

EarTouch: Facilitating Smartphone Use for Visually Impaired People in Mobile and Public Scenarios

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ABSTRACT

Interacting with a smartphone using touch input and speech output is challenging for visually impaired people in public and when commuting, where only one hand may be available for input (e.g., while holding a cane) and using the loud-speaker for speech output is constrained by environmental noise, privacy, and social concerns. To address these issues, we propose EarTouch, a one-handed interaction technique that allows the users to interact with a smartphone using the ear-touch gestures. Users hold the phone to their ear and listen to speech output from ear speaker privately. We report how the technique was designed, implemented, and evaluated through a series of studies. Results show that EarTouch is easy, efficient, fun and socially acceptable to use.

CCS CONCEPTS

• **Human-centered computing** → **Accessibility technologies**; *Participatory design*;

KEYWORDS

Accessibility; Vision Impairment; Smartphone; One-handed Interaction; EarTouch; Capacitive Sensing

ACM Reference Format:

Ruolin Wang, Chun Yu, Xing-Dong Yang, Weijie He, Yuanchun Shi. 2019. EarTouch: Facilitating Smartphone Use for Visually Impaired People in Mobile and Public Scenarios. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019)*, May 4–9, 2019,

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CHI 2019, May 4–9, 2019, Glasgow, Scotland Uk

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ACM ISBN 978-1-4503-5970-2/19/05...\$15.00

<https://doi.org/10.1145/3290605.3300254>

Glasgow, Scotland Uk. ACM, New York, NY, USA, 13 pages. <https://doi.org/10.1145/3290605.3300254>

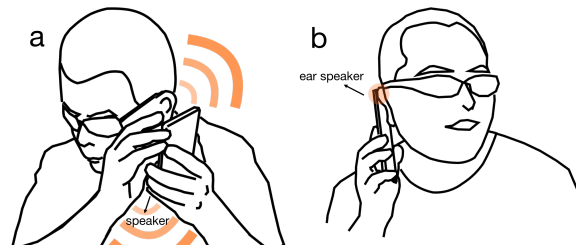


Figure 1: (a) FingerTouch vs. (b) EarTouch. The Shadow indicates the range of sound propagation of speech output.

1 INTRODUCTION

Smartphones have become an important part of the life for Blind and Visually Impaired (BVI) persons, who rely on screen readers (e.g., VoiceOver [30] and Talkback [40]) to interact with the phone. However, interacting with a smartphone using touch and speech output has significant limitations for BVI users in mobile and public scenarios as input often requires both hands, with one hand holding the phone and the other interacting with the screen. This can be frustrating while in transit, especially when one hand is occupied, such as holding a cane. Additionally, using the smartphone speaker for output is constrained by environmental noise, privacy and social concerns in public settings. BVI users have to hold the smartphone close to the ear, which enables auditory comprehension at the expense of input comfort and convenience (Figure 1.a).

In this paper, we propose EarTouch, a one-handed interaction technique that allows BVI persons to interact with a smartphone using the ear to tap or draw gestures on the touchscreen. Since the smartphone is held against the ear, the user can hear the speech output played via the ear speaker privately (Figure 1.b). This technique is unique because it supports touch and auditory reception in one natural posture, facilitating one-handed use and providing an alternative to

headphones. Designed to be used in mobile and public scenarios, the technique supports common tasks for BVI users, like answering a phone call or sending an audio message.

The proposed technique creates a new space for novel interactions for BVI users. However, there exist technical and human-factor challenges to overcome. The ear is soft with a complex shape. Therefore, its contact patterns with the touchscreen are complicated, as opposed to the single point of a finger touch, this makes it hard for the phone to track its movement and gestural input. Additionally, the ergonomics of interaction are reversed: Ear-touch gestures has to be performed by moving the device and not the input apparatus (ear). So the design of interaction paradigm cannot be generated by directly leveraging the knowledge that we have about finger-based touch.

To extract design goals for EarTouch, we first conducted formative interviews to better understand the current practice of BVI smartphone users while in mobile and public scenarios. To explore the feasibility of EarTouch, we conducted a user-elicitation study to identify a set of ear-touch gestures that are socially appropriate and acceptable, as well as being comfortable to perform by the BVI users. Based on the results of our study, we then designed and implemented our EarTouch prototype on a commodity smartphone using the capacitive images of the touchscreen and inertial sensor data. Finally, we conducted two user studies to evaluate the technique efficiency and user experience in practical scenarios. Results showed that EarTouch was easy, fast, and fun to use, and address privacy and social concerns. Our participants acquired EarTouch in less than 10 minutes and expressed a strong interest in using this technique in their daily life.

Our contributions are three-fold: (1) formative interviews with 30 BVI smartphone users, and a user elicitation study with 23 BVI participants to motivate and guide the design of EarTouch; (2) EarTouch, a novel interaction technique including ear-touch gestures set, suitable application tasks and an image processing algorithm that can recognize and track ear movement on the touchscreen of a commercial smartphone; and (3) two user studies with 22 BVI participants in total, evaluating the performance of one-handed interactions and user experience in mobile and public scenarios.

2 RELATED WORKS

In this section, we briefly discuss the existing research on smartphones, including issues of screen readers for BVI person, works on one-handed techniques and novel touch input.

