Design of and Subjective Response to On-body Input for People With Visual Impairments

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ABSTRACT

For users with visual impairments, who do not necessarily need the visual display of a mobile device, non-visual on-body interaction (*e.g.*, *Imaginary Interfaces*) could provide accessible input in a mobile context. Such interaction provides the potential advantages of an always-available input surface, and increased tactile and proprioceptive feedback compared to a smooth touchscreen. To investigate preferences for and design of accessible on-body interaction, we conducted a study with 12 visually impaired participants. Participants evaluated five locations for on-body input and compared on-phone to on-hand interaction with one versus two hands. Our findings show that the least preferred areas were the face/neck and the forearm, while locations on the hands were considered to be more discreet and natural. The findings also suggest that participants may prioritize social acceptability over ease of use and physical comfort when assessing the feasibility of input at different locations of the body. Finally, tradeoffs were seen in preferences for touchscreen versus on-body input, with on-body input considered useful for contexts where one hand is busy (*e.g.*, holding a cane or dog leash). We provide implications for the design of accessible on-body input.

Categories and Subject Descriptors

H.5.2. [User Interfaces]: Input devices and strategies; H.5.m. [Information Interfaces and Presentation (e.g., HCI)]: Miscellaneous; K.4.2. [Social Issues]: Assistive technologies for persons with disabilities.

Keywords

Visual impairments; mobile; gestural interfaces; on-body input; eyes-free interaction; design recommendations.

1. INTRODUCTION

On-body input such as that found in SixthSense [21], OmniTouch [14], Imaginary Phone [7], and others [3,12,14] allows users to employ their own body as an input surface with the support of a wearable camera or other sensors. Such techniques could provide new means of mobile interaction for people with disabilities, yet little work has explored this potential. For users with visual impairments, who do not necessarily need the visual display of a phone, non-visual on-body input is particularly compelling (*e.g.*, *Imaginary Interfaces* [6,7,29]).

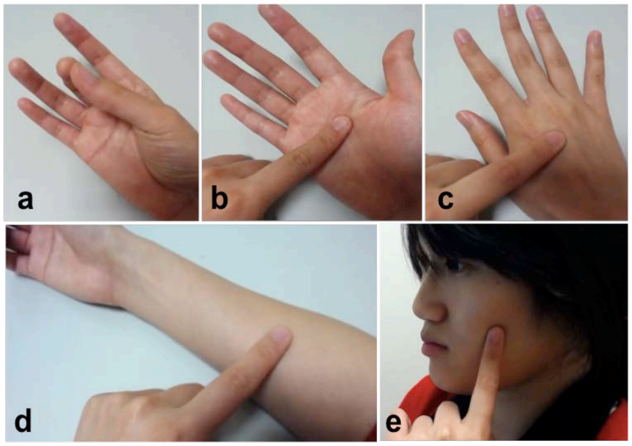


Figure 1. The five on-body input locations explored in our study: (a) same hand, (b) other hand-palm, (c) other hand-back, (d) forearm, and (e) neck and face area.

While advances in mobile screenreaders (*e.g.*, iOS VoiceOver) have led to the adoption of conventional smartphones by people with visual impairments [32], basic tasks can still be time consuming. As an *alternative* or *complementary* means of mobile interaction, on-body input including taps or swipes on the hand has the potential to provide efficient, always-available interaction. On-body input also provides increased tactile and proprioceptive feedback compared to the smooth screen of a smartphone [8], which could be particularly useful for non-visual interaction.

To investigate the design of and subjective response to on-body interaction for people with visual impairments, we conducted a lab study with 12 participants. Our first goal was to answer questions such as what locations and gestures are preferred (*e.g.*, touchscreen-style, location-specific), and what factors affect these preferences. Our second goal was to compare subjective responses to on-body input versus mobile touchscreen input. Toward the first goal, we adapted a method employed by Weigel *et al.* [33] to examine gesture preferences at five on-body locations (Figure 1) and to evaluate these locations on factors such as social acceptability, comfort, and ease of use. Toward the second goal, we implemented an on-hand sensing system that controls the VoiceOver software on an Apple iOS device and asked participants to complete basic mobile tasks with both on-hand input and a touchscreen smartphone.

