Investigating Microinteractions for People with Visual Impairments and the Potential Role of On-Body Interaction

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ABSTRACT

For screenreader users who are blind or visually impaired (VI), today's mobile devices, while reasonably *accessible*, are not necessarily *efficient*. This inefficiency may be especially problematic for microinteractions, which are brief but high-frequency interactions that take only a few seconds for sighted users to complete (*e.g.,* checking the weather or for new messages). One potential solution to support efficient non-visual microinteractions is on-body input, which appropriates the user's own body as the interaction medium. In this paper, we address two related research questions: *How well are microinteractions currently supported for VI users? How should on-body interaction be designed to best support microinteractions for this user group?* We conducted two studies: (1) an online survey to compare current microinteraction use between VI and sighted users (N=117); and (2) an in-person study where 12 VI screenreader users qualitatively evaluated a real-time on-body interaction system that provided three contrasting input designs. Our findings suggest that efficient microinteractions are not currently well-supported for VI users, at least using manual input, which highlights the need for new interaction approaches. On-body input offers this potential and the qualitative evaluation revealed tradeoffs with different on-body interaction techniques in terms of perceived efficiency, learnability, social acceptability, and ability to use on the go.

CCS Concepts

• Human-Centered Computing → Accessibility → Empirical Studies in Accessibility

Keywords

Visual impairments; mobile; microinteraction; wearable technology; on-body interaction.

1. INTRODUCTION

Today's mobile devices are reasonably *accessible* for blind and visually impaired (VI) users but are not necessarily *efficient*. This inefficiency may be especially problematic for microinteractions—that is, brief but high-frequency interactions that typically take sighted users only a few seconds to complete [3]. Manually finding and playing a song, for example, can take 15 seconds for a blind user [20] while entering a four-digit passcode to unlock a smartphone requires on average eight seconds, leading many blind users to forgo this security feature altogether [6].

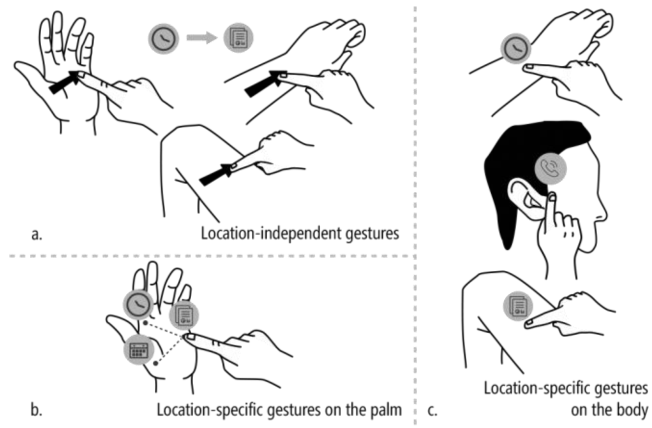


Figure 1. The three on-body interaction techniques explored for microinteractions in Study 2: (a) location-independent taps and swipes that can be performed anywhere on the body, (b) location-specific input that allows users to directly access a specific set of applications by tapping a dedicated location on the palm only or (c) on the body. See also video figure.

While many approaches could be taken to support efficient non-visual microinteractions, one particularly promising direction is *on-body input* [16,17], which appropriates the user's own body as the interaction medium. Prior work has shown that on-body input can be more efficient than touchscreen interaction for non-visual use, even without including the time to first retrieve the smartphone from a pocket or bag [14,26].

In this paper, we address two interrelated research questions: *(1) How well are microinteractions currently supported for blind and visually impaired users? (2) How should on-body interaction be designed to best support microinteractions for this user group?* Prior work in on-body interaction for users who are blind or visually impaired has identified a desire for socially acceptable input locations and the potential to support use on-the-go [25]. However, important issues related to efficient input remain, including understanding VI users' experiences with existing microinteractions (*e.g.,* on smartwatches, smartphones) and reactions to on-body interaction, as well as how to best leverage the body for microinteraction input (*e.g.,* taps and swipes anywhere on the body *vs.* at specific locations; Figure 1).

To investigate current support for accessible microinteractions and the design of on-body microinteractions for VI users, we conducted two studies. The first study was a formative online survey with 117 users (56 sighted and 61 VI) to characterize current microinteraction use and identify barriers therein. For the second study, we recruited 12 screenreader users who participated in an in-person semi-structured interview on the same themes and completed a qualitative evaluation of a real-time on-body interaction prototype that we developed. For the latter, participants compared three complementary on-body interaction techniques: location-independent gestures (*i.e.*, taps and swipes anywhere on the body), location-specific gestures on the hand (*i.e.*, pointing to different hand locations), and location-specific gestures on the body (*i.e.*, pointing to different hand and body locations).

Our findings suggest that efficient microinteractions are not currently well-supported for VI users, at least using manual input. While speech input is a common alternative, it is not always appropriate, thus highlighting the need for new approaches to support frequent and fast non-visual interactions. The qualitative evaluation of the three on-body interaction techniques to support microinteractions revealed tradeoffs in terms of perceived efficiency, learnability, social acceptability, and the ability to use on the go. For example, participants considered input at *specific* locations across the body to be the least efficient whereas location-independent gestures, which can be performed anywhere, were seen as supporting learning and offering flexibility for use on-the-go. In summary, the primary contributions of this paper are: (1) an identification of the needs, barriers, and strategies for enabling microinteractions for users with visual impairments in comparison to sighted users, and (2) design implications for supporting microinteractions for VI users via on-body input.

2. RELATED WORK

Our research is informed by prior work on microinteractions and mobile and wearable technologies for VI users.

2.1 Microinteractions

Microinteractions are defined by Ashbrook [3] as interactions that take less than four seconds to complete, such as changing the volume or dialing a number. These interaction durations are important because they can profoundly influence usage of an application or device [28,34]. Mobile contexts also increase the need for efficient interaction: Oulasvirta *et al.* [28] showed that mobile interaction typically occurs in short bursts of attention that are only four to eight seconds long.

Research on understanding and supporting microinteractions has largely focused on sighted users. Pizza *et al.* [29] found that the most frequent smartwatch interactions under 10 seconds were glancing at the watch face, accessing notifications, and setting and checking timers. As well, in an analysis of over 4,000 Android smartphone users, Bömer *et al.* [7], found that tasks related to communication (*e.g.*, text messaging, phone calls) were among the shortest and most frequently used tasks. Efforts to support more efficient microinteractions have largely focused on wearable devices because wearables enable quicker access times and less disruptive transitions between the device and the physical world compared to mobile phones [4,22,24]. In comparison to sighted users, however, VI users—our focus—typically have longer interaction times [5,6], which is particularly problematic in mobile contexts since device access is already limited [1,33,39]. While some wearable devices for VI users arguably support microinteractions (e.g., *EyeRing*'s barcode scanning and currency identification [24]), to our knowledge, no study has thoroughly examined VI users' microinteraction needs and how well these needs are currently supported.

2.2 Accessible Mobile/Wearable Interaction

Mobile technology plays an important role for VI users, particularly in supporting independence [21]. Yet, touchscreen smartphones are not innately accessible due to a heavy reliance on visual cues and the minimal tactile feedback of the smooth touchscreen [18,23]. One approach for non-visual use is to employ location-insensitive gestures that do not require accurate hand-eye coordination [8,13,20]. For example, *Apple VoiceOver*[1] and *Google TalkBack*[2], two popular mobile screenreaders, provide location-insensitive taps and swipes that can be performed anywhere on the screen. These solutions also support location-specific interaction by allowing users to touch down and move the finger around to hear audio output for each element that is touched. Despite these advances, however, touchscreen interactions can still be time-consuming for VI users [5,6,20,39]—likely impacting microinteraction efficiency.