Issues of Screen Readers in Mobile Public Scenarios

Since the introduction of Slide Rule [22], screen readers have become the most important tool for BVI smartphone users. However, research to-date suggests that BVI smartphone

users still face numerous challenges in daily life, especially in mobile and public scenarios, where issues such as the constraints to two-handed interaction [1, 10, 23, 50], environmental noise [4, 10, 23], privacy [1, 2, 23, 35, 50], social concerns [1, 45, 50], social etiquette [1, 50], safety [4, 5, 45] and portability [35] issues of using earphones are common.

Touch interaction with a screen reader often requires the smartphone to be held stable, and thus requires two hands [12, 15]. BVI persons invented more gestures that used two hands than sighted persons [24] while multi-touch techniques [8] are nearly impossible to perform with one hand [31]. Researchers have suggested that performing gestures while walking is particularly difficult [10]. Freeing the hand from holding a cane or guide dog to interact with the touchscreen is regarded as being unsafe [1] and cumbersome [23, 50]. Kane et al. [23] found more than 70% of the participants carried a cane in public, this shows a pressing need for an effective one-handed interaction technique.

Speech output is difficult to properly comprehend in a noisy environment [4, 10, 23]. Privacy is another big concern in public scenarios, which may restrict the use of smartphones [1, 2, 23, 35, 50]. This problem worsens in situations where the user is unaware of their social environment [2]. In addition to privacy, playing auditory output in public may draw attention from nearby people, making it less social acceptability [50]. On the other hand, from the user's perspective, playing auditory output loudly in the public may draw unwanted attention from the others [1, 45]. Research has shown that there is a desire from the visually impaired community to avoid noise from the screen reader intruding to the personal space of nearby people [50], this can be challenging, especially in a quiet public environment, where the simplest task could be difficult to perform without interfering the others [1]. Headphones can provide the desired privacy for auditory interaction [50]. However, safety is one of the major concerns for not using headphones because background sound is blocked [4, 5, 45]. The portability issue of using headphones has also been mentioned [35].

One-Handed Techniques

One-handed interaction techniques have been widely studied on smartphones for sighted users, including applications for text entry [6, 13, 51], target acquisition [25, 29], and web browsing [44]. To support this wide range of applications, novel input techniques have also been developed to allow users to interact with the smartphone via tapping the body of the phone [42, 43], gesturing on the back of the device [48], gesturing on or above the screen [7, 18, 29, 52], and bending [14] or tilting [46] the device.

In contrast, relatively little effort has been made to support one-handed smartphone use for visually impaired users. The

existing works include text entry using Braille [3, 11, 54], target acquisition using tactile icons when walking [39], outdoor navigation using bluetooth [27] and access to application shortcuts [31]. We argue that visually impaired users should not be cut off from the latest advances for sighted users, such as techniques that improves one-handed usability.

Novel Touch Input

Beyond fingertips, other body parts could extend input possibilities by serving as an input device or an input surface. Researches have looked into the different parts of the body as an input device for the touchscreen, including using the knuckle [17], nose [53], and back of the hand [34]. Holz, et al. [21] use the capacitive image of the ear, fist, and palm for smartphone authentication. Different parts of the body can also serve as a touch input surface. With the additional sensing technique worn on finger or body, users could use the finger to touch on the ear [26, 32, 33, 37], cheek [49], and palm [36, 37]. In EarTouch, ear serves as an input device on smartphone touch screens. Our work support ear gestures to facilitate smartphone interaction for BVI users.

3 FORMATIVE INTERVIEWS

Although prior studies provided some insights, we want to better understand the current practice and issues in smartphone usage of BVI persons in mobile and public scenarios, and to uncover the reasons behind these issues. Specifically, we wanted to understand: (1) the current use of hands and speech output when interacting with a smartphone in daily life while in transit, issues and how people deal with them; (2) motivations and situations, in which people will need one-handed techniques and alternatives for headphones, which motivated and guided EarTouch.

We conducted formative interviews with 30 BVI smartphone users (10 females) between the age of 20 and 29 (average 23). Participants used an Android phone or iPhone and screen readers. 14 of them were totally blind and the remaining participants had residual vision. All of them lived in a city with a population over 20 million people. Data was recorded by written notes, audio, and questionnaires, based on which our findings were reported.

Issues of Two-handed Interaction

Most (27/30) participants used both hands to interact with a smartphone on a daily basis: one holding the phone, the other one interacting with the screen by using touch-and-explore, flicking left and right, generating multi-touch gestures, etc. With this practise, participants would have to free both hands first if they wanted to use the phone, their current tasks would have to be interrupted. In mobile scenarios, simple, frequent or time-sensitive actions (e.g., picking up a call) can be very frustrating. Participants reported that they

would stop walking, stand still and then interact with their smartphone, with their cane held under the armpit tightly.

Participants also reported posture was affected by considerations for environmental noise, privacy and social concerns in public settings. When using speakers, they need to adjust the volume of the speaker and lift up the phone as close as possible (see Figure 1a), this made it difficult and tiresome to interact with the touchscreen at the same time. Except for the discomfort, and the tiresome and unnatural feeling, participants commented that this posture was socially awkward because this posture seems different to their sighted counterparts. To ensure listening privately or clearly, they may even listen to the phone with the loud speaker held against the ear, and the phone is thus held horizontally. In this case, they need to frequently switch the smartphone from the input position to listening position.