Our findings show that the least preferred areas for on-body input were the face and neck, and the forearm; in contrast, locations on the hands were considered to be more discreet and natural. The results also suggest that participants may be prioritizing social acceptability over ease of use and physical comfort when assessing the feasibility of input at different locations of the body.

ASSETS '14, October 20 - 22 2014, Rochester, NY, USA

http://dx.doi.org/10.1145/2661334.2661376

Finally, tradeoffs were seen in preferences for touchscreen versus on-body input, with on-body input considered useful for contexts where one hand is busy (*e.g.*, holding a cane or dog leash). The contributions of this paper are: (1) investigation of the potential of on-body input for people with visual impairments—the first in-depth study at this intersection; (2) characterization of preferences for different on-body input locations and one- versus two-handed use; (3) an exploratory, subjective comparison of on-body versus touchscreen input; and (4) design implications for accessible on-body interaction.

2. RELATED WORK

Our research builds on work in mobile accessibility and on-body interaction. We also highlight findings on the social acceptability of wearable devices more generally.

2.1 Mobile Accessibility

Mobile devices can make people with disabilities feel safer and make it easier to access information on the go [10]. Solutions to improve touchscreen accessibility for people with visual impairments have included both hardware or physical overlays to provide enhanced tactile cues [16,20,31], and software solutions that incorporate touchscreen gestures [2,4,5,9]. *Slide Rule* [9], for example, combines multi-touch gestures and audio to allow users to navigate through information on the touchscreen. Commercial accessibility features such as Apple's *VoiceOver* and Android's *TalkBack* provide built-in software that combines accessible gestures and auditory output. While these software-only techniques can be widely disseminated, they provide limited tactile feedback due to the flat input surface of the touchscreen. Ultimately, our goal is to combine on-body input—with its additional tactile and proprioceptive characteristics [8]—with audio interfaces as an alternate means of mobile interaction.

2.2 On-body (Skin-based) Interaction

Many on-body (skin-based) interaction methods have been proposed, primarily combining gestures sensed by camera [3] or acoustically [12] and a small visual display projected on the user's hand or arm [12,13,14,21,30] or on a wristwatch [18]. More closely inspiring our work is on-body interaction that exploits the user's tactile and proprioceptive senses without employing visual displays [3,7,17], allowing for eyes-free interaction. Gustafson *et al.*'s [6] *Imaginary Interfaces* provide spatial, non-visual interaction, where the user points one hand to or near the non-dominant hand. *Imaginary Phone*, for example, mimicked the layout of a smartphone for non-visual interaction on the user's hand, allowing the user to transfer existing spatial knowledge of the interface layout to their hand [7]. A recent study of the tactile and proprioceptive characteristics of palm-based imaginary interfaces showed that while sighted users primarily relied on vision to accurately target on their hand, a palm-based interface was still usable for eyes-free input [8]. That work also included an exploratory evaluation with one blind participant who reacted positively to the palm-based interaction—further motivating our study. To our knowledge, however, no larger evaluation has explored on-body interaction for visually impaired users.

Our study also builds on recent work by Weigel *et al.* [33], who investigated skin input modalities and preferred locations with sighted users. When asked to create their own on-body gestures, participants in Weigel *et al.*'s study primarily used conventional multi-touch gestures, and preferred to use the forearm and the hand over a location on the upper limb. The first of our two study tasks borrows heavily from Weigel *et al.*'s method, adapting it for users with visual impairments.