Accessible wearable interaction has largely focused on supporting tasks in the physical world, such as way-finding [11], object or character recognition [32,35], and currency detection [24]. For instance, *OrCam* includes a wearable camera and provides speech output for reading or identification when the user points to a document, object, or face [27]. A smaller body of work has focused on providing mobile digital information access through wearable technologies for VI users, such as Ye *et al.*'s [39] study of a wristband that pairs with a phone to control audio screenreader output. That study also investigated the advantages and limitations of wearable devices over smartphones for VI users and found that potential advantages included quick interaction, discretion, and use on the go. We build on these prior studies by focusing on microinteractions specifically and the ability of on-body input to support these interactions for VI users.

On-body input [16,17] offers the same advantages as most other wearable input: portable and quick to access. Moreover, with tactile and proprioceptive feedback from the user's own body, on-body input is efficient for eyes-free use [14]—a finding that has been extended to VI users [26]. Studies on the *design* of on-body interaction have focused primarily on sighted users (*e.g.*, [15,38]). For example, Weigel *et al*. [38] investigated characteristics of different skin input modalities and preferred input locations, and found that the most preferred location was the palm. As an exception, Oh and Findlater [25] studied the design of on-body input by asking VI users to create on-body input gestures and to compare location-independent input gestures on the hand to on a touchscreen phone. Findings showed that input on the hands and arms was considered relatively socially acceptable and on-body input in general was seen as valuable compared to the phone during hands-busy use (*e.g.*, one hand holding a cane or dog leash). However, the authors did not investigate *location-specific* on-body input, which has been shown to offer potential performance benefits over touchscreen interaction [26].

3. STUDY 1: MICROINTERACTION SURVEY

We conducted an online survey with 61 VI and 56 sighted smartphone users to compare microinteraction usage patterns between these two groups. We targeted VI users who interact primarily through audio output (*e.g.*, screenreaders) rather than visual output (*e.g.*, screen magnifiers). Thus, our VI group only includes participants who reported using screenreaders most or all of the time when interacting with their mobile device.

[1] http://www.apple.com/accessibility/ios/voiceover/

[2] https://play.google.com/store/apps/details?id=com.google.android.marvin.talkback

Smartwatch: A smartwatch offers many of the same features as a smartphone, but has a smaller screen that is roughly the size of a large watch face. Smartwatches often include a camera, speaker, microphone, and sensors that can track information like the number of steps you've taken.

On-body interaction: Imagine a small wearable device such as a wristband or a ring that can sense when you do taps, swipes or other gestures on the surface of your body. This device can be paired with a small speaker for audio output or with a projected image on your arm or hand and would allow you to do many of the same actions as you can do on a smartphone or smartwatch. For example, you can perform taps and swipes on your bare palm in the same way you usually use the touchscreen on a phone or smartwatch. You can also tap or perform other gestures at specific locations on your body, such as the wrist, a fingertip, or ear to execute specific actions (e.g., check the time, answer a phone call, change a song's volume).

Figure 2. Descriptions of smartwatches and on-body interaction used in the online survey.

The survey focused on microinteractions with smartphones and smartwatches but also solicited open-ended feedback about on-body interaction. We hoped to learn:

1. What are the most common microinteractions currently used by sighted and VI users?
2. What tasks, if any, are not supported as microinteractions for VI users but would be valuable to support in the future?
3. How do users perceive the use of wearable devices (specifically, smartwatches) for microinteractions compared to smartphones?
4. How do people react to the idea of on-body interaction and what potential use cases do they foresee?

3.1 Method

We created an accessible online survey via *SurveyMonkey*, which was designed to take ~25 minutes for screenreader users. Smartphone owners were recruited to participate through email lists, a university bulletin board, community organizations, Facebook, and word of mouth. After completion, participants could opt into a drawing for a $100 Amazon gift certificate.

3.1.1 Survey Design

The survey, included in Appendix A, consisted of 32-36 questions depending on the participant's level of vision. For smartwatch owners, we asked an additional 24 questions. Questions included general background (*e.g.*, age, gender), current mobile and wearable technology use (*e.g.*, device type, frequency of use), and perceived tradeoffs between smartphones and smartwatches. The survey also asked respondents to estimate the time needed for them to complete specific microinteractions that are common for sighted users on mobile and wearable devices [2,37]—see Table 1. At the end of the survey, we also solicited feedback on the idea of on-body interaction. To aid understanding, we provided brief descriptions of smartwatches and on-body interaction (Figure 2).

3.1.2 Data and Analysis

During a one-month period, we received 134 fully completed and 13 partially completed survey responses (dropout rate of 8.8%). Fifty-six participants reported normal or corrected-to-normal vision (*sighted* participants) and 61 participants reported having a visual impairment and using a screenreader most or all of the time (*VI* participants); an additional 17 VI participants who were infrequent screenreader users were excluded from analysis. Of the VI group, one participant had 20/70 to 20/200 vision, 13 were legally blind (at best 20/200), 17 were blind with some light perception, and 30 were totally blind. Participants were asked to specify their age within a range (*e.g.*, 35–44, 45–54); the median age range was 45–54 for VI participants (38 female, 22 male, 1 other) and 25–34 for sighted participants (30 female, 26 male).

Table 1. The ten microinteractions examined in our online survey. This list is based on [7,29].

Task Label	Task Description
Alarm	Set an alarm or timer
App launch	Find and open a specific app
Calendar	Check your calendar for an overview of the day's schedule
Clock	Check the current time
Music	Pause a music player
Navigation	Set a destination to get navigation directions
Phone calls	Dial a phone number
Read message	Read a text message that is two sentences long
Respond to msg.	Respond to a text message with a two-word reply
Weather	Check the weather

Table 2. Mobile tasks reported as being frequent and fast to complete (≤ 10 seconds) by at least five VI or sighted participants, sorted by popularity among VI participants. Bolding and '*' indicate tasks that were significantly different between the two user groups.

Task	VI (*N*=61)	Sighted(*N*=56)
Email interactions, primarily checking for new email	80.3%	73.2%
Text message interactions, primarily checking for new messages	68.9%	76.8%
Checking the weather*	41.0%	21.4%
Voice call interactions (*e.g.,* answering or declining calls, dialing, checking missed calls)*	34.4%	10.7%
Checking the time	31.1%	28.6%
Checking notifications other than calls, emails, text messages, social media	26.2%	19.6%
Social media, primarily checking for updates	19.7%	30.4%
Information search (*e.g.,* trivia, bus schedule)	19.7%	17.9%
Music player control	18.0%	8.9%
Changing device settings (*e.g.,* volume, wifi)	9.8%	5.4%
Calendar interactions	8.2%	8.9%

We used chi-square tests of independence to analyze the impact of user groups (VI *vs.* sighted) on frequency data (*e.g.*, from multiple-choice questions on microinteraction usage). For the seven open-ended questions in the survey, we followed an iterative coding process [19]. Two researchers together developed initial codebooks for each question, then independently coded a randomly selected subset of 20-40 responses. Cohen's kappa was computed to assess interrater reliability for each code and problematic codes were refined; three to four iterations of this process were completed for each question. The average kappa score across all codes after the final iteration was 0.87 (SD = 0.12; range 0.53–1.0).

