ARO: Exploring the Design of Smart-Ring Interactions for Encumbered Hands

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ABSTRACT

Fingertip computing has seen increased interest through miniaturized smart-rings for augmenting digital peripherals. One key advantages of such always-available input devices is the non-necessity to hold a device for interaction, as it remains affixed to a finger for access when needed. Such a wearable device makes it possible to interaction with content even when the hand is encumbered, by grasping or holding objects. Our investigation aims at understanding the properties of this fundamental smart-ring advantage. We designed a smart-ring prototype, ARO (in-Air, on-Ring, on-Object interaction), which facilitates input while grasping objects. To better identify interaction possibilities, we present the results of an elicitation study through which we grouped various forms of micro-gestures possible with ARO while holding objects under different grasp requirements. We then explored the ability for users to perform different navigation tasks (i.e. zooming and panning) using the smart-ring with encumbered hands. In our studies, users were most efficient when using either In-air or On-ring interactions, in comparisons to gestures detected On-object. Furthermore, In-air was the most preferred by our participants. Based on our findings, we conclude with recommendations for the design of future smart-rings and fingertip devices at large, to allow efficient interaction while hands are encumbered.

CCS CONCEPTS

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

KEYWORDS

smart-ring; touch interaction; mid-air gestures; wearable computing

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1 INTRODUCTION

Commercial smart-rings are emerging on the consumer market and to a large extent are designed to replace current pointing devices [47]. With the potential for miniaturization such fingertip computing devices are presenting their viability for future use in our day-to-day lives. Research in this area has shown advantages for smart-rings in affording multiple interaction modalities [47] and providing always-available input [1, 20, 59]. However, a less recognized advantage of smart-rings is their use while users' hands are encumbered, as the device itself does not required to be grasped. Such interactions include scenarios when holding a bike handlebar or carrying bags. To the best of our knowledge, while use cases

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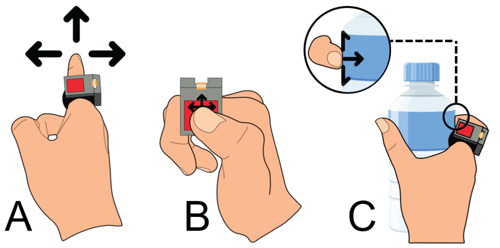

Figure 1: Interaction modalities using the ARO smart-ring; A) In-air technique (mid-air interaction); B) On-ring technique (interaction on the smart-ring); C) On-object technique (interaction directly on the grasped object).

while encumbered provide novel interaction opportunities, such a fundamental use-case has seen limited exploration.

Grasping an object in one of the six common modes (cylindrical, tip, hook, palmar, spherical, and lateral) [43] can constrain the user's interacting finger. Recently, Sharma et al. [46] elicited from participants an array of different micro-gestures possible while holding objects in each of the above grasps. While very informative, their outcomes do not inform how such proposed gestures can be detected and captured using a device. In our paper, by building off prior work on grasp interactions [46] and on smart-ring interaction capabilities [47], we aim to unveil how people interact with a smart-ring while holding objects during tasks that require continuous and/or repeated interactions, specifically zooming and panning. These are widely used and are difficult to perform in encumbered contexts [48]. We explore two research questions: 1) How do grasp types constrain finger movement for enabling smart-ring micro-gestures?; and 2) How well do the various smart-ring micro-gestures support common navigation tasks, specifically zooming and panning?

To answer these questions, we first develop ARO (in-**A**ir, on-**R**ing, on-**O**bject), a smart-ring embedded with common sensors, enabling the thumb to interact with the ring's touch capacitive surface, or by gesturing with the index finger to perform an action. We then conduct an elicitation study while users are wearing ARO and grasping objects. We identify that our participants aim to use simple and non-strenuous interactions. We group the resulting interactions into three main locations: in mid-air/finger gesturing (In-air), on the device itself (On-ring), and interaction directly on the grasped object (On-object), see Figure 1. We then implement the most proposed interaction techniques for the navigation tasks: zooming and panning, through circular motion and directional flick respectively. We find that our users performed faster when using either In-air or On-ring locations compared to On-object. Our participants preferred In-air location for both zooming and panning tasks. Finally, we discuss the benefits and limitations of ARO ring and we address recommendations to design smart-rings that can be used while hands are encumbered.

Our contributions in this paper are twofold: 1) the results of an elicitation study while wearing a smart-ring device and holding a variety of objects with different grasp types. We provide an understanding on how people want to interact with a finger-worn device while encumbered; and 2) the evaluation and comparison of the different elicited input possibilities, for the navigation tasks of zooming and panning when hands are holding cylindrical objects or not.

2 RELATED WORK

Our research was inspired by prior works on finger-worn devices, with a focus on input devices, on the different grasp types as well as by studies investigating the interaction while encumbered.

2.1 Finger-worn input devices

While not a comprehensive review in and of itself, we touch on the general aspects of finger-worn input devices and provide a breakdown of smart-ring literature goals to frame our discussion and work (i.e. by interactivity and encumbrance usage); see Figure 2. Readers may also appreciate a surveyed perspective on finger-worn devices as proposed by Shilkrot et al. [47]. Broadly stated, finger-worn computing can provide users with an always-available device. Shilkrot et al. [47] have classified the different finger-worn computing studies into seven distinct device form factors: ring [1, 18, 20, 21, 68], distal addendums [10], whole-finger addendums [50, 63, 64], fingernail addendums [25, 30], sleeves [29], thumb addendums [9] and on the palm [28, 32, 40]. Prior works have mainly used the device on the index finger [1, 18, 20, 27]. In addition, finger-worn computing can be divided into four main modalities of interaction. These include *clicking or touching the device, touching a surface with the finger, pointing or an external action and gesturing the device in air* [47]. For the authors, Shilkrot et al. [47], the most common modality is to click or touch the smart-ring itself with the opposite thumb. This form of interaction was mainly used to enhance cursor manipulation [26]. Pointing in-air with the finger is often used to refer to an object in one's surrounding. Finally, detecting a finger's movement through the smart-ring benefits user by enhancing the finger's input modality. Several works combine multiple modalities [1, 50] or integrate the finger-worn device with other platforms to ensure fine-grained detection [14, 62].