2.3 Eyes-free Wearable Devices

Beyond on-body interaction, a number of wearable input devices have been proposed that support *eyes-free* interaction. Aimed at users with visual impairments, *EyeRing* [22] is a finger-mounted camera that supports activities such as reading text and detecting color/currency. Ye *et al.* [37] explored projected impacts of a wristband input device by people with visual impairments, identifying potential for increased inclusion in social contexts and ability to access information on the go. In terms of mainstream use (*i.e.*, not focused on accessibility), several projects have proposed hand-worn or wrist-worn devices. A few examples supporting eyes-free interaction include a haptic wristwatch [26, 27], a finger-mounted camera that supports touch input on arbitrary surfaces [36], and ring-based devices such as *Nenya* [1] and *Magic Ring* [15]. While these projects did not focus on improving mobile accessibility, they offer varying degrees of applicability for accessible input. Devices that interfere with tactile perception (*e.g.,* [36]) could be problematic, whereas ring-based interaction (*e.g.*, [1]) would allow fingertips to remain free.

2.4 Social Acceptability of Wearable Input

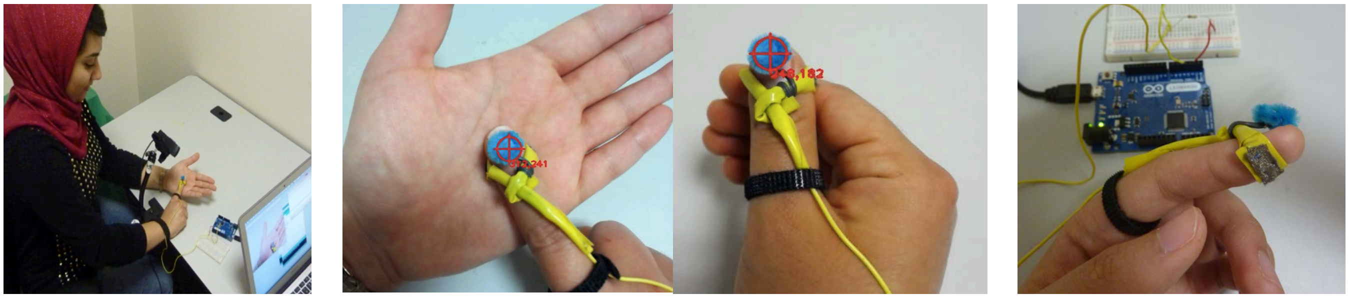
Although not focused on wearable devices, Shinohara and Wobbrock [28] found that social stigma and misperceptions of assistive technology can impact how people with disabilities adopt devices. More recently, Ye *et al.* [37] showed that the majority of participants with visual impairments were interested in trying wearable input devices. Most work on social acceptability of wearable input, however, has looked at users without disabilities, comparing input at different on-body locations [11,25] or of different gestures [26,27]. One study on a novel textile input technique, for example, found that the upper arm was the best location for balancing orientation, ease of use, and social acceptance [22], which contrasts findings for on-body (skin) input [33]. From an observer rather than wearer point of view, Profita *et al.* [25] found that wrist and forearm locations are most popular for wearable input across both Korean and American cultures. Finally, Rico *et al.* [27] examined social acceptance of device-specific and body-specific gestures, finding participants' willingness to perform a particular gesture was significantly impacted by location and audience. We borrow from their method to examine similar questions with users with visual impairments.

3. METHOD

To investigate the design of on-body interaction for people with visual impairments and the potential impacts of such interaction, we conducted a lab-based study that included two tasks. The first task collected subjective assessments of five locations for on-body input, and the second task compared on-body versus touchscreen phone input using one or two hands.

