compact haptic actuation in the form of electrotactile stimulation. For multi-touch input, it uses capacitive sensing. This allows RingIO to implement a completely eyes-free, symmetric interaction on smart rings: the user touches the ring for input, and the ring touches the user for output. We validated, in a user study, that users can input via touch on a smart ring with collocated electrotactile output. Finally, in a series of applications, we demonstrate eyes-free interactions on smart rings.

While this exploration resorted to external actuators and microcontrollers for rapid prototyping, future work may improve the long-term wearability, comfort, fit variability, and social acceptability of touch-based ring interfaces by miniaturizing the stimulation and multiplexing devices [5, 55] and automating the calibration process [24]. Additionally, if miniaturized, alternative sensors (e.g., IMUs [26], magnetometers [2]) and actuators (e.g., skin dragging [15, 17], poking [16, 38]) may replace/complement RingIO's capacitive sensors and electrotactile stimulation. Finally, future work may expand the vocabulary of tactile animations beyond the four animations that we evaluated in our study.

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