We have also witnessed a growing number of scenarios and application domains for finger-worn devices. Initially, research focused on augmenting the mouse [39, 40, 50] and the keyboard [8, 15, 16, 38]. Commercial smart-rings such as the *Ring Mouse, Finger Ring Mouse* or *Padrone Ring*[1] are designed to control the on-screen cursor. They include physical buttons to enable left and right clicks. Recently, Weigel and Steimle [54] proposed a novel approach of embedding physical buttons on the ring. Their device enables touch and pressure but also shear and pinch to enlarge the set of possible actions on input devices. Finger-worn devices have also facilitated complex tasks such as text-entry applications [20, 27, 59]. For example, Kim et al. [27] proposed a miniature trackpad on a smart-ring that allows users to interact with their thumb. Researchers have also explored the use of finger-worn computing in other domains such as in remote control applications [18], AR/VR applications [14] or while doing physical activity [6]. However, while research denotes that interacting with a small form factor is efficient, devices are built to serve specific applications and do not take into account any day-to-day interactions. A key opportunity

[1]https://www.padrone.design/

here which often occurs in our lives, use while encumbered, is still under explored and the impact of encumbered use is relatively unknown. To our knowledge, aside from [19, 23, 25, 32], papers do not explore this important component which could aid in adoption.

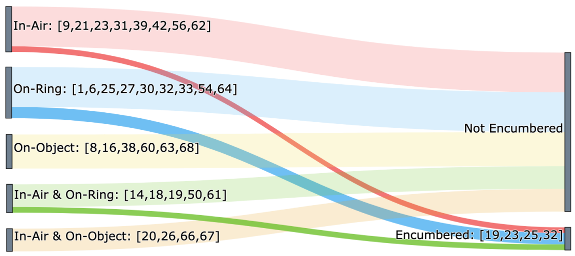

Figure 2: Existing focus on finger-worn input devices function based on the surveyed literature.

2.2 Taxonomy of grasp

Similarly, a taxonomy proposed by Schwarz and Taylor [44] and defined by Schlesinger [43] was defined according to object shape: cylindrical, tip, hook, palmar, spherical, and lateral (see Figure 4 at the top of the table). Cylindrical, for example, involves holding a cylindrical object such as a hammer, a coffee mug or a bottle; tip is holding a small object with the fingertip such as a pen or a nail; hook is holding an object by a handle such as a toolbox or a backpack; palmar is holding objects with the palm such as a box or a book; spherical is holding spherical objects such as a ball or a bowl; and lateral is holding flat objects such as a disk or a piece of paper. This taxonomy has since been used in several studies [22, 41, 46]. In this paper, we build on this taxonomy, but also augment it for our exploration with the possibility of grasping anchored objects (i.e. a steering wheel) or unanchored objects (i.e. a bag).

2.3 Interaction while encumbered

Several works have looked at the impact on input performance while grasping interactive devices, such as a smartphone or smartwatch [4, 13, 36, 37, 48], or common objects such as a handlebar or a steering wheel [17, 24, 49, 65]. For instance, Jung et al. [24] enhanced voice interaction while driving with tactile input. The results of their study showed that Voice+Tactile interactions improved voice-only input efficiency, and more importantly the authors did not find any significant additional distractions while driving. While this work showed promising results, we focus on implementing techniques to interact on continuous and/or repeated interactions, thus voice interaction may not be an optimal input modality. In addition, voice input can be difficult to perform in certain contexts, such as in outdoor environments, due to external noises or social barriers. Finally, simple interaction techniques can be performed while hands are encumbered and while on-the-go using common devices [37, 48] which rely mainly on touch interactions, therefore, we expand this line of research on a finger-worn device.

2.4 Elicitation studies

Elicitation studies play an important role in generating interaction techniques. The interest to include end-users in eliciting designs has grown in recent years as noted by Villarreal-Narvaez et al. [53] in their review. Wolf et al. [58] and Sharma et al. [46] proposed to hold different objects during their elicitation studies. Wolf et al. [58] focused on three objects (a steering wheel, a cash card and a pen). They asked a panel of experts with knowledge on motor abilities to propose micro-gestures while holding those objects and their results highlighted 21 different micro-gestures proposed. More recently, Sharma et al. [46] proposed an elicitation study that explored gestures while holding objects. They proposed two categories for the size of objects (small and large) with a total of twelve objects studied. They asked participants to propose a gesture for common tasks such as select/reject, next/previous, increase/decrease, rotate, etc. while holding these objects. Their study did not constrain proposed gestures to a held device. Their results revealed an impact of grasp and object size on usable micro-gestures. Also, the authors proposed a set of one-handed gestures that can be performed with the common grasp types. Their gestures rely not only on gestures of the thumb and index fingers, but also involve movement of other fingers. As multiple input modalities can be seen as beneficial, this raises the challenge of capturing all their proposed gestures, using a finger-worn device. Gheran et al. [18] asked their participants to wear a ring on their index finger. The results highlighted a set of gestures in which participants proposed to use either one or two hands to interact with everyday tasks (such as turning the TV or lights on and off or answering calls). Participants showed a propensity towards flicking and circular gestures, or directly interacting with the ring (i.e. with buttons or touch). Prior elicitation studies did not inform the user with technical constraints as they did not use any prototype. We decided to build on these works and asked our participants to wear a smart-ring prototype while holding different objects. Our elicitation study places a key importance on the capabilities of the sensing device to generate novel designs for a smart-ring device while hands are encumbered.