3.1 Participants

Twelve participants (6 male, 6 female) were recruited via campus e-mail lists and local organizations that serve people with visual impairments. The average age was 44.3 (*SD* = 12.9, range 23–62). Nine participants were totally blind; six were born blind while the rest became blind later in life (years post onset: *M* = 22.8, *SD* = 14.4, range 3–42). Three participants had low vision, respectively: 20/200 for both eyes, none for left eye and 20/200 for right eye, and 20/3000. All but two participants were right-handed. While nine participants used touchscreen phones on a regular basis, the remaining three had feature phones. Participants reported using their phone at least once every few hours, with the exception of one participant who used it once a day. Participants were compensated for their time and transportation.



(a) Experiment setup (b) Fingertip tracking for one and two hands (c) Touch detection

Figure 2. On-hand sensing system used in Task 2. Participants wore a lightweight ring that included a color marker (tracked by a camera) and a capacitive touch sensor. The ring could be placed so as not to cover the fingertip.

3.2 Apparatus

To avoid limiting participants' on-body gesture creation process, no sensing technology was used for the first task, as was done by Weigel *et al.* [33] and is common more broadly with a user-defined gesture approach [34]. For the second task, we built a system that senses on-hand input to control the VoiceOver screenreading software on an Apple iOS device (Figure 2). The system could recognize four gestures: *double tap*, *left-to-right-swipe*, *right-to-left swipe* and *long* tap. These gestures were used as direct replacements for the same VoiceOver gestures, with the exception of a long press to replace the home button.

While we ultimately want to support on-hand input without instrumenting the fingers, participants wore a lightweight ring for tracking. The ring included a color marker on the top and a capacitive touch sensor made of conductive fabric on the bottom (shielded from the gesturing finger itself by non-conductive tape). To prevent tangling, thin Velcro straps held the wires around the gesturing finger and the wrist.

The system additionally consisted of a computer vision module to track *x*,*y* finger location, and a touch-detection module. For the computer vision module, which tracked the color marker on the participant's gesturing finger, we used a Logitech Webcam C930e and custom software running on a laptop with an Intel Core i5 processor. The custom touch-detection module ran on an Arduino Leonardo board and used the *SoftwareSerial* and *CapSense* libraries to detect capacitive input. The laptop communicated timestamped finger locations to the Arduino software, which combined them with the touch state to classify the user's gestures. Finally, the Arduino converted the sensed gestures to VoiceOver keyboard shortcuts and sent them via Bluetooth to an iPhone 4S. The participant could control VoiceOver by touching their hand.

3.3 Procedure

The procedure was designed to fit in a single two-hour session consisting of two tasks and questionnaires.

3.3.1 Task 1: Location Preference for On-body Input

Inspired by user-defined gesture protocols where users create gestures that can be analyzed to determine guessability and preferences [33][34], participants first created gestures for five mobile actions at each of five different on-body locations. Participants were allowed to use any number of fingers including their thumb, and they were asked to perform on-body gestures with their dominant hand only. They were asked to think aloud while doing so. The locations, as shown in Figure 1, were: *same hand*, *other hand-palm*, *other hand-back*, *forearm*, and *neck and face* area including the ears. These locations overlap with Weigel *et al.* [33], but we focused on those where the skin would likely be exposed, adding *same hand* and *neck and face* in the process.

Our participants performed five mobile actions, which were chosen to cover a range of common mobile tasks: (1) *previous*: moving to the previous item in a list, (2) *next*: moving to the next item in a list, (3) *open*: opening a selected item, (4) *home screen*: returning to the home screen, and (5) *e-mail*: creating a shortcut gesture to open an e-mail app. The on-body locations were presented in random order to each participant, and the mobile actions were further presented in random order for each location.

After creating gestures for all five on-body locations, participants evaluated each location in terms of ease of use, physical comfort, and social acceptance. We also asked about participants' openness to performing a gesture at each location in the following contexts:

- **Place:** private (*e.g.*, home), crowded public (*e.g.*, public transit, restaurant), non-crowded public (*e.g.*, library), workplace.
- **Audience:** alone, partner, friends, family, colleagues, strangers.
- **Physical constraints:**
    - *Pose*: seated, standing, walking
    - *Available hands*: both hands free, one hand busy (*e.g.*, holding a cane or a dog leash)
- ***Input***: handwriting, keyboard, number pad, sketching, and touchpad (from Weigel *et al.* [33]).