3.2 Findings

We describe participants' experiences with microinteractions, perceived tradeoffs between smartphones and smartwatches, and responses to the idea of on-body interaction. Asterisks in tables and figures indicate statistically significant differences ($p < .05$) between the VI and sighted participant groups.

3.2.1 Device Ownership and Frequency of Use

As required to complete the survey, all participants owned smartphones. Most VI participants had iOS devices (59 iOS, 8 Android, 1 other), while sighted participants were more evenly split (29 iOS, 30 Android, 5 other), confirming previously identified patterns of adoption [5,37,39]; some participants reported multiple devices. Participants used their devices frequently: 56 VI and 55 sighted participants reported using their smartphone at least once every few hours. Thirteen participants (4 VI, 9 sighted) owned a smartwatch and all reported using it at least every few hours.

3.2.2 Frequently Used Microinteractions

To compare what current smartphone tasks can be classified as microinteractions for VI users versus sighted users, we asked

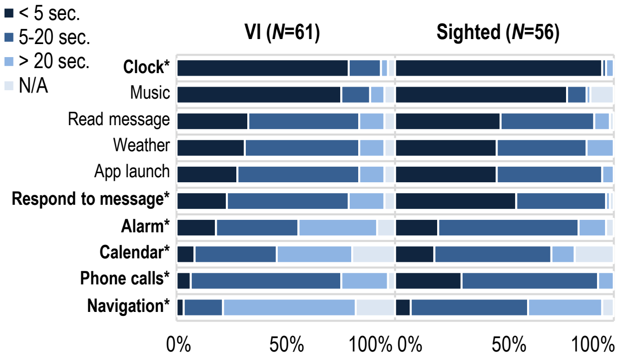


Figure 3. Percentage of survey participants reporting different task completion times across 10 common microinteraction tasks, sorted by the percentage of VI participants who reported '*< 5 seconds*'.

participants to list tasks that were *frequent* and *fast* (≤ 10 seconds to complete). This was an open-ended question and responses are shown in Table 2. While overall trends are similar across the two groups, VI participants were significantly more likely to list *'checking the weather'* (41% *vs.* 21%; $\chi^2_{(1)} = 5.16$, $p = .023$, $\phi = .21$) and *'voice call interactions'* (34% *vs.* 11%; $\chi^2_{(1)} = 9.25$, $p = .002$, $\phi = .28$) than sighted participants. The voice call interactions by VI users consisted primarily of checking for missed calls and voicemails. These differences may reflect the utility of auditory information for VI users, such as hearing a weather forecast versus looking out the window or talking versus composing a text message. As for accessibility-specific tasks such as OCR or identifying colors, only one participant reported such a task as taking 10 seconds or less to complete: '*identifying currency'*.

3.2.3 Task Completion Time for Microinteractions

To quantify how screenreader use impacts microinteraction task completion time, we asked participants to estimate their time to complete each of the 10 microinteractions listed in Table 1 using manual input (*i.e.*, without speech dictation); options were *'< 5 seconds'*, *'5-20 seconds'* and *'> 20 seconds'*. Figure 3 shows the reported durations for each task. Generally, a greater percentage of sighted participants reported being able to complete the tasks in *'< 5 seconds'* compared to VI users. The frequencies of reported completion times were significantly different between the two participant groups for more than half of the tasks (Table 3). While prior work has shown that screenreader users are slower at mobile tasks than sighted users [5,21], these results emphasize how widespread this trend is for tasks that are often deemed to be microinteractions. Focusing on the responses that were *'< 5 seconds'* (a microinteraction duration), the most substantial difference between the two groups was related to text entry (*'Respond to Message'*). Only 23% of VI participants reported *'< 5 seconds'* for this task compared to 55.4% of sighted participants, perhaps due to the inefficiency of manual text entry for users with visual impairments [5,8].

3.2.4 Use of Speech Input

Motivated by studies showing that speech input (*e.g.*, *Apple Siri*) is more popular for blind users than sighted users [5,39], we examined speech input use for microinteractions. Overall, and confirming prior work, a significantly greater number of VI participants (36.1%) reported using speech input at least '*most of the time*' compared to sighted participants (8.9%); chi-square test ($\chi^2_{(1)} = 12.11$, $p = .001$, $\phi = .32$). We also asked participants to indicate whether they '*usually'* use speech input for each microinteraction

Table 3. Chi-square test results comparing reported microinteraction task durations between the sighted and VI groups (does not include responses of "N/A"). Only the six tasks (of 10) that were significantly different are listed.

Task	N_{VI}	$N_{Sighted}$	$\chi^2_{(2)}$	p	ϕ
Clock*	59	56	6.57	.038	.24
Respond to Message*	58	55	15.84	<.001	.38
Phone Calls*	59	56	13.38	.001	.34
Alarm*	56	54	10.59	.005	.31
Calendar*	49	46	10.84	.004	.34
Navigation*	50	53	15.18	.001	.39

Table 4. Percentage of participants who '*usually*' use speech input for each of ten given microinteractions, with chi-square test results comparing the two participant groups. Bolding and '*' indicate tasks that were significantly different between the two user groups.

Task	VI (*N*=61)	Sighted (*N*=55)	$\chi^2_{(3)}$	p	ϕ
Phone calls*	73.8%	25.0%	27.78	<.001	.49
Alarm*	72.1%	33.9%	17.15	<.001	.38
Respond to message*	67.2%	17.9%	28.93	<.001	.50
Navigation*	63.9%	30.4%	6.73	.01	.24
Weather*	52.5%	21.4%	11.98	.001	.32
App launch*	50.8%	16.1%	15.67	<.001	.37
Read message*	34.4%	7.1%	12.94	<.001	.33
Clock*	34.4%	7.1%	12.94	<.001	.33
Calendar*	32.8%	7.1%	11.78	.001	.32
Music	16.4%	7.1%	2.37	.124	.14

listed in Table 1 (responses: yes/no). VI participants were significantly more likely to use speech input than sighted participants for all tasks except '*Music*' (Table 4). The biggest effect size was for '*Respond to Message*' where VI users were almost 4x as likely to use speech, again perhaps reflecting the difficulty of manual text entry for this user group [5,8].

3.2.5 Comparison of Smartphones and Smartwatches

While wearable devices like smartwatches have been shown to be particularly useful for supporting microinteractions for sighted users [3], we wanted to understand whether perceptions differ for VI users. Specifically, we asked four open-ended questions comparing smartwatches and smartphones: two about perceived advantages/disadvantages of smartwatches (Table 5) and two about tasks conducive to each technology. Because only a small number of participants owned a smartwatch (9 sighted, 4 VI), our analysis does not just focus on their responses but instead includes all 117 participants.

Table 5 shows smartwatch advantages and disadvantages mentioned by at least five participants in either user group, along with chi-square test results comparing the groups. VI participants were significantly more likely to mention advantages due to the watch's small size (*e.g.*, lightweight, portable) (30.9% *vs.* 12.7%), while sighted participants were significantly more likely to mention disadvantages due to size (*e.g.*, small input/output area) (72.7% *vs.* 53.7%). VI participants were also significantly more concerned about '*sound-related issues*' such as low volume or not being able to pair with/plug in headphones (16.7% *vs.* 0.0%). Overall, these differences may reflect a reliance on visual output by sighted users compared to audio output by VI users.