2.5 Summary

Our work is inspired by Shilkrot et al. [47] and Sharma et al. [46] works as they provide valuable guidelines for our context. However, few works on finger-worn input devices have focused on encumbrance while holding objects through a variety of grasp types. This area of research needs to be expanded upon to unveil how users can interact with a smart-ring while holding objects during continuous and/or repeated interactions (e.g. panning and zooming). As mentioned before, works on grasping objects do not often take into account how to capture the finger's movement. In summary, our work is at the intersection of research on finger-worn input devices and object grasp, thus while the user's hands are encumbered.

3 ARO SMART-RING

3.1 Concept and Design of ARO

The main aspect when designing our smart-ring was to be able to interact with the device while hands are encumbered. Users should be able to grasp any object while wearing ARO without drastically changing their natural grasp. We therefore explored three factors when conceiving our prototype: input modality, the location and position of the ring and social acceptability.

3.1.1 Input Modality. Based on prior work [47], four input modalities have been identified: *clicking or touching the device, touching a surface with the finger, pointing or external actions and gesturing the device in-air*. In our case, as we focused on encumbered scenarios, touching a surface can be considered equivalent to touching the surface of the object being held. While a hand is holding an object, the nearest surface to touch is the object itself. We designed our ring to meet these four modalities. Therefore, our smart-ring is embedded with an IMU and a touchpad. We decided to use a touchpad as it allows for an increased set of interactions, in contrast to a physical buttons [27].

3.1.2 Location of the ring. Shilkrot et al. [47] groups all the different locations used to wear a smart-ring in prior works and they highlight that wearing a smart-ring on the index finger is the most used. Our pre-tests identified that the proximal phalanx of the index finger was more effective than other locations as it does not alter the grasp of an object being held.

3.1.3 Social acceptability. Shilkrot et al. [47] showed that the form factor of a smart-ring is socially acceptable by users and lets users' hands remain free. Performing discrete interactions is one of the prime benefits of a smart-ring. We considered subtle input methods to avoid social attention when performing micro-gestures with our ring. Even if the ARO smart-ring is an initial prototype, we aimed to take into account the social acceptance from our users.

3.2 Implementation

3.2.1 Hardware. The developed prototype was manufactured using a rigid-flex printed circuit board technology. The device consists of two 18.2mm x 22mm sub-assemblies which contain the various surface mount circuit components, and are connected using an 8.2mm x 20mm flexible ribbon segment, see Figure 3-B. The one sub-assembly acts as the interface to the user and boasts a 14mm x 18mm projected capacitive touch display driven by the MTCH6102 touch controller Integrated Circuit and an MPU-6050 IMU IC to detect orientation and motion. The other sub-assembly contains the bulk of the circuitry including the power regulation circuit, an ATmega328P micro-controller for onboard data processing, and a BM71 BLE module to enable wireless connectivity. Power and data bus connections between these two sub-assemblies is provided by the flexible ribbon segment. The device is powered using a 3.7V 70mAh Lithium Ion Polymer rechargeable battery, measuring only 15mm x 20mm x 4.8mm. The case was 3D-printed using PolyLactic Acid, see Figure 3-A. A strap was attached at the bottom of the case to allow users to comfortably adjust the ring to the size of their finger. Once the circuit board is assembled with the 3D case, the dimension of the ring is 42mm x 23mm x 27mm for a total weight of 8 grams.

3.2.2 Software. All the data from the on-board capacitive touch driver are communicated to the micro-controller over a single I2C data bus. The firmware filters and processes this incoming data are then transmitted to the BLE module. On the micro-controller, a Kalman filter [55] is used to estimate the optimal state of the system which is similar to the weighted average. Unity was selected as the platform to build the receiving protocol of the BLE module.

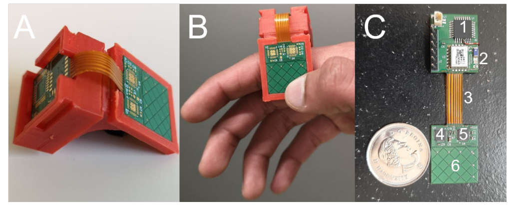

Figure 3: A) The touch capacitive sensor and circuit board attached to the 3D printed case; B) The smart-ring when worn; C) The components (1: Micro-controller; 2: BLE; 3: Flexible ribbon; 4: IMU; 5: Gyro/Accelerometer; 6: Touchpad) shown to scale using a coin with a ~24mm diameter.

4 STUDY 1: ELICITATION STUDY

To explore the potential of the ARO smart-ring, we elicited user input through an elicitation study [7, 46, 57]. Our goal was to investigate the mapping of possible micro-gestures from ARO and common mobile devices' tasks (inspired and adapted from Chan et al. [7] and Serrano et al. [45]).

4.1 Overview and rationale

Prior work on elicitation studies has allowed participants to propose micro-gestures unrestricted of the capacities of the sensors or other factors surrounding the device. In this work, we decided to use a different approach and presented to our participants our smart-ring device. This was motivated by two reasons. First, this would focus on interaction techniques for which we already have a sensing capability. Second, this would allow for an easy transfer to ecologically valid scenarios using the proposed hardware. Therefore, participants proposed a set of interactions that have the potential to be further developed and tested based on the hardware. We considered this approach to further solidify the real-case usage scenario of ARO (i.e. a single a smart-ring which cannot capture all fingers' movement, thus we were not interested in participants elicitations regarding multiple fingers).