Issues of One-handed Interactions

Only 3 participants use one hand to interact with smartphone on a daily basis. Their use of one-handed interaction is limited to special conditions and methods, such as putting the phone inside trouser pockets to free the holding hand, flicking on the screen by one finger of the holding hand which has been shown inefficient [9, 38], or using the nose, chin or lips to touch. The majority of participants commented that these methods are not generalizable. Within the 27 participants who mainly use two-hands, 2 participants perform one-handed interactions when needed. The remaining 25 participants think one-handed interaction is difficult, especially while in transit. First, the size of current smartphones are too large for the thumb to cover the screen space to use explore-by-touch (the user moves the finger around the screen to hear screen contents) or flicking on the screen. Second, when walking or in a public space, participants hold their phone tighter to prevent it from dropping onto the street. This constrains movements of the holding hand and makes it even harder for the user to interact with the touchscreen.

Is one-handed interaction needed?

The answer is definitely yes. Participants told us many situations where they hope the smartphone can be used by one hand, as summarized in Table 1. The most frequently mentioned situation is when the hands are occupied, such

Table 1: one-handed needs

cases	mentions
Hands occupied at home or work space	25
Walking with a cane or guide dog	20
Hand holding a bus handle	16
Walking when holding the hand of a guide	12
Receiving or placing a call	10

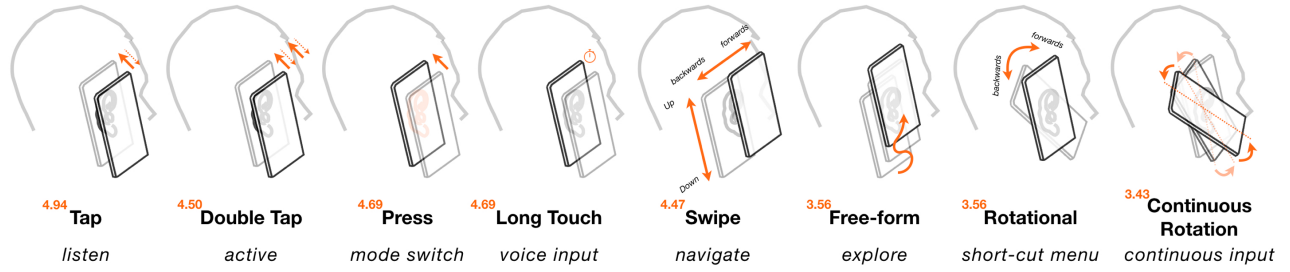


Figure 2: Final set of ear interactions including ratings of "easy to perform" (5 = strongly agree) and typical use

as when holding a cane, bus handle, or shopping bags. Note that one-handed interaction is most wanted when in public or while in transit, where safety, privacy, and social awkwardness are the major concerns. It is also wanted in time-sensitive situations, such as receiving or placing a call because it takes time to free up a hand.

Issues of Speech Output

When using the speaker for speech output in public, most (25/30) participants considered privacy, social awkwardness (e.g., social acceptability and social etiquette) as their major concerns. The remaining 5 participants are willing to give up their privacy or accept social awkwardness to trade for ease and comfort. When using headphones, most (28/30) participants were concerned about hearing damage. 11 participants still rely highly on using headphones for speech output to avoid issues of using speakers, while the remaining intentionally restrained their headphone usage.

When using headphones while in mobile scenarios, users considered safety and portability issues as major concerns. 25 users reported ever using only one earphone, which is less blocking of surrounding sounds, to address safety concerns. The remaining 5 participants just try to avoid headphones. The trade-off using a single earphone is sound quality/clearness due to environmental noises. Participants often had to increase the volume sharply, so two earphones are still preferred in general if headphones have to be used. Beyond the portability issue mentioned by Naftali et al. [35], our participants reported organizing and using headphones as being a challenge without vision, especially in cases where the users are in a hurry (e.g., picking up a call). To avoid tangled wires, two participants used wireless headphones. Participants also mentioned open-air/bone-conduction headphones, but none of them use it in daily life for concerns of price, battery life and sound quality. They needed an alternative for headphones to address privacy and social concerns.

Design Goals

Based on the interview results, we summarized four points that have to be considered in order to design a one-handed

interaction technique for BVI users to use in mobile and public scenarios, which motivate the idea of EarTouch. First, the technique should support common smartphone tasks effectively and efficiently. Second, it should provide the user with an alternative to headphones for speech output. Third, the new technique should allow the user to perform touch input and receive speech output with the phone held in a relatively fixed position. Finally, The technique should be inconspicuous to avoid social awkwardness.

4 BRAINSTORMING EARTOUCH INTERACTIONS

We conducted a participatory design workshop with 23 visually impaired smartphone users (all participated in formative interviews) to brainstorm EarTouch interactions. Our workshop followed the same procedure used in [16, 28], where we divided participants into four groups of six or five participants. During brainstorming, participants were encouraged to think aloud and use their smartphones as a prop to imagine potential interactions. Each group had a moderator, who was also responsible for recording notes of the discussions. The workshop contained three phases, with the first phase focusing on brainstorming possible ear gestures, the second phase focusing on brainstorming potential applications for the ear-touch interactions, and the last phase focusing on the design requirements for the ear-touch interactions. In each phase, the groups first discussed separately, then the moderators presented the ideas from each group to all participants to solicit feedback. The entire workshop lasted around 100 minutes. Figure 2. shows the final set of interactions we picked from our workshop.

Phase 1: Brainstorming Ear-touch Gestures

This phase focused on brainstorming all the possible ear-touch gestures without deeply considering usability.

Ear-touch gestures that mimic finger use. Ear could perform many common single finger gestures, including tap, double tap, long touch, swipe, and free-form shape gestures. Using common touchscreen gestures allows the user to adopt the existing mappings between the gestures and their corresponding actions to minimize learning.