When participants were asked about tasks they would prefer to do on a smartwatch compared to a smartphone, the top responses were fitness tracking (39.3% of VI *vs.* 33.9% of sighted participants), clock (32.8% *vs.* 37.5%), and text messaging (32.8% *vs.* 33.9%). Interestingly, 29.3% of VI participants said they would prefer the

Table 5. Perceived advantages and disadvantages of smartwatches compared to smartphones mentioned by at least five VI or sighted participants, sorted by popularity among VI participants. Items with significantly different response rates between the two groups are bolded and marked with '*'.

Advantages	VI (*N*=55)	Sighted (*N*=55)	$\chi^2_{(1)}$	*p*	ϕ
Quick/easy access	50.9%	52.7%	0.04	.849	-.02
Small – lightweight*	**30.9%**	**12.7%**	**5.33**	**.021**	**.22**
Portable	21.8%	14.5%	0.98	.323	.09
Not having to hold a device	9.1%	9.1%	0.00	1.00	.00
Less distracting*	**0.0%**	**9.1%**	**5.24**	**.022**	**-.22**

Disadvantages	VI (*N*=54)	Sighted (*N*=55)	$\chi^2_{(1)}$	*p*	ϕ
Small – input/output space*	**53.7%**	**72.7%**	**4.25**	**.039**	**-.20**
Limited functionality	22.2%	16.4%	0.60	.438	.07
Sound-related issues*	**16.7%**	**0.0%**	**9.99**	**.002**	**.30**
Not a stand-alone device	14.8%	10.9%	0.37	.542	.06

phone for all tasks compared to only 13.2% of sighted participants; this difference was significant ($\chi^2_{(1)} = 4.24$, $p = .040$, $\phi = .20$).

3.2.6 Attitude Toward On-body Interaction.

Finally, we asked two open-ended questions about on-body interaction: overall reactions to the concept and for what specific tasks, if any, such interaction may be useful. Five VI participants did not answer this question and are excluded from this analysis. Participants were roughly evenly split in mentioning potential benefits or concerns of on-body interaction. 48.2% of VI and 60.7% sighted participants mentioned at least one benefit, such as quick/easy access or larger interaction surface than a smartphone. However, 46.4% of VI and 46.4% of sighted participants also mentioned at least one concern, such as social acceptability, technical challenges (*e.g.*, sensing accuracy), and learning curve. The most frequent concern for VI users was social acceptability, although this was mentioned by only 12.5% of VI participants; 3.6% of sighted participants reported the same. Fifty-five VI users and 51 sighted users provided suggestions for tasks where on-body interaction would be especially useful. The most common were making phone calls (29.1% of VI and 39.2% of sighted responses) and checking the time (27.3% of VI and 31.4% of sighted responses). Other suggestions included changing device settings, reading/checking new messages, and controlling a media player.

3.3 Summary

Our findings emphasize differences between VI and sighted users' experiences with microinteractions. VI users took longer to complete microinteractions for most tasks and were more likely to use speech input. In terms of attitudes towards smartwatches, VI users were more likely to appreciate the small size of the device but to also be concerned about audio quality compared to sighted users. Both groups of participants responded largely similarly to the idea of on-body interaction, expressing potential benefits (*e.g.*, larger interaction space) and some concerns (*e.g.*, social acceptability).

4. Study 2: Interview & Prototype Evaluation

We conducted an in-person study with 12 VI participants to re-examine the survey themes in more depth and to subjectively compare different on-body interaction techniques for microinteractions. Previous work has shown that on-body input is more efficient for VI users than smartphone input when using *location-specific* gestures—such as pointing to different areas of the hand [26]. But, how does such input compare subjectively to more flexible *location-independent* input, such as taps or swipes

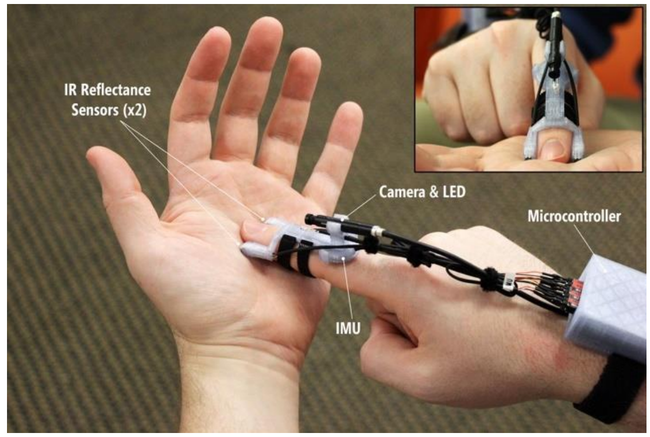


Figure 4. Our wearable, on-body interaction prototype system consists of a finger-worn package including a camera and LED, two IR reflectance sensors, and an IMU. Computer vision and machine learning algorithms are used to support location-specific, on-body gestural interaction.

anywhere on the body? Moreover, for location-specific input, do users value semantic mappings between locations and microinteractions (*e.g.*, tapping the wrist to hear the time) or more discreet but less meaningful locations? To address these questions, we built and asked participants to use a real-time system that supported three on-body interaction techniques: location-independent input, location-specific input at different body locations, and location-specific input on only the hand.

4.1 Participants

We recruited 12 smartphone users with visual impairments (7 female) through email lists, local organizations, and word of mouth; three of them (P1, P6 and P9) also participated in Study 1. Nine were blind and three had low vision. They were on average 46.2 years old (*SD* = 12.0, range 29–65). All participants had owned a smartphone for more than a year and used a screenreader "*all of the time*", except for P11 who used a screenreader "*most of the time.*" P5 used an Android phone, while the remaining participants used iPhones. Only two participants owned a wearable device: P10 had a fitness tracker and P5 had previously owned a smartwatch but rarely used it. As with the survey, the use of speech input was prevalent: ten participants used speech at least some of the time; seven of these reported regular use. Participants were compensated $60 for their time and travel costs.

4.2 Real-time Wearable System

We built a real-time wearable system, shown in Figure 4, to explore microinteractions using three different on-body interaction techniques: location-independent gestures, location-specific gestures on the palm only, and location-specific gestures at a wider variety of body locations.

4.2.1 System and Algorithms

The system includes several finger-worn sensors, as shown in Figure 4: a pair of infrared (IR) reflectance sensors[3] near the tip of the finger to sense *touch-down* and *touch-up* events, a camera[4] that localizes the user's touch using computer vision, an LED to provide consistent lighting for the camera, and an inertial measurement unit (IMU)[5] for sensing movements and recognizing gestures. Placing the sensors on the gesturing finger rather than elsewhere on the

[3] Fairchild Semiconductor QRE113GR

[4] Awaiba NanEye GS Idule Demo Kit

[5] Adafruit Flora LSM9DS0

Table 6. Our system supports 16 microinteractions organized in a two-level hierarchical menu. An * identifies items that we asked participants to select in our user study.