We envision that a prime opportunity for the use of a smart-ring can be seen when hands are encumbered. Consequently, we focused our study on scenarios where users may typically have their hands encumbered, such as using handlebars while biking, or carrying bags.

4.2 Referents

We focused on common mobile device tasks to choose our referents. We chose music control, which affords discrete interaction, and map navigation tasks, which allow for continuous interaction. These referents were inspired and adapted from Chan et al. [7] and Serrano et al. [45]). Therefore, our list of referents is: *volume up, volume down, next, previous, mute, play, pause, pan, zoom-in, zoom-out*. We are aware that usually pan is broken down into four referents (i.e. pan-left, pan-right, pan-top and pan-down) in prior works. However, we considered that pan is mostly used in directional gestures (for example going South-West in a single interaction), therefore we treated it as single referent where interactions can be adapted for multiple directions.

4.3 List of objects

We chose our objects according to the six grasp types proposed by [43]: cylindrical, palmar, hook, lateral, tip and spherical. Everyday grasping involves two types of objects, anchored and unanchored. We considered an anchored object as an object that constrains the range of motion of the person while holding the object. These objects can be heavy (e.g. suitcase) or attached to other larger objects (e.g. steering wheel). In contrast, an unanchored object is an object that can be carried easily by the user with one hand and does not constrain normal movement. For each of the six grasp types, we considered one anchored object and one unanchored object for this study. Thus, our list of objects in this study are: *handlebar, bottle, large box, book, laced shoe, lip balm, large suitcase, bag, large watermelon, tennis ball, backpack strap, key*, see Figure 4.

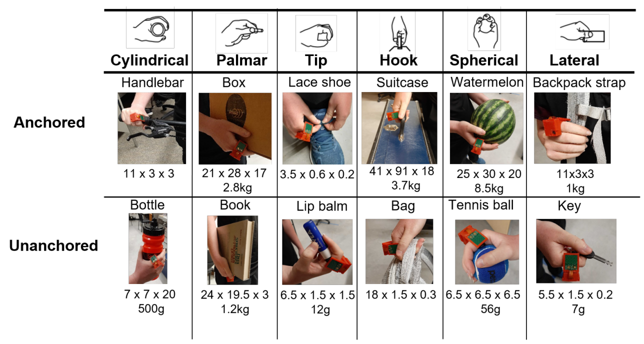

Figure 4: Corresponding objects according to the grasp. The dimensions are in centimeters.

4.4 Task and instructions

The task was to propose a single interaction technique for each combination of referents and objects. Before the study, the experimenter explained the capabilities supported by our ARO smart-ring. This included how to wear the ring, which different sensors are embedded and their possibilities for interaction, as well as its limitations. We informed the participants that the proposed interaction technique could utilize combined modalities (i.e., using the trackpad while making a gesture with the index finger). The experimenter presented the list of objects and referents that were used during the study. To engage our participants to think about interaction, the experimenter presented to them four scenarios. We pointed out to the participants that sometimes, the task and the object held might not be related but the grasp is more important than the object itself. Participants had to wear the ring and hold the objects using their dominant hand. At the end of the study, we asked our participants to propose several delimiter interactions, requiring at least one. The delimitation of the interaction technique was necessary to avoid trigger commands by mistake, therefore we probed our participants for their suggestions.

4.5 Participants

We recruited 12 participants (1 female and 11 males) from our local university. Participants were aged 24.2 on average (SD=3.9). Among them ten had a background in Computer Science and two in Physics. Eleven participants were right-handed and one was left-handed.

4.6 Design and Procedure

This study was conducted during the COVID-19 pandemic. As such, special permission from the university ethics board was obtained for in-person human subjects data collection, and up-to-date health guidelines were strictly followed before, during, and after the experiment. Our elicitation followed a within-subjects design. The order of objects and referents were randomized. We asked participants to be standing (to put them in a realistic situation), during the whole study, however breaks were offered when needed. The experimenter presented each of the objects to the participants and how to correctly hold the object. Then the participant had to propose a single interaction technique for each of the ten referents. The study took approximately 1 hour.

4.7 Apparatus and collected data

All the objects proposed were from a real-world environment and were not 3D-printed. The ring was positioned on the index finger at the segment of the finger closest to the palm (i.e. the proximal phalanx). We recorded all user's verbal comments and annotated every proposed interaction technique. In total, we collected 12 (objects) x 10 (referents) x 12 (participants) for a total of 1440 number of proposed interactions.

4.8 Results

4.8.1 Compiling interactions. To reach the same vocabulary across participants, we refined the proposed interactions of our participants, in the same manner as [46]. Experimenters clustered the interactions into five specific factors: the location of the interaction (i.e. On-ring, On-object, In-air), the type of the interaction (i.e. taps, flick, gestures), the direction of the action (i.e. left, right, up, down, inward, forward), the number of interactions (i.e. double-tap, triple-tap) and the initiators of the interaction (i.e. thumb, index, wrist). Every interaction technique was coded following this procedure. Overall, we found 54 different interaction.

4.8.2 Agreement Rate. As in previous works, we calculated the agreement rate (AR) using the Agreement Analysis Toolkit proposed by Vatavu and Wobbrock [51]. However, we decided to not take into account the direction of the interaction in the calculation of the consensus score (for example, flicking left versus flicking right are both considered as a general flick). We were interested in high level interactions being elicited and then grouped only by location and type.

The mean AR across all objects and of all referents was 0.385 (SD = 0.228). Figure 5 displays the agreement rate among the objects and referents. Our highest AR was 1 and our lowest AR was 0.045. The referents zoom-in and zoom-out generated the most disagreement among users compared to the other referents.