Ear-touch gestures specific to the Ear. The unique characteristics of the ear (auricle) enable many new forms of touch interactions. The auricle is soft and consists of different parts such as helix and earlobe. Using different parts of the auricle to touch or using different levels of pressure to touch can trigger different actions. Additionally, when rotating the screen on the ear, the orientation of the auricle in relation to the screen's x, y coordinate system can be detected for continuous or discrete input.

Phase 2: Brainstorming Potential Applications

The most mentioned applications for ear-touch interactions were making/receiving phone calls or voice messages, using a map, and ride-sharing apps. Participants expressed a strong desire to use them with one hand on-the-go in a relatively private and socially acceptable manner. To show how well ear-touch can support these applications, we discuss the required interactions into three major categories:

Touch input Only. There are situations, where the user needs to finish a task as quick as possible without needing to listen to the speech output. Examples include making an emergency call, sending a predefined message, starting to record a classroom lecture, and launching a frequently used app. Ear-touch enables this type of interactions with one hand when on-the-go. This relieves users from multiple actions and distracted from feedback when walking. It could also facilitate use in quiet public space such as classrooms to avoid social etiquette.

Touch input with speech output. In situations, where the user needs to listen to the speech output (e.g., retrieving caller information, checking time, or navigating a map), ear-touch allows the user to listen to the default speaker of the phone since the phone is held in the talking position. This largely mitigates the issues in privacy and social awkwardness.

Touch and speech input with speech output. There are many situations, where the user needs to alternate between touch and speech input while listening to the speech output. For example, when interacting with a ride-sharing app, the user is required to touch the screen to navigate the map or the app interface, use speech to specify destination, and listen to speech feedback for feedback to the input. Ear-touch is performed with the phone held in the talking position, naturally suitable for this type of interactions. The user does not need to frequently switch the phone's position for talking, listening, and touch input.

Phase 3: Design Considerations

In the last phase of this work, we present all the proposed gestures and applications to our participants, and let them reflect on the interactions and give design suggestions. We

selected eight gestures for our implementation and study. Figure 2 summarizes the gestures, participants ratings (5 = easy to perform), and potential application for each gesture based on the following design guidelines.

Ease of use. The ear-touch gestures should be simple, easy and reliable to use. They should require minimal effort from the user to learn, since understanding or discovering new gestures and the associated functions is difficult for visually impaired users. Participants mentioned not every BVI person has the graphic concept of drawing letters or numbers. They also found it hard to precisely interact with the touchscreen using different part of the auricle.

Operation limitations. Ear-touch should not replace finger interactions and it is widely acceptable to only focus on a small set of applications that work well to solve the aforementioned issues. For example, participants agreed that ear-touch should not be used for precise pointing because ears have a larger contact area than the fingertip, although it may support accessing tiny icons by shortcuts. They were also unsure about swiping the screen using the ear for a relatively long distance because the helix may fold when moving the touchscreen forward, which may suggest less use of explore-by-touch. Finally, participants noted that ear-touch should not be used for a long period of time (e.g., browsing the news) due to potential fatigue issues, while they all agreed on the effectiveness of ear-touch for time-sensitive tasks, such as the ones we listed in Table 3.

5 MODE SWITCH FOR EARTOUCH

We consider ear-touch as a good complement to finger input on smartphones in mobile and public scenarios. Therefore, our technique should allow the users to switch between the two input methods. Since the auricle has a unique shape, a naive approach to distinguish the ear from the finger is by comparing their contact patterns. We found that users preferred to interact with the phone using a part of the ear (e.g., top helix in Figure 4) for easy and efficient operations. As such, a complete contact pattern of the ear cannot be guaranteed, which makes it difficult to distinguish an ear-touch from a finger touch. For example, the contact pattern of the ear could be similar to that of the thumb when touching the screen on the side.

We designed a mode switch technique to account for these concerns. Our idea is to use the complete contact pattern of the ear as an explicit trigger of the EarTouch Mode, where all the subsequent touch events will be interpreted as EarTouch. As shown in Figure 3, our system is by default in the Idle Mode. It constantly checks the capacitive images of the touch object and detects whether or not it is the ear. If it is, the system will start the EarTouch Mode. Otherwise, it takes all the input as finger touch. Exiting the EarTouch mode is

triggered by putting the smartphone back in front of the user (as shown in Figure 1.a). This is the position for normal touch input, and can be reliably detected using the inertial sensor of the smartphone.

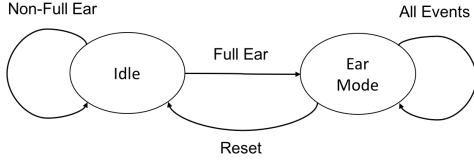


Figure 3: The state transition of our mode switch design. Voice feedback is provided to a user to indicate the entering and exiting of Ear Mode.

Our mode switch technique has the following benefits. It is robust and reliable, with which, a user is easily aware of the system state and confident for interaction. Additionally, with the complete contact pattern of the ear, the system can detect which ear is used or even the user’s identity [21]. This is important contextual information that can be further used for rich interactions.

6 EAR RECOGNITION AND TRACKING

We implement our EarTouch prototype on a Huawei Mate10 running Android OS. We obtained the capacitive images of the touchscreen from the hardware abstraction layer, and transferred the data to the application layer in 45 Hz using the jni mechanism. Our image processing pipeline was written in Java, and ran in the application layer on the smartphone.