Category	Application	Description
Clock	Time	Check the current time
	Alarm*	Check the next alarm
	Timer*	Check the time remaining
	Stopwatch	Check the time elapsed
Daily Summary	Date	Check today's date
	Calendar*	Check the next event
	Weather*	Check the current temperature and weather conditions
Notifications	Summary	Summarize notifications (*e.g.*, "one missed phone call and two new messages")
	Missed phone call*	Check missed phone calls (*e.g.*, "missed phone call from Alice")
	New message #1	Check first new message (*e.g.*, "message from Bob")
	New message #2*	Check second new message (*e.g.*, "message from Charlie")
Health and Activities	Distance	Check the miles traveled
	Steps*	Check the number of steps taken
	Calories	Check the calories burnt
	Heart rate*	Check the heart rate
*Speech Input**	(No sub-menu)	Activate voice input

body mitigates the camera framing issues that VI users often face [2] and enabled flexible input at a variety of locations.

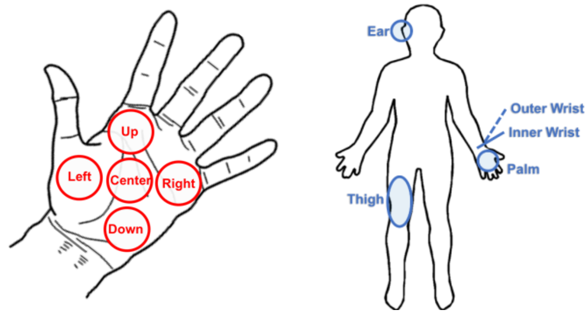
Our system use the camera images that occur between touch-down and touch-up events to localize patches of skin, an approach adapted from [36]. While the algorithms are not the focus of the current paper, in short, the approach is as follows. The visual texture, represented as a histogram of rotation-invariant local binary patterns at multiple scales, is classified using support vector machines (SVMs). To achieve real-time use (~35 fps), we remove the geometric verification stage reported in [36] and compensate for the resulting loss in accuracy by combining location estimates across 20 video frames (~570ms window). Once the location has been classified, an SVM trained on accelerometer, gyroscope, and IR features classifies the gesture itself (*e.g.*, tap, directional swipe). The image-based localization step requires training per participant, as described in the procedure section below.

The hardware components were mounted on the user's index finger via a 3D-printed ring and Velcro strips, and were positioned to avoid interfering with the user's fingertip sensitivity or range of motion. The IMU and IR sensors were connected to a wristband containing an Arduino microcontroller[6], which in turn connected along with the camera to a desktop computer[7]. Speech feedback was provided through a pair of speakers using the *Microsoft .NET* speech synthesis libraries. This prototype was intended to explore possible on-body interaction designs, and we envision a future system to be much smaller and self-contained.

4.2.2 Interaction Techniques

The system allowed users to access 16 applications that align with the microinteraction findings in Study 1. As shown in Table 6, the applications were arranged in a two-level menu hierarchy with five top-level categories; only the *Speech Input* category had no sub-menu. We implemented the following three interaction techniques, shown in Figure 1 and in the accompanying video figure, for accessing the top-level categories.

Location-independent gestures (LI). Touching anywhere on the body and swiping left and right allows the user to linearly navigate through the top-level menu categories, while a double-tap activates the currently selected category. This interface is simple and flexible, but similar location-independent interaction on the touchscreen has been shown to be time-consuming for VI users navigating a long list of items [20].



(a) Five LS_{palm} locations **(b) Five LS_{body} locations**

Figure 5. Locations used for LS_{palm} and LS_{body} interaction techniques: (a) LS_{palm} mapped five microinteraction categories arbitrarily to five locations on palm; (b) LS_{body} mapped the categories when possible to semantically meaningful body locations (e.g., wrist for *Clock*).

Location-specific gestures on the palm (LS_{palm}). The top-level categories are arbitrarily mapped to the five palm locations shown in Figure 5a: up (*Notifications*), left (*Clock*), right (*Daily Summary*), down (*Health and Activities*), and center (*Voice Input*). Users can select a category by directly tapping on its location or they can "touch and explore"—touching down anywhere on the palm, sliding the finger around to hear each touched item read aloud, then lifting up when the desired item is found. VoiceOver and TalkBack support a similar touch-and-explore functionality.

Location-specific gestures on the body (LS_{body}). The top-level categories are mapped to five locations on the body, with semantic mappings where possible (Figure 5b). Semantic body mappings, have shown promise for body-centric mobile interactions [10,12]. The five locations included: tapping the outer wrist for *Clock*, the ear for *Speech Input*, and the thigh for *Health and Activities* (*e.g.*, step count). Other mappings were the palm for *Notifications* and the inner wrist for *Daily Summary*.

Once the top-level category is selected and activated using one of these three interaction techniques, users swipe left/right to navigate the submenu items and double-tap to select the current item. This submenu interaction is similar to basic interface navigation with VoiceOver and TalkBack, with which our participants were familiar (all were screenreader users). Of the three interaction techniques, the location-specific options should theoretically be fastest because they allow for direct access to menu categories, while the location-independent option provides more flexibility.

4.3 Procedure

The study session began with a background questionnaire, followed by semi-structured interview questions (~20 minutes) that focused on the same themes as the survey. After the interview, we calibrated and trained the localization component of the wearable on-body interaction prototype (~30 minutes), which included collecting several images of each location shown in Figure 5. The three interaction techniques were then presented in counterbalanced order. For each interaction technique, participants were given a short introduction (~5 minutes) before independently completing a set of 10 microinteractions. Each microinteraction consisted of navigating to, selecting, and briefly using an application (*e.g.*,

[6] Sparkfun Arduino Pro Micro (5V/16MHz)

[7] Dell Precision T7910 (Intel Xeon, 8-core, 2.1Ghz, NVIDIA GeForce GTX 750Ti)

Alarm item within the *Clock* category). The set included two applications from each of the five menu categories (Table 6) except for the *Speech Input* category, which was simply selected twice since it had no submenu items. For each microinteraction, the tester stated which application to select along with its category. The session concluded with open-ended questions about the user experience and comparison of the three interaction techniques in terms of preference, ease of use, efficiency, and use in public.

4.4 Data Analysis

We audio-recorded and transcribed participants' open-ended responses for analysis. For questions that were also in the online survey, we reused the same analytical codebook (*e.g.*, "*What tasks or actions do you do frequently on your phone?*"). Other questions were analyzed by one researcher based on themes of interest [9] (*e.g.*, one-handed use of phone, interaction on-the-go), while allowing for new, emergent themes.

4.5 Findings

We briefly cover findings that confirm and extend the survey responses on general microinteraction use before presenting subjective responses to the on-body interaction techniques.

4.5.1 Current Microinteraction Experience

In general, trends were similar to the survey responses from VI participants, thus we highlight only new findings and examples.

Overall microinteraction use. The most frequently used and fast (≤ 10 seconds) smartphone tasks with manual input were: voice call interactions (*N*=9 participants out of 12), text message interactions (*N*=8), looking up information (*N*=6), and checking the weather (*N*=4). Seven participants specified that some tasks take less than 10 seconds only when using speech input (*e.g.*, voice search, dictation) emphasizing again the importance of speech input for supporting efficient interaction for VI users. In terms of accessibility-related tasks, three participants mentioned frequent use of *TapTapSee*[8], a money/object identification app, although it was not considered fast (≤ 10 seconds).