4.8.3 Interaction location. We analyzed where the location of the interaction took place, and identified three main locations: In-air, On-ring, On-object. To reiterate, In-air means moving the index finger or the wrist in mid-air to perform the command. On-ring means that the interaction is on the trackpad. On-object means an

	Anchored objects						Unanchored objects					
Referents	Cylindrical	Palmar	Hook	Lateral	Tip	Spherical	Cylindrical	Palmar	Hook	Lateral	Tip	Spherical
Volume Up	0.424	0.333	0.682	0.182	0.197	0.439	0.212	0.348	0.833	0.439	0.258	0.561
Volume Down	0.424	0.333	0.561	0.182	0.197	0.439	0.273	0.258	0.833	0.439	0.348	0.561
Mute	0.288	0.288	0.591	0.152	0.045	0.288	0.258	0.439	0.561	0.136	0.242	0.333
Play	0.697	0.439	1	0.273	0.106	0.328	0.58	0.833	1	0.136	0.258	0.833
Pause	0.591	0.439	1	0.273	0.121	0.47	0.288	0.697	1	0.136	0.258	0.833
Next	0.197	0.227	0.591	0.182	0.242	0.182	0.424	0.242	0.439	0.697	0.455	0.242
Previous	0.212	0.258	0.591	0.197	0.364	0.348	0.424	0.258	0.545	0.697	0.455	0.242
Pan	0.379	0.288	0.561	0.561	0.471	0.379	0.591	0.682	0.561	0.697	0.833	0.197
Zoom In	0.121	0.106	0.258	0.242	0.121	0.212	0.167	0.106	0.197	0.561	0.439	0.121
Zoom Out	0.106	0.106	0.258	0.258	0.136	0.212	0.242	0.106	0.197	0.561	0.364	0.136

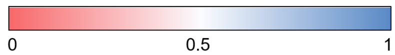

Figure 5: Agreement Rate for all referents and objects.

interaction takes place on the object held. Furthermore, we found few specific interactions (less than 1.8%) that derived themselves from both In-air and On-object locations. In this rare case, we defined these interactions as On-body, which are defined as using or referring to a part of the body itself. For example, this may include rubbing your index finger and thumb together or pointing to a specific body part such as a shoulder.

While using anchored objects, the most preferred location was On-ring (56.39% on average) and In-air (27.37%), see Figure 6-Left. For unanchored objects, the results showed that In-air is the most preferred with 48.06% and On-ring (39.76%). We further note, when the object is cumbersome or difficult to move with, participants preferred to use the On-ring location.

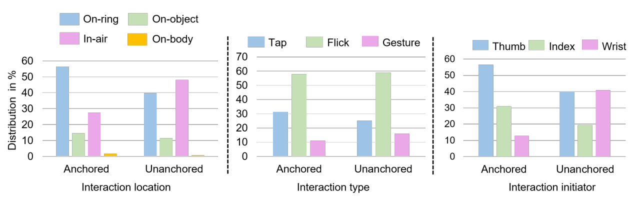

Figure 6: Left: Location of the interaction for our objects; Middle: Type of interaction for our objects; Right: Interaction initiator for our objects.

4.8.4 Interaction type. We analyzed the types of interaction that the participants proposed. We found three main interactions: tap, flick and gesture. Note that all these interaction techniques can be performed on all locations (In-air, On-ring, On-object, or On-body). Tap interactions are short and can include any number of taps when an interaction was proposed. Flick is any directional sliding movement from the finger or wrist. Finally, gestures include any movement or shaped drawing proposed by the participants.

While using anchored objects, the types of interactions preferred by our participants were flick (57.8% in average), then tap (31.2%), and finally gesture (10.98%), see Figure 6-Middle. For unanchored objects, following the same trend as anchored, the results showed that 58.90% of our participants proposed flick interactions, 25.23% proposed tap interactions and 15.87% proposed gesture interactions.

4.8.5 Interaction initiator. We analyzed the initiators (or delimiters) to perform the interaction. ARO smart-ring offers 3 possibilities to initiate the interaction: using either the thumb, the index finger or the wrist. The thumb entails interacting on the trackpad, while the index finger and wrist movement allow for mid-air interactions.

While using anchored objects, the most preferred initiator was the thumb (56.39% in average), then the index finger (30.75%) and finally the wrist (12.84%), see Figure 6-Right. For unanchored objects, the results showed that the wrist was the most used at 40.98% of proposed interactions, then the thumb and index finger at 39.76% and 19.25% respectively. When holding unanchored objects, our participants felt more free in their movements, therefore they tended to proposed wrist interactions the most. Furthermore, some grasps (especially lateral grasps) do not physically allow to perform On-ring interactions, as the thumb is used to grasp the object.

4.8.6 Combined interactions. We found that 5.76% of all interactions proposed were combined. Among these combined interactions, we analyzed the type of interactions used: 41.23% of our participants proposed only interactions on the trackpad (for example, tap then hold), 28.04% proposed only gestures (for example, mid-air flick gestures then pointing in mid-air) and 30.48% proposed both (for example, a tap on the trackpad followed by pointing in mid-air). Vernier and Nigay [52] proposed a framework on the temporal relationship between input modalities. Among the five they introduced (order, succession, intersection, inclusion, simultaneity), our combined gestures were either succession, at 65% on average, or simultaneity, at 35% on average.