Preprocessing

The raw data from the touchscreen is a 32x18 matrix of sensor values. We followed Hinckley et al.’s approach [20] by interpolating the data into a 160x90 matrix using the Lanczos4 algorithm. Background noise was removed under a fixed threshold. Figure 4 shows a few examples of the resulting capacitive images.

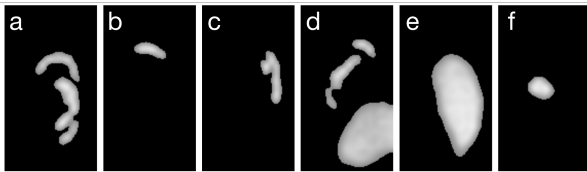


Figure 4: Some example images of touch after preprocessing: (a) full ear, (b) the top helix of an ear, (c) the dome-shaped helix of an ear, (d) ear+face, (e) face, and (f) finger.

Ear Recognition

Because the ear is soft and its shape is complicated, the capacitive image of the ear may appear differently depending

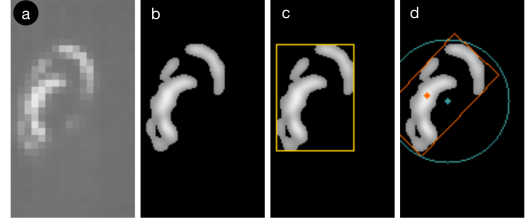


Figure 5: The Pipeline of image processing. (a) Raw Image (b) preprocessing interpolation (c) clustering algorithm (d) recognize ear (bounding box, weighted center, circle fitting for judging orientation)

on how the ear is in contact with the touchscreen, as shown in Figure 4 (a)-(d). The most challenging problem is to distinguish the ear from the fingertip, as shown in Figure 4 (b) and (f). Section 5 discusses this issue and describes how we avoid this problem using a mode switch mechanism. Additionally, if the cheek touches the screen correspondingly with the ear, it should be removed from considerations. As such, we define our recognition algorithm as a three-category classification problem to distinguish between the full ear, face and others.

Figure 5 provides an example of a complete ear in contact with the touchscreen. Our recognition pipeline has four steps: 1) We extracted individual connected regions using a flooding algorithm. 2) We used K-means clustering to merge the adjacent regions into a single one. 3) We fit the bounding box for each region. 4) For each region, we classified it into three categories: ear, face or others, using a C4.5 decision tree with a set of features including the area of the region, number of sub regions, the width and length of the bounding box, and the location.

Ear Tracking

Tracking the position of the ear on the touchscreen is challenging because the auricle deforms when the touchscreen is lifted, or moved against the ear. To address this issue, we first defined two states: *EarOn* and *EarOff*. *EarOn* is identified if the ear contacts on screen in a stable state when the brightness reaches the peak within a time window size of 10 frames. The starting position of the ear is determined as the weighted center of its contact region. *EarOff* is identified if the ear leaves the touchscreen. Second, we tracked ear movement using the KCF (Kernelized Correlation Filter) algorithm [19], suitable in detecting small and non-rigid deformation with high efficiency and accuracy. The limitation of the algorithm is that it is unable to deal with large deformations of the tracked object. To address this problem, we extended the algorithm by maintaining two KCF trackers with one actively producing the tracking result, while the other works in the background ready to kick in if the active KCF loses track of the ear on the touchscreen due to

the accumulative deformation of the ear. The two trackers alternate every 500ms to ensure that the ear movement can be reliably tracked. The relative movement of the ear on the touchscreen can be estimated by comparing two successive frames. We also employed a cubical smoothing algorithm to smooth the trajectory of the ear movement.

Ear Gestures

We recognized the gestures shown in Figure 2 using the data from the capacitive images and the phone’s inertial sensor. The latter is used to capture the rotational degree of the rotating gestures. To recognize users’ intention, we adopt another C4.5 decision tree model, which takes into account of time (from *EarOn* to the present), moving distance and rotation degree. Finally, a double tap was registered if two consecutive taps occurred within 300 ms.

System Evaluation

We evaluate our algorithm with offline classification.

Training data. The data we used for developing the image processing algorithm and training classification models were collected from the visually impaired participants who simulated gestures after brainstorming and sighted persons after pilot studies.

Testing data. Testing samples were collected with sixteen visually impaired participants, where the recorded data including: 1) each kind of gestures (tap, double tap, long touch, free-form shape, swipe in four directions, rotate in two directions) repeated 10 times, 2) the complete shape of the ear (to enter the Ear Mode), 3) the process of putting smartphone down to the normal touch position (to quit the Ear Mode), 4) finger touches by interacting with daily apps as negative samples. Data was recorded from the touchscreen (e.g., capacitive images) and the smartphone’s inertial sensor. Not all the collected data can be used due to log file writing errors. We discarded them from our analysis, resulting in 1600 samples for 1), 148 samples for 2), 158 samples for 3), and 157 samples for 4).

Results. With all the remaining data, our system achieved an accuracy of 96.2% on detecting the start of the Ear Mode and 98.7% on detecting the end of the Ear Mode, zero false recognition of the Ear Mode during finger touch, and 95.8%

on recognizing the gestures with a delay less than 500 ms. Table 2 shows the the confusion matrix between each gesture.

7 USER STUDY 1: PERFORMANCE OF EARTOUCH

The goal of this study was to compare the efficiency of EarTouch (customized UI and Text-To-Speech) and Finger-Touch (unmodified Android UI and Talkback) in performing daily tasks on a smartphone using one hand. We were also interested in collecting users’ subjective feedback regarding the usability of the two techniques in one-handed situations.