Microinteractions on-the-go. Previous work on the design of on-body interaction for VI users emphasized the importance of one-handed interaction to support use on-the-go, since users may be holding a cane or service dog leash [25]. Participant responses confirm that finding. When asked about using their phone with one hand, eight participants commented that one-handed use is important when walking. At the same time, nine participants also preferred not to use their phone at all when using a cane due to safety concerns, confirming that the perceived cost of interacting with a mobile device on-the-go is high for VI users [1,33,39]. For example, P8 said, *"See, when I'm walking, I have to use my cane, so I don't even be [sic] on the phone. To me, that's almost like driving and being on the phone. […] That'll put a blind person in danger."* Although limited to answering/rejecting a call or using speech input, six participants reported that they use a headphone or a headset to remotely control their phone while walking.

Advantages and limitations of smartwatches. We also asked about perceived advantages and limitations of smartwatches compared to smartphones. In general, responses reflected trends seen in the survey, such as advantages of quick/easy access (*N*=6), hands-free (*N*=5), and portability (*N*=4), and limitations related to the small size (*N*=9), functionality (*N*=3), need for a paired phone (*N*=3), and sound-related issues (*N*=2). Of the nine participants who

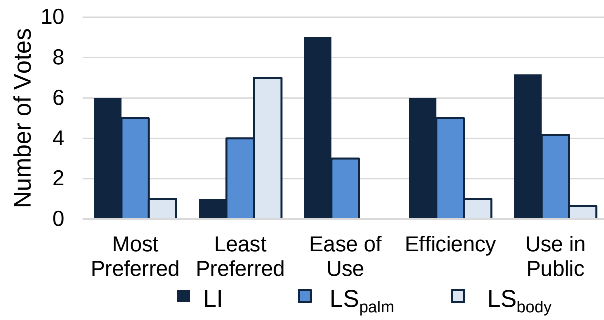


Figure 6. Vote counts for the interaction techniques that are the most and least preferred overall, most efficient, easiest to use, and most comfortable to use in public. Participants were allowed to vote for multiple options for *Use in Public*, but in such cases the votes were adjusted to sum to 1.0 per participant. (*N* = 12)

reported limitations related to size, eight specified that the small screen would make input difficult, for example:

> *"…because [the phone] has [a] wider space so I can find the layout of the keyboard, and I'll have a wider area of navigation between the letters and the keys. But in the case of [a] smartwatch, it's much, much smaller, so it will be compact and difficult to locate each letter."* (P1)

4.5.2 On-body Prototype Evaluation

We summarize overall reactions to on-body interaction then compare subjective responses to our three interaction techniques.

General reactions. We asked participants for their thoughts about on-body interaction *before* using our prototype and again *after* using it in comparison to smartphones and smartwatches (open-ended). Most participants (*N*=9) reacted positively beforehand, citing similar reasons as in the survey: quick and easy access (*N*=7), being able to map different body locations to different interactive tasks (*N*=6), and not having to hold the phone in hand (*N*=4). After use, when compared with a smartwatch or a smartphone, reactions focused on technical/physical aspects of the interaction, such as the number of devices to be carried (*N*=6) or sensor/speaker locations (*N*=6). After using the prototype, three participants still felt that they would prefer to use their phone due to familiarity. For instance, P9 said: *"I would rather use the phone. […] I have no problem with using the body. It's just that I'm not used to it."*

Preferred interaction techniques. Figure 6 shows the subjective votes along several dimensions: overall most and least preferred, easiest to use, most efficient, and most appropriate for public use. Due to the sample size (*N*=12), we do not report on statistical tests on this data, but instead analyze the subjective rationale provided to support the votes. For overall preference, location-independent gestures (*LI*), where taps and swipes could be performed at any location, and gestures performed at specific locations on the palm only (LS_{palm}) were preferred to gestures performed at specific locations across the body (LS_{body}). The reasons for these preferences are broken down in the sections below.

Ease of use and learnability. As shown in Figure 5, most participants (*N*=9) felt that *LI* was the easiest to use of the three interaction techniques, for reasons such as: the microinteractions were easy to perform (*N*=7), the interaction was similar to that on a phone (*N*=6), and the input location was flexible (*N*=5). At the same time, about half of the participants considered the need to learn and remember specific locations to be a drawback of both LS_{palm} (*N*=7)

[8] http://www.taptapsee.com

and LS_{body} (N=6), although the semantic mappings of LS_{body} (*e.g.*, tap wrist for *Clock*) were seen by some (N=5) as beneficial for learning. Another valued interaction was the touch-and-explore feature of LS_{palm}, which four participants noted as supporting learning, even for novices. For example:

> *"So someone who's new to it, I think they can pick it up fairly simple. […I like] the browsing part and being able to also open the apps. I can go back the center of my palm and still browse through that." (P5)*

Efficiency. We expected that *LI* would be perceived as less efficient than the two *LS* interfaces, since *LI* required a longer sequence of inputs (several swipes) compared to selecting a category by simply tapping its dedicated location. However, as seen in Figure 5, participants were roughly split between *LI* and LS_{palm} as the most efficient interaction technique, while only one participant selected LS_{body}. Seven participants commented that LS_{body}'s efficiency was impacted by the large motion required to point to different locations, which was especially of concern before learning the mappings. For instance:

> *"[With LS_{palm}] it's easy to search through. Because if it's not here, it's somewhere in this area. But [with LS_{body}] if you have it on your wrist and then your palm and on your ear, you gotta remember which one you need to touch." (P12)*

Social acceptability. Social acceptability is an important concern for wearable interaction [31] and for on-body interaction for VI users specifically, as seen both in prior work [25] and in Study 1. Nine participants felt they would be most comfortable using either *LI* or LS_{palm} in public compared to LS_{body} because the latter was less discreet. The remaining three participants felt that all three interaction techniques would be equally appropriate or inappropriate for public use. For example, P1 stated *"[LS_{body}] looks weird and a bit obnoxious. I mean, not pleasing for the onlooker. […] So I don't feel comfortable using it publicly."* The specific body locations included in the interface, however, would likely impact this perception (as found in [25]). For example:

> *"The [outer] wrist, I think is okay. I guess the inside of the wrist is okay, too. […] But ear, nose, thigh, all those things would be more uncomfortable." (P6)*

Interaction on-the-go and input availability. We found that participants appreciated having multiple options for input locations, especially for mobile contexts where one hand is busy. For this reason, six participants liked that *LI* did not restrict the input location, whereas microinteractions in the *LS* conditions could only be accessed from their dedicated input location, which may not always be available. For instance, P10 preferred locations other than the palm for flexibility, commenting, *"If you have something in your hand, it's like for me, if I'm holding my cane, or I'm standing somewhere, I want to check the time, I can just tap on my wrist. So it's easier, because my hand is not always going to be free."*

Customization. At the end of the study, we asked participants if they would want to customize the prototype to support different apps. A variety of preferences emerged, in terms of both interaction location and tasks to support. While seven participants wanted to use the palm for input, others suggested different body locations. P12, for example, wished to use specific locations for different tasks, suggesting some possibilities that had not been evaluated in the study, such as fingertips for making phone calls, ear lobe for answering phone calls, wrist for checking the time, thigh for notifications, and even lips for activating voice input. Furthermore, participants differed in the applications they wanted to support. For instance, P2 wanted to perform only phone call-related tasks, while P8 wanted a wider variety of tasks, such as opening apps like a calendar, a clock, and games, as well as checking notifications and heart rate. This diversity suggests that customization may be beneficial.