4.8.7 Subjective report. First, none of our participants declared that wearing ARO while holding objects was an issue; they could all grasp naturally all objects with the device. All the participants reported that they initially attempted to reach the trackpad on the ring while holding a new object; this was in order to first perceive if the On-ring interaction technique was feasible. This denoted a strong tendency toward using the On-ring technique. Furthermore, our participants reported that using the trackpad was the most simple and natural technique to use. They declared that the On-ring technique was the most discrete compared to the other locations; this favored interaction technique was noted as not drawing any attention in public spaces. Participants tended to map the referents with their habits: for instance, for previous/next using the same interaction technique as on common mobile devices. Although, when participants declared it difficult to achieve a certain directional interaction technique they desired, due to the grasp and the object, interestingly they would default to choosing the more comfortable direction for both previous/next referents, i.e. flick left interactions for both previous and next referents.

4.8.8 Summary of the results. As our participants wore ARO as well as held different objects, the results of our elicitation study show some differences with prior works that did not constrain users. First, our participants mostly elicited the use of the trackpad on the ring while holding objects (more than 50% on average). These findings suggest that participants mainly relied on capacitive touch, a traditional interaction modality. The agreement score shows that lateral and tip grasps generate the most disagreement between our participants. These grasps constrain the movement of the fingers and the findings suggest than when participants cannot rely on popular input modalities, they do not reach a consensus. Contrary to the hook grasp, where participants proposed similar interactions as they rely mainly on the trackpad. In contrast to Sharma et al. [46], interaction On-object was less solicited, however the participants of their study did not wear any device, therefore they could not rely on a specific technology. This major difference between the two elicitation studies played a key role in the results. Asking participants to wear the ARO smart-ring during the study, with the knowledge of its capabilities, allowed participants to use and explore the device as an input modality to its full potential. Yet, we found similar results in the type of interactions proposed, which confirmed that participants mainly considered well-known micro-gestures to trigger a command. Finally, in our study, we also considered the aspect of using anchored objects and unanchored objects. We found that the size and the manoeuvrability of an object impacted the proposed interactions. In-air techniques tended to be less proposed with an anchored object, where participants preferred On-ring techniques.

5 MATERIAL AND METHODS

The goal of our studies was to evaluate the performance, the error rate and the user preference of zooming (Study 2) and panning (Study 3) tasks using the three techniques (In-air, On-ring and On-object) while encumbered, as well as an unencumbered condition which acted as our baseline.

5.1 Interaction techniques

We selected techniques based on the results of the elicitation study to further investigate the performance with common navigation tasks (zooming and panning). Such tasks provide a basis for interacting with many workspaces and we decided to explore these in this first investigation. We decided to focus on a single factor: the location of the techniques. We discarded the On-body technique as this technique was barely proposed by participants in our previous study (less than 2%). Therefore, we focused on these three locations: In-air, On-ring and On-object see Figure 1. These locations can be used regardless of which object is being held. From our elicitation study, we chose the most commonly proposed techniques for the zoom and pan referents, by combining the results of the three locations, which were circular motions and the directional flicks respectively. Therefore, the same interaction technique is used for all three locations. We developed circular motion gestures to allow zoom-in/out interactions using the same implementation as [34] and [45].

5.2 Objects

To keep the length of the study reasonable, we decided to only use cylindrical grasp, one of the most common grasps, for our study; thus we used a handlebar and a bottle (one anchored and one unanchored object). To represent the handlebar for the study, we used a cylindrical bar that we placed on a desk raised by a few centimeters. This bar was fixed, it could not fall during the study. Also, the rise allowed the participants to hold the bar with the same grip as an actual handlebar, see Figure 7-C.

5.3 Tasks

For the zooming task (Study 2), we required participants to reach a targeted donut shape. This target stayed in the same position across all trials. A circle, which needed to be zoomed-in/out had six levels of zoom: three smaller than the target and three larger. The goal was to match the circle with the target donut. Participants were instructed to complete the task as accurately and as fast as possible. To avoid the need for memorization, we placed arrows to show participants the direction (clockwise or counterclockwise) needed to reach the target, see Figure 7-A. For the panning task (Study 3), we asked participants to reach a targeted icon. This target was located outside of the window, which required participants to perform pan gestures to reach it. The cursor was represented by an arrow and showed participants the direction they needed to go in order to reach the highlighted target (the task was not about searching for the target), see Figure 7-B.

5.4 Design and Procedure

The two studies followed a 3x3 within-participants design with Usage Scenario (unencumbered, anchored object, unanchored object) and Locations (In-air, On-ring, On-object) as factors. We counterbalanced our factors across participants using a counterbalanced Latin Square Design. First, for each participant and all usage scenarios and locations, we tuned the range of the interaction to their index's motion capacities. Then, participants practiced with each technique to perform the task. Once they felt comfortable with the technique, they could start the trials. For the On-object unencumbered usage scenario, we asked participants to perform the gestures on the desk directly, thus the finger moved on the surface of the desk.

5.5 Apparatus

We used our ARO smart-ring to detect user's gestures. ARO was connected to a computer using Bluetooth and we implemented the gestures and the interface for the study using Unity. Participants were sitting at a desk and trials were displayed on a monitor, see Figure 7-C. To record time performance, we provided participants with a numeric keypad. Whenever, participants were ready to start a trial, they could touch any key to set the timer. The timer stopped when the trial was completed successfully (i.e. when the correct zoom level was reached).

5.6 Collected data

We logged all tracking movements and measured the time to complete the trial and considered an error as the participant crossing over/past the target. At the end of the study, we asked the participants to rank their preferred techniques for each Usage Scenario. For each studies, we collected 3 (usage scenarios) × 3 (techniques) × 6 (target) x 3 (repetitions) x 12 (participants) = 1944 trials in total.