Participants and Apparatus

16 BVI participants (5 females, aged from 20 to 30, all participated in interviews and participatory design workshop) volunteered in this study. 7 of them had participated in the elicitation study while all the remaining participants were new to this concept. All of our participants had a minimum 5 years experience of using a smartphone. 13 participants barely used the smartphone using one hand, while the other 3 reported that sometimes they used the thumb or index finger for one-handed input if they had to (Figure 6). Our study apparatus was a 5.9-inch (150.5 mm x 77.8 mm) Huawei Mate10 smartphone. In our study, only one participant used index finger and the remaining participants used thumb finger of the holding hand.

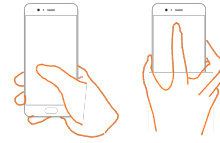


Figure 6: thumb or index finger for one-handed input

Design and Procedure

The independent variable is Technique (EarTouch vs. FingerTouch), which was counter-balanced among participants. Based on formative interviews, we selected 7 tasks to represent the common tasks BVI users may perform on a smartphone in one-handed situations. Table 3 summarizes the tasks as well as how the tasks were performed using EarTouch and FingerTouch. Operations of FingerTouch were standard Android operations supported by Talkback. All the tasks were perform one-handedly and speech output were played through speakers. At the beginning of the experiment, we introduced both techniques to participants, who were then given 10 minutes to practice them. Participants were asked to complete each task three times using one of the two techniques in a seated position. Within each Technique condition, the presentation order of the 21 (7*3) tasks was randomized for each participant.

Table 2: confusion matrix

Truth	Predicted						Acc
	Tap	Double Tap	Swipe	Rotate	Explore	Long Touch	
Tap	160	0	0	0	0	0	100%
Double Tap	7	153	0	0	0	0	95.6%
Swipe	22	1	615	1	1	0	96.1%
Rotate	8	0	9	300	1	2	93.8%
Free-form	1	0	9	0	147	3	91.9%
Long touch	0	0	0	0	1	159	99.4%
							95.8%

Table 3: Tasks and Operations.

Answer a phone call	
EarTouch	Tap to hear the caller info; double-tap to answer the phone; swipe in any direction to reject or hang up a call
FingerTouch	Talkback supported using explore-by-touch (e.g., touch to find the location of a desired button) or swipe (e.g., left or right) to navigate a linear list of the screen widgets, double tap to trigger an action. Participants first located the desired widget then trigger it.
Send a voice message	
EarTouch	Long touch to initiate voice input ->hold the phone against the ear to speak ->lift up the phone to send the voice message or swipe up to withdraw the action.
FingerTouch	Double tap the "Talk" button without lifting the finger of the second tap to initiate voice input, lift the finger up to send the message or swipe up to withdraw
Specify a map destination using voice and start navigation	
EarTouch	Long touch to initiate voice input to specify a map destination ->swipe forwards or backwards to navigate search results ->double-tap to confirm ->swipe down to start navigation.
FingerTouch	Explore-by-touch or swipe left/right to locate the desired widgets (e.g., voice input button or search result), then double tap to start navigation.
Shortcut menu	
EarTouch	Rotational gesture to start the menu ->swipe forwards or backwards to navigate manu items; double-tap to select a menu item.
FingerTouch	Draw an "L" gesture to start the menu (standard Android operation) ->swipe left or right to navigate menu items ->double tap to select a menu item
Enter a series of numbers	
EarTouch	Touch to select number 5 ->lift up to enter 5 or otherwise ->rotate the phone forward to access 4,3,2, 1, 0 or backwards to access 6,7,8,9 ->lift up to enter the selected number.
FingerTouch	Navigate a 3 x 4 numeric number pad using explore-by-touch ->lift up to select the number.
Launch an app	
EarTouch	Touch and navigate a 2*3 grid of targets of 4cm wide and 5cm high ->lift up to select a target (target size was determined via a pilot study)
FingerTouch	Same as EarTouch except that participants used the finger.
Listen to time or battery level	
EarTouch	Tap the top half of the touchscreen to access time; tap the bottom half of touchscreen to access battery level
FingerTouch	Explore-by-touch or swipe left/right to navigate a linear list of targets

Results and Discussion

All participants acquired EarTouch in less than 10 minutes (average = 8.06, SD =1.44). With FingerTouch, participants were able to finish 83.04% of the tasks, some of them failed to finished one or more tasks due to fatigue and error-prone. With EarTouch, they were able to successfully completed all the tasks (100%). In total, we collected 3*7*16=336 trials for EarTouch and 279 trials for FingerTouch. 23 errors occurred in 336 EarTouch trails, mainly when using continuous rotation gestures. 19 errors occurred in 279 FingerTouch trails, mainly when touching and exploring with needs of moving hands.

Task completion time. The mean task completion time was 5.81s (SD=4.46) for EarTouch and 7.55s (SD=6.22) for FingerTouch. EarTouch was significantly faster than FingerTouch ($F(1, 6) = 11.6, p = 0.01$). The overall time was calculated using the data from participants who succeeded in all the tasks using both techniques (data from 9 people removed). The same strategy was used for comparison of each individual task (See details in Table 4). We discussed the performance of EarTouch and FingerTouch as follows.