4.5.3 Summary
Our interview findings reinforced the survey responses regarding current support for microinteractions, specifically strategic use of voice input. The perceived trade-offs between three interaction techniques from the real-time system evaluation revealed VI users' needs and preferences for on-body interaction in terms of ease of use (*e.g.*, touch-and-explore to support learnability), efficiency (*e.g.*, downside of LS_{body}'s large movements), and use in public (*e.g.*, differences across body locations). The ability to support use on-the-go by supporting flexibility of input was also important.

5. Discussion
We reflect on the implications of our findings, focusing on how to better support microinteractions for people with visual impairments.

5.1 Accessible Microinteractions
Our findings suggest that efficient manual input for microinteractions is not well-supported for users with visual impairments. Only two microinteractions, checking the time and controlling a music player, were reported as taking < 5 seconds for most of our VI survey respondents. As seen in both the survey and interviews, voice input is a valuable tool for addressing the inefficiencies of screenreaders for microinteractions. This finding reflects previous more general studies showing that voice input is more popular for VI users than for sighted users [5,39]. However, because voice input may not always be appropriate due to background noise or privacy concerns [1,5,39], it is also important to develop more efficient manual input approaches to better support non-visual microinteractions.

Tasks that use mobile technology to increase the accessibility of the physical world, such as OCR, currency detection, and object recognition, arose rarely in the survey and interviews. This was, perhaps, because our focus was on tasks that are frequent *and* fast. Responses from three interview participants support this possibility: all three mentioned using their phone frequently for accessibility-specific tasks but not efficiently enough to qualify as a microinteraction; only one of the 61 survey respondents mentioned such a task (currency detection) as taking < 10 seconds. There is thus an opportunity for new wearable devices or even redesigned smartphone apps or operating systems to much more efficiently support accessibility-specific physical world tasks.

As already mentioned, wearable devices are particularly well-suited to support microinteractions [4,22,24]—whether smartwatches, on-body interaction, or other devices. However, differences in how VI and sighted users perceive smartwatches suggest that the ideal wearable form factor for each user group may differ, particularly in terms of the bulk and size needed to support visual versus auditory output modalities. VI users were more likely than sighted users to perceive the small size of a smartwatch to be an advantage, whereas sighted users, who rely on the visual output of the display, were more likely to see this size as a disadvantage. Still, some VI users were concerned about the touchscreen size from a gestural input perspective.

5.2 On-body Input for Microinteractions
While a variety of approaches—such as new wearable devices and redesigned touchscreen interactions—should be considered for future work on non-visual microinteractions, our findings provide specific guidance for implementing an on-body solution. Overall,

there were tradeoffs between the three on-body interaction techniques in efficiency, learnability, use on-the-go, and social acceptability. For efficiency, we had expected that the location-specific interaction techniques would fare well because they allowed for direct access to menu items or applications rather than requiring a series of swipes to find a specific item. However, participants felt that the two techniques that supported interaction within a small space were the most efficient: location-specific palm gestures and location-independent gestures, the latter of which participants often did on their hand. This finding suggests that quick access to all information within a constrained, discreet space may overshadow the efficiency advantages of direct selection at more distributed locations on the body, as well as the utility of semantic mappings (*e.g.*, wrist for time, ear for volume).

Learnability of the interface was also a concern. Half the participants mentioned that a strength of the location-independent gestures was not having to memorize the mappings between locations and menu items. Although we had expected that the touch-to-explore feature of location-specific gestures would allow users to discover items and support novice use, this was not seen in our study. However, a larger set of menu items and a longer-term study (rather than a single session) would likely affect perceptions of learnability. As users transition to experts, they may better appreciate the speed with which they can directly access items at specific hand and/or body locations. Thus, enabling both location-independent and location-specific gestures may best support both novice and expert users, similar to how iOS and Android support both gesture-based navigation as well as exploration by touch.

The three interaction techniques vary in their ability to support use on-the-go since not all input locations will always be available (*e.g.*, hand or thigh). Thus, in mobile contexts, input locations that move less when the whole body is in motion (*e.g.*, chest *vs.* leg) or that can be used even when one hand is busy (*e.g.*, holding a cane or bag) may be preferred. Alternatively, location-independent gestures, which are not restricted to a specific location, would allow for the flexibility to adapt the interaction to any given body posture or movement. As with issues of learnability, a combination of location-independent and location-specific input may also be useful to explore for use on-the-go. Regardless, complementing manual input with voice input is critical for efficient, on-the-go interaction.

Finally, social acceptability is a common concern with wearable assistive technology for VI users [30,39]. This concern arose with on-body interaction in Study 1 but was less pronounced in Study 2 where participants had experience using a real-time prototype. The gestures at locations across the body (*e.g.*, ear, thigh, wrist) were seen as less appropriate for use in public than the other two interaction techniques, which supported much smaller input areas. Socially acceptability concerns may be mitigated by supporting location-independent gestures as users can choose any input location that they consider discreet or by mapping all applications to a concentrated area that can support subtle gestures. Allowing users to customize body locations may also be useful, as appropriate locations may differ from one person to another (*e.g.*, due to gender or personal preference).

5.3 Limitations

A limitation of the online survey and first portion of the in-person study is that the data on microinteraction timing and frequency of use is based on subjective estimates. As such, it important for future work to complement these findings with log data of actual use. Another survey limitation is that the VI user group was older than the sighted user group, which may have impacted results. For the in-person study, while our system offered real-time interaction, it was still an early prototype and had drawbacks that could have impacted user perceptions. Most notably, the wearable components were bulkier than we envision a future system would be and the system required a lengthy training process (~30 minutes) to collect training images of the user's hands and body. As well, the system included only five application categories, which were accessed via location-specific taps or location-independent swipes and taps. A larger number of top-level items in the interface may change how users view the efficiency tradeoffs between the different interaction techniques. Finally, a longer-term evaluation of the on-body interaction techniques may yield different tradeoffs by addressing novelty effects and allowing users to develop expertise.

6. CONCLUSION

Our goal is to support not only *accessible* mobile interaction for users with visual impairments but *efficient* interaction. We investigated how well microinteractions are supported on smartphones and smartwatches for people with visual impairments compared to sighted users. Our findings suggest that manual input does not sufficiently support efficient non-visual microinteractions, highlighting the need for new interaction approaches. Speech input was a commonly used workaround for VI users in our online survey, but is not always appropriate due to privacy and noise concerns. As an alternative manual input approach, we evaluated three different on-body interaction techniques, which revealed tradeoffs in terms of perceived efficiency, learnability, social acceptability and ability to use on the go. Future work should examine to what extent it is possible to combine the strengths of these different on-body interaction techniques into a single system to ultimately allow for efficient and socially acceptable input.