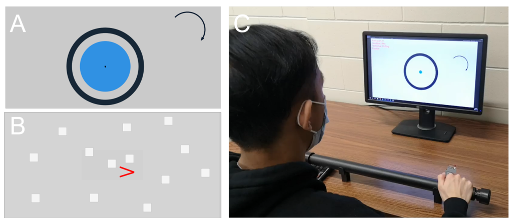

Figure 7: A) Visual feedback for the zooming task. The goal was to ensure the Blue solid circle filled in the donut; B) Visual feedback for the panning task. The goal was to ensure the off-screen target was placed at the center of the screen, denoted by a cross-hair. The arrow shows the direction to pan to reach the off-screen target; C) Apparatus for the study pictured for the zooming while holding a handlebar.

5.7 Analysis

Recently, criticism of the null-hypothesis significance testing (NHST) to analyze experiments [3, 11, 12] led us to report our results using estimation techniques and confidence intervals (0.95) instead of p-values, consistent with the APA recommendations [2]. We followed the analysis used by Besançon [5] which is available online[2].

6 STUDY 2: ZOOMING TASK USING ARO

6.1 Participants

We recruited 12 participants for this study (3 females and 9 males) aged 27 years on average (SD=8.9) from our local university. All of them were right-handed and none of our participants were color blind.

6.2 Results

6.2.1 Quantitative results. For each condition and location, we measured in seconds the time taken and the error made per trial, see Figure 8. As the study is a within-subject design, we can compute the difference individually for every participant. We measured the pair-wise difference of the confidence intervals between the In-air and the other techniques. Concerning the response time, our finding shows evidence than In-air location is faster than On-ring and On-object, when using unanchored objects (the intervals do not overlap). Concerning the error rate, within the unencumbered condition and the anchored object, On-object is less prone to errors than In-air location (the intervals do not overlap).

[2]https://aviz.fr/ci/

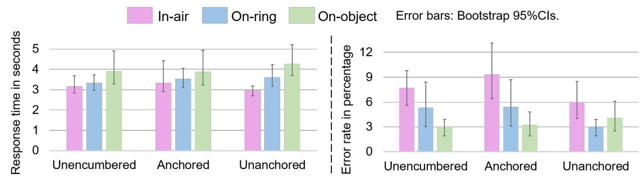

Figure 8: Left) Response time in seconds for the zooming task; Right) Error rate in percentage.

6.2.2 User preference and qualitative results. Participants ranked first the In-air location (5 participants) then On-ring (4 participants) and On-object (3 participants) across the three Usage Scenarios. Participants felt "comfortable" with On-ring location (P5 and P12) and were "natural to use" (P1, P8, P11). However, some participants complained about the size of the trackpad being "too small" (P4 and P11) and depending on the grasp, participants had some difficulty to reach the trackpad (P4 and P9). When using the On-object location, interestingly, participants felt more "accurate than the other techniques" (P3, P7, P9 and P12) but they declared that "the range of motion was smaller" compared to the other techniques (P4 and P9). Using In-air techniques, participants stated that they felt "comfortable" (P1, P2, P3, P9 and P12), ARO was "easy to use" and (P2, P5 and P7) and had a large "motion of control/ freedom on the movements" (P7, P8 and P9). Yet, they are not willing to use this location in a social context (P2, P3, P4).

6.2.3 Summary. In-air location performed faster than On-object location while holding an unanchored object. On the contrary, while using On-object location, participants were more precise than In-air while holding anchored objects. These findings show that participants show more confidence using In-air location however they tend to be more prone to errors. For On-object location, participants were slower but permits to show better results in term of error rate. Finally, In-air location was preferred among the locations by our participants.

7 STUDY 3: PANNING TASK USING ARO

7.1 Participants

We recruited 12 participants for this study (3 females and 9 males) aged 28.5 years on average (SD=6.1) from our local university. All of them were right-handed and none of our participants were color blind.

7.2 Results

7.2.1 Quantitative results. As done in Study 2, for each condition and location, we measured in seconds the time taken and the error made to perform the task, see Figure 9. We calculated the pair-wise difference between On-object to On-ring and In-air. Concerning the response time, we found that across all Usage Scenarios, On-Object performed worse than On-ring and In-air. The results showed strong evidence that On-Object is slower than the other locations across all Usage Scenarios (the intervals do not overlap). Concerning the error rate, we do not observe any difference across all usage scenarios and locations.

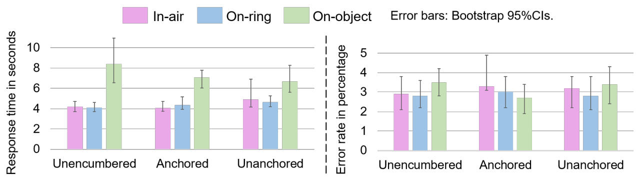

Figure 9: Left) Response time in seconds for the panning task; Right) Error rate in percentage.

7.2.2 User preference and qualitative results. Participants ranked first the In-air location (6 participants) then On-ring (4 participants) and On-object (2 participants) across the three Usage Scenarios. Overall, participants stated the same pros and cons from the previous study. However, there are some differences when performing a panning task. For our participants, using the On-ring location allowed more "controlling" of the speed and the direction when compared to the other techniques (P1, P4, P5, P7). Contrary to the zooming task, when using the On-object location participants felt less fatigue for the panning task (P2, P3). Furthermore, moving in all directions was sometimes "difficult" while holding both anchored and unanchored objects (P4, P6).

7.2.3 Summary. We observe across our Usage Scenarios, that In-air and On-ring locations performed equally well and were preferred. The On-object location performed the worst during the panning task, although having some qualitative benefit. Finally, we note that participants tended to slightly prefer the In-air location over On-ring, both of which were preferred to On-object. The three locations performed equally in terms of error rate.