(1) *Phone, Message, Navigation and Time/Battery:* With FingerTouch, all these tasks required participants to acquire small widgets, such as icons, button, or search bar by using explore-by-touch or flicks, which was time consuming and frustrating. In contrast, the same set of tasks could be performed using quicker ear gestures with EarTouch, for example, using long touch of ear for voice input instead of searching for the voice input button, tapping the top half of screen to access time in lock screen interface. Users are relieved from looking for the exact target position.

(2) *Message and Navigation:* With FingerTouch, participants were required to switch the smartphone between different postures. To be specific, they had to hold the smartphone in front of the chest for touch input and lift it up to ear for speech output, then hold it close to the mouth for voice input, finally switch back to the posture for touch input. With EarTouch, all interactions could be carried with the smartphone held in the talking position, which relieves users from switching postures.

(3) *Numbers and Launching apps:* To input numbers, participants used touch and take-off strategy with FingerTouch,

Table 4: Task completion time. N shows the number of participants who successfully finished the task (total: 16 persons). Time (seconds) is the average task completion time calculated based on N.

Task	Technique	N	Time	RM-ANOVA
Answer a phone	EarTouch	16	6.91	$F(1,14) = 15.9257, p = 0.0013^*$
	FingerTouch	15	9.65	
Input numbers	EarTouch	16	4.02	$F(1,13) = 25.4513, p = 0.0002^*$
	FingerTouch	14	1.97	
Voice message	EarTouch	16	4.51	$F(1,14) = 18.3420, p = 0.0008^*$
	FingerTouch	15	6.55	
Navigation	EarTouch	16	14.98	$F(1,10) = 10.0432, p = 0.0100^*$
	FingerTouch	10	20.28	
Launch apps	EarTouch	16	2.15	$F(1,13) = 0.4099, p = 0.5332$
	FingerTouch	14	1.99	
Shortcut menu	EarTouch	16	6.27	$F(1, 9) = 0.2159, p = 0.6532$
	FingerTouch	10	5.96	
Time/Battery	EarTouch	16	2.01	$F(1,13) = 34.2559, p <0.0001^*$
	FingerTouch	14	6.26	

which should be faster than using continuously rotation input with EarTouch. To launch an app, both tasks required using touch and take-off strategy in a grid of touch icons with one using the finger and the other one using the ear. The result suggested that their performances were competitive.

(4) *Shortcut menu*: With FingerTouch, opening the menu required drawing directional gesture like an "L", which is difficult because the one-handed posture constrains the finger movement of the holding hand. In contrast, performing a rotational gesture to open the menu using EarTouch was much easier, enabling more participants to finish the task. After opening the shortcut menu, both tasks required participants to use flick/swipe to navigate in the menu list. EarTouch and FingerTouch is equivalent in completion time.

Subjective Feedback. After the experimentl phase, participants indicated their agreements on the six statements shown in Table 5 using a 5-point Likert scale. Data was analyzed using Wilcoxon test. EarTouch outperformed FingerTouch on metrics, including "Technique was fun to use" ($z = -3.00, p < .05$) and "Technique was fast to use" ($z = -2.00, p < .05$). We also found that individual differences, especially in motor control skills, may affect user preferences on EarTouch techniques. For example, four participants told us that continuously rotating the phone was a little bit hard to control. Since participants were familiar with FingerTouch, we did not ask them to give responses to "Technique was easy to learn", "My performance improved with practices" and "I would use the technique on my smartphone". For these three questions, participants found EarTouch easy to learn and their performance improved with practice. They all expressed interest in using EarTouch on their own smartphone, even though not every current designs were satisfactory. What was really encouraging was that participants thought that the current functions provided by EarTouch was already sufficient to satisfy their daily needs in one-handed situations.

Table 5: The subjective feedback. 1=Disagree strongly, 5=Agree strongly

Statement	Ear Touch	Finger Touch
Technique was easy to use	3.78 (0.85)	3.25 (0.83)
Technique was fun to use*	4.18 (0.88)	2.56 (0.61)
Technique was fast to use*	4.09 (0.62)	3.47 (0.89)
Technique was easy to learn	4.625 (0.48)	–
My performance improve with practices	4.625 (0.48)	–
I would use the technique on my smartphone	4.625 (0.60)	–

8 USER STUDY 2: PRIVACY AND SOCIAL AWKWARDNESS

The goal was to compare the user experience of EarTouch with FingerTouch in terms of privacy and social awkwardness in mobile and public settings.

Table 6: The average sound volume used by participants during the study. Standard deviation shown in brackets

Technique	Merto Station	Quiet Meeting Room
EarTouch with ear speaker	88% (0.12)	55% (0.13)
FingerTouch with speaker	100% (0.00)	44% (0.18)
FingerTouch with earphone	69% (0.07)	44% (0.05)

Participants and Apparatus

Six BVI smartphone users (2 females, aged from 21 to 31) of more than 7 years experience participated in the study. One participant occasionally uses one hand to interact with the smartphone if had to, while the others use both hands for daily interaction with their smartphone. All participants had normal hearing and were not involved in the previous studies. The apparatus was the same as in User Study 1.

Design and Procedure

The independent variable of this study is Technique: 1) EarTouch with ear speaker for speech output, 2) FingerTouch with headphone, and 3) FingerTouch with speakerphone. In particular, participants used FingerTouch with one or two hands as per their habit. For all three conditions, participants were asked to adjust the volume of the sound to a comfortable level (Table 6). The study was conducted in a busy metro station and a quiet meeting room.