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8. REFERENCES

1. Abdolrahmani, A., Kuber, R., and Hurst, A. 2016. An Empirical Investigation of the Situationally-Induced Impairments Experienced by Blind Mobile Device Users. *ACM W4A '16*: 21.
2. Adams, D., Morales, L., and Kurniawan, S. 2013. A qualitative study to support a blind photography mobile application. *ACM PETRA '13*, 1–8.
3. Ashbrook, D. L. 2010. Enabling Mobile Microinteractions. *PhD Thesis*.
4. Ashbrook, D. L., Clawson, J. R., Lyons, K., Starner, T. E., and Patel, N. 2008. Quickdraw: The Impact of Mobility and On-Body Placement on Device Access Time. *ACM CHI '*08, 219–222.
5. Azenkot, S. and Lee, N. B. 2013. Exploring the use of speech input by blind people on mobile devices. *ACM ASSETS '13*: 11.
6. Azenkot, S. Rector, K., Ladner, R., and Wobbrock, J. O. 2012. PassChords: Secure Multi-Touch Authentication for Blind People. *ACM ASSETS '12,* 159–166.
7. Böhmer, M., Hecht, B., Schöning, J., Krüger, A., and Bauer, G. 2011. Falling Asleep with Angry Birds, Facebook and Kindle: A Large Scale Study on Mobile Application Usage. *ACM MobileHCI '11*, 47–56.
8. Bonner, M. N., Brudvik, J. T., Abowd, G. D., and Edwards, W.

K. 2010. No-look Notes: Accessible Eyes-free Multi-touch Text Entry. *Springer-Verlag Pervasive '10*, 409–426.

9. Braun V. and Clarke, V. 2006. Using Thematic Analysis in Psychology. *Qualitative research in psychology* 3, 2: 77–101.
10. Chen, X. A., Marquardt, N., Tang, A., Boring, S., and Greenberg, S. 2012. Extending a mobile device's interaction space through body-centric interaction. *ACM MobieHCI '12*, 151–160.
11. Dakopoulos. D. and Bourbakis, N. G. 2010. Wearable obstacle avoidance electronic travel aids for blind: a survey. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on* 40, 1: 25–35.
12. Guerreiro, T., Gamboa, R., and Jorge, J. 2007. Mnemonical body shortcuts for interacting with mobile devices. *International Gesture Workshop*, 261–271.
13. Guerreiro, T., Lagoá, P., Nicolau, H., Gonçalves, D., and Jorge. J. 2008. From Tapping to Touching: Making Touch Screens Accessible to Blind Users. *IEEE MultiMedia '08*.
14. Gustafson, S., Rabe, B., and Baudisch, P. 2013. Understanding Palm-based Imaginary Interfaces: The Role of Visual and Tactile Cues when Browsing. *ACM CHI '13*, 889–898.
15. Gustafson S., Holz, C., and Baudisch, P. 2011. Imaginary Phone: Learning Imaginary Interfaces by Transferring Spatial Memory from a Familiar Device. *ACM UIST '11*, 283–292.
16. Harrison, C., Ramamurthy, S., and Hudson, S. E. 2012. On-body Interaction: Armed and Dangerous. *ACM TEI '12*, 69–76.
17. Harrison, C., Tan, D., and Morris, D. 2010. Skinput: Appropriating the Body As an Input Surface. *ACM CHI '10*, 453–462.
18. Hoggan, E., Brewster S. A., and Johnston, J. 2008. Investigating the Effectiveness of Tactile Feedback for Mobile Touchscreens. *ACM CHI '08*, 1573–1582.
19. Hruschka, D. J., Schwartz, D., St.John D. C., Picone-Decaro, E., Jenkins, R. A., and Carey, J. W. 2004. Reliability in Coding Open-Ended Data: Lessons Learned from HIV Behavioral Research. *Field Methods* '04: 16(3), 307–331.
20. Kane, S. K., Bigham, J. P., and Wobbrock, J. O. 2008. Slide Rule: Making Mobile Touch Screens Accessible to Blind People Using Multi-touch Interaction Techniques. *ACM ASSETS '08*, 73–80.
21. Kane, S. K., Jayant, C., Wobbrock, J. O., and Ladner, R. E. 2009. Freedom to Roam: A Study of Mobile Device Adoption and Accessibility for People with Visual and Motor Disabilities. *ACM ASSETS '09*, 115–122.
22. Loclair, C., Gustafson, S., and Baudisch, P. 2010. PinchWatch: A Wearable Device for One-Handed Microinteractions. *ACM MobieHCI '10:*10
23. McGookin, D., Brewster, S., and Jiang, W. 2008. Investigating Touchscreen Accessibility for People with Visual Impairments. *ACM NordiCHI '08*, 298–307.
24. Nanayakkara, S., Shilkrot, R., Yeo, K. P., and Maes, P. 2013. EyeRing: A Finger-worn Input Device for Seamless Interactions with Our Surroundings. *ACM AH '13*, 13–20.
25. Oh, U. and Findlater, L. 2014. Design of and Subjective Responses to on-Body Input for People With Visual Impairments. *ACM ASSETS '14*: 8.
26. Oh, U. and Findlater, L. 2015. A Performance Comparison of On-hand versus On-phone Non-Visual Input by Blind and Sighted Users. *ACM TACCESS '15:* 7(4), 14.
27. OrCam Technologies Ltd. http://www.orcam.com. .
28. Oulasvirta, A., Tamminen, S., Roto, V., and Kuorelahti, J. 2005. Interaction in 4-Second Bursts: The Fragmented Nature of Attentional Resources in Mobile HCI. *ACM CHI '05*, 919–928.
29. Pizza, S., Brown, B., McMillan, D., and Lampinen, A. 2016. Smartwatch in Vivo. *ACM CHI '16*, 5456–5469.
30. Profita, H., Albaghli, R., Findlater, L., Jaeger, P., and Kane, S. K. 2016. The AT Effect: How Disability Affects the Perceived Social Acceptability of Head-Mounted Display Use. *ACM CHI '16*, 4884–4895.
31. Profita, H. P., Clawson, J., Gilliland, S., Zeagler, C., Startner, T., Budd, J., and Do, E.Y. 2013. Don't Mind Me Touching My Wrist: A Case Study of Interacting with On-body Technology in Public. *ACM ISWC '13*, 89–96.
32. Shilkrot, R., Huber, J., Ee, W. M., Maes, P., and Nanayakkara, S. C. 2015. FingerReader: A Wearable Device to Explore Printed Text on the Go. *ACM CHI '15 Extended Abstracts*, 2363–2372.
33. Shinohara, K. and Wobbrock, J. O. 2011. In the Shadow of Misperception: Assistive Technology Use and Social Interactions. *ACM CHI '11*, 705–714.
34. Starner, T. E., Snoeck, C. M., Wong, B. A., and McGuire, R. M. 2004. Use of Mobile Appointment Scheduling Devices. *ACM CHI '04 Extended Abstracts*, 1501–1504.
35. Stearns, L., Du, R., Oh, U., Jou, C., Findlater, L., Ross, D. A., and Froehilich, J. E. 2016. Evaluating Haptic and Auditory Directional Guidance to Assist Blind Persons in Reading Printed Text Using Finger-Mounted Cameras. *ACM TACCESS '16:*9(1), 1–38.
36. Stearns, L., Oh, U., Cheng, B. J., Findlater, L., Ross, D., Chellappa, R., and Froehlich, J.E. 2016. Localization of Skin Features on the Hand and Wrist from Small Image Patches. *IEEE ICPR '16*, 1003–1010.
37. WebAIM. *Screen Reader User Survey #4. http://webaim.org/projects/screenreadersurvey4/#demographics*.
38. Weigel, M., Mehta, V., and Steimle, J. 2014. More Than Touch: Understanding How People Use Skin As an Input Surface for Mobile Computing. *ACM CHI '14*, 179–188.
39. Ye H., Malu, M., Oh, U., and Findlater, L. 2014. Current and Future Mobile and Wearable Device Use by People with Visual Impairments. *ACM CHI '14*, 3123–3132.