8 DISCUSSION, LIMITATIONS AND FUTURE WORK

8.1 Discussion of the three studies

Contrary to several elicitation studies, we decided to ask our participants to wear and familiarize themselves with our ARO smart-ring as well as the objects to be held. By doing this, we wanted to put our participants in a directly relevant context, involving a smart-ring. Thus, participants had to propose interactions that were able to be captured by ARO. The results of our elicitation study (Study 1) permitted us to highlight three locations of interactions: In-air, On-ring and On-object. Similar to [46], we found that the grasp type and the use of different objects (size and manoeuvrability) impacts the interactions proposed by our participants. We also note that the interactions by our participants are well-known, and simple techniques which indicate that participants tend to reproduce daily interactions on their finger-worn wearable devices [35]. However, while grasping objects, we note that participants wanted to take advantage of the object, so as not to disrupt their grasp, and thus chose to directly interact on the object. Having participants physically wear ARO, that is always-available to them through multiple input modalities, allowed participants to explore this and other capabilities for interacting with a smart-ring.

We developed and tested three locations by focusing on navigation tasks (Study 2 - zooming and Study 3 - panning). Among the two studies, In-air was the preferred location according to our participants. While the On-object input was highly elicited in Study 1, the performance outcomes of this region tends to perform slower than the two other approaches. However, for the zoom study, On-object was the most precise compared to the others. One reason might be that the On-object allows for a smaller range of motion due to the grasp needed on the object. Indeed, while holding the object the participants had to interact with the same hand, resulting in the movement of the index finger being reduced and therefore impacting performance but providing more precision. This finding is supported by the feedback from our participants that felt more constrained in their finger range-of-motion with such a grasp.

8.2 Applications Scenarios

To illustrate the feasibility and potential applications using a smart-ring while hands are encumbered, we suggest two scenarios: 1) while cooking and 2) while on-the-go. These applications often require a user to touch the display of their device, but while hands are encumbered it can become challenging. For instance, following a specific video recipe can require several back-and-forth scrubbing actions as well as pause/play to follow the different steps at our own pace. Using a smart-ring while cooking, and thus while using different grasps for the cooking actions needed, can facilitate the interaction. For example, In-air location can be used for video scrubbing while holding a bowl and spoon during mixing. Another encumbered usage scenario is to interact with the smart-ring while on-the-go. For instance, a user holding grocery bags can use the smart-ring and the On-Ring technique in a natural position to efficiently interact with their smartwatch while quickly navigating through text messages or an e-mail. The above scenarios highlight two of many instances where there is need for interaction techniques that can be used while hands are encumbered and how the results of this work can be utilized.

8.3 Recommendations for designing smart-ring interactions

Embed with multiple sensors. During our elicitation study, we found that our participants did not hesitate to take advantage of all the sensors. This finding supports the fact that the ring should be embedded by multiple sensors to allow a wide range of possible interactions in different locations. Holding objects while interacting with the ring is one of the prime benefits of its use and thus, depending on the size and grasp of the objects being held, users will prefer different interaction types for their tasks. On-ring location was the most elicited, however our navigation studies revealed that In-air location was the most preferred to perform panning and zooming tasks. There is also a need to propose different locations for the same commands. This can allow the user to find their most appropriate and preferred locations for performing the desired task regardless of grasp type.

In-air location should be prioritized. Our results highlighted In-air location was the most preferred by our participants for navigation tasks. Therefore, when designing future smart-rings, the devices should support such an input modality. During our elicitation study, In-air input was the most elicited (48%) when using unanchored objects. This suggests that participants, when holding objects that are not heavy and/or not cumbersome, prefer to interact through mid-air finger gestures.

8.4 Limitations and future work

Improve ARO ring prototype. While our participants were able to perform the interaction techniques with the ring while holding objects, there is a need to further reshape and resize our ARO ring to reach a design that is as minimal and thus as comfortable as possible.

Expand to other grasps types. For our navigation studies (Study 2 and Study 3), we only focused on cylindrical grasp. Future work should expand on our studies to evaluate the impact on a wider array of grasps.

Evaluate while on-the-go. For the scope of this paper we focused on smart-ring interaction while grasping objects, therefore our studies were performed in a controlled environment and in a seated condition. To truly study such interactions we aim to evaluate our approach while on-the-go, under walking and/or running conditions, in future work. The increase in cognitive load on the user is another factor to study under this condition.
Combined with other inputs modalities. While our paper is an initial step on the use of finger-worn devices while hands are encumbered, there is benefit to exploring the use of multi-modal inputs, such as adding voice with the current interactions. Expanding ARO with Jung et al.'s work could potentially facilitate the use of increased interaction techniques allowing for a complete range of interaction in complex tasks and across all grasp types.

9 CONCLUSION

This paper investigates the performance of a finger-worn device, the ARO smart-ring, which benefits from multiple interaction capabilities during encumbered scenarios. First, through an elicitation study, we asked participants to perform micro-gestures with the ring while holding anchored and unanchored objects requiring an array of grasps. The results shown that participants proposed 54 different interactions, located into three main locations: In-air, On-ring and On-object. From this, we designed three interactions based on the above locations. We took the preferred techniques for the zoom and pan referents, which were circular motions and flick gestures respectively. In a second study, we evaluated our modalities in a zooming task while unencumbered, holding an anchored object, and an unanchored object. We found that In-air and On-ring locations were the most efficient to perform the task across all usage scenarios. Finally, in a third study, we explored flick gestures in the desired direction for panning. The On-object location performed the worst across all our usage scenarios. Furthermore, we consider that smart-rings are well-suited for encumbered scenarios, and thus we address design recommendations for future works on smart-rings while users have their hands encumbered.

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