After a brief introduction, each participant practiced both techniques on the tasks used in Study 1. The study was conducted one participant at a time, each participant performing the 7 tasks using the three techniques. The same set of 7 tasks were performed during the study within each technique conditions, the presentation of which was fixed: FingerTouch with speakerphone, FingerTouch with headphone, and EarTouch. In the metro station condition, participants were asked to perform the tasks while walking with a cane. To measure whether or not speech output could be heard from nearby people, we had an experimenter walking beside the participant at a distance of about 0.3m. The ambient sound was measured as 75dB. In the meeting room condition, participants were arranged to be seated close to each other in about 30 cm distance. All the other participants reported whether they were able to hear the auditory feedback. After the experiments, participants indicated their agreement on the following 6 statements using a 5-point Likert scale: 1) I can hear my phone clearly in the noisy environment; 2) I do not interfere the others in a quite environment; 3) Technique protects my privacy and avoids social awkwardness in the public; 4) Technique can be easily used with one hand; 5) Technique is natural to perform; 6) Technique is inconspicuous. An experimenter took notes on their comments.

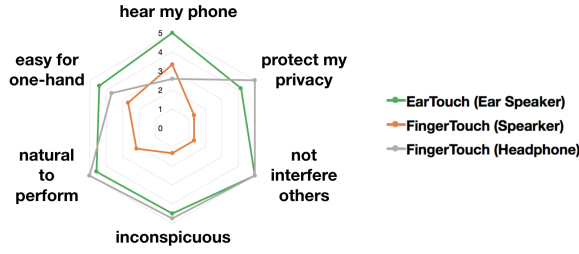


Figure 7: Users' subjective agreement with the statements

Results

Participants' ratings are shown Figure 7. In all statements, we observed a clear advantage of EarTouch with ear speaker over FingerTouch with speaker. Regarding the ability to protect user privacy and avoid interfering with nearby people, earphones were considered the most effective technique over all the 6 assessments, followed by EarTouch, which received quite competitive scores. When in the quiet meeting room using the phone's speaker, participants reported that they had tried the lowest possible volume but were still able to hear other people's phones, which in fact made it hard for them to hear and concentrate on their own phone. It turned out that participants chose to give up on the privacy concern and turn the speaker louder to get the tasks done.

Although participants agreed that earphone allowed them to hear the speech output clearly, they were reluctant to use them in a noisy public environment. P1 commented as *"The earphones may block the environmental sound from me, making me feel unsafe"*. We expect it feasible for visually impaired users to use only one piece of earphone to avoid complete isolation from the ambient sounds. However, P3 told us that even wearing one of the pair of earphones can still distract her full attention from the ambient sounds. Participants liked EarTouch even though they found that the ear speaker could be off the ear when performing a gesture. They informed us that they were still able to hear the sound from the ear speaker for most cases, especially in a quiet environment. In cases where the environmental noise was too loud, it was still feasible for them to quickly move the ear speaker to the ear without missing the speech message or losing contact with the environmental sounds. Equally important is that participants reported that speech output played via the ear speaker was extremely hard to be picked up by nearby people.

9 DISCUSSION

EarTouch extends smartphone interaction by using an ear as an input apparatus. EarTouch cannot replace fingers for all the smartphone's primitives, but serves as an effective supplementary to improve one-handed input, protect privacy

and address social concerns for BVI users in mobile and public scenarios. Participants also see the potential of EarTouch being used in combination with finger-based interaction on smartphones. For example, users can perform ear-touch gestures with the thumb touching the screen or the index finger tapping on the back of the phone simultaneously.

Adopting a perspective of ability-based design [47], this work could make smartphones more accessible to a much wider range of users. Although we designed EarTouch for BVI smartphone users, the technique could also benefit users with motor impairments (e.g., one-armed disabled people) and non-disabled users with situational impairments [41] (e.g., parents holding babies in one hand). Future works would include investigating the effectiveness of EarTouch for more users and supporting auto-adjustment for output and customization for gestures. EarTouch supports ear speaker to play speech output, participants liked the design, meanwhile they expect the volume, and switching from ear speaker to loud speaker could adjust automatically (be adaptive) due to environmental conditions and the relative position of ear-touch on the screen. An authoring tool should also allow end-user customization.

Finally, there are two limitations in our user study. First, the controlled study was conducted in a sitting position as to the participants' preference. So, it is unclear if the results can be generalized to standing or walking conditions. Second, FingerTouch (the baseline) is not specially designed for one-handed interaction. Therefore, the comparison results do not demonstrate that EarTouch outperforms finger-based touch for one-handed input. In our research, we opted FingerTouch (unmodified Android UI and Talkback) as one representation of the current practice, for its general-purpose and adoption by BVI smartphone users.

10 CONCLUSION

We present EarTouch, a novel interaction technique that facilitates smartphone use for BVI people in mobile and public scenarios. EarTouch not only improves one-handed use, but also provides an alternative to protect privacy and avoid social awkwardness. We actively engaged 36 BVI smartphone users in the design and evaluation of EarTouch based on formative interviews and user-participatory design activities. In a broader sense, EarTouch brings us an important step closer to accessible smartphones for all users of all abilities.

11 ACKNOWLEDGEMENTS

The authors thank all participants. This work is supported by the National Key Research and Development Plan under Grant No. 2016YFB1001200, the Natural Science Foundation of China under Grant No. 61572276 and No. 61672314, Tsinghua University Research Funding No. 20151080408, and also by Beijing Key Lab of Networked Multimedia.

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