3.3.2 Task 2: Phone vs. On-hand Input

Task 2 compared smartphone input to on-hand input with one or two hands (Figure 3). The task was set up as a 2x2 within-subjects design, with factors of *device* (touchscreen phone *vs.* on-body) and *hand count* (one *vs.* two). Input in all conditions controlled the VoiceOver screenreader on an iPhone 4S, which allows for eyes-free interaction; for participants with low vision the screen curtain functionality was enabled so that the screen itself was blank. The order of presentation for the four conditions was counterbalanced using a balanced Latin square and participants were randomly assigned to orders.

Each of the four conditions in Task 2 began with brief training on basic VoiceOver gestures: horizontal flick to navigate left and right, double tap to open/activate selection, and pressing the home button (or, for on-hand input, a long press) to return to the home

Figure 3. The four input methods used for Task 2, from left to right: two-handed phone, one-handed phone, two-handed on-body, one-handed on-body.

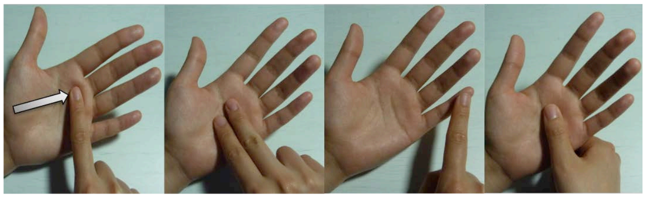


Figure 4. Participants created distinct gestures by varying (left to right): the basic gesture itself, number of fingers, landmarks used, or the gesturing finger (*e.g.*, thumb or index).

screen. These gestures were selected because they allow users to perform a range of activities on the phone like reading through e-mail and texts, and browsing a webpage. Participants then performed the same set of basic tasks per condition, including navigating through apps and information within an app, opening apps, and returning to the home screen. The task set took approximately five minutes for each condition, including training. Feedback questions were asked after each condition.

3.4 Data Analysis

Because the work is exploratory, we did not have specific hypotheses. For subjective ratings, we specify which statistical tests we used throughout the Results section. In general, however, because the normality assumption of parametric tests may not hold for the 5-point rating scale data that we collected, we used non-parametric tests: Friedman tests, repeated measures ANOVAs with Aligned Rank Transform (ART) [35], and, for pairwise comparisons, Wilcoxon signed ranks tests. Bonferroni adjustments were used to protect against Type I error for all posthoc pairwise comparisons. For qualitative data, observation notes on gesture characteristics were recorded during the sessions and later categorized. We also conducted a qualitative analysis of the think-aloud data and other participant comments.

4. FINDINGS

Our findings cover gesture creation strategies, location preferences for on-body input, and subjective tradeoffs between touchscreen phone and on-body input.

4.1 Task 1: Gesture Creation Strategies

During the Task 1 gesture creation process, we collected 300 gestures (5 gestures x 5 locations x 12 participants). For all participants across all body locations, *directional swipe* was the most commonly used gesture for navigating to a *previous* or *next* item. For the other mobile actions, however, participants created a wider variety of gestures.

Participants used the four following strategies to create their on-body gestures (Figure 4): varying a common touchscreen gesture (*e.g.*, swipe, single tap, double tap), varying the number of fingers (*e.g.*, one *vs.* two), using specific body landmarks (*e.g.*, pointing to a fingertip *vs.* palm), and varying which fingers were used (*e.g.*, index *vs.* middle). Table 1 shows the number of participants who used each strategy while creating a set of gestures at each on-body location. All participants employed more than one common touchscreen gesture at each location (*i.e.*, varying the "basic gesture" in Table 1), except for with the *same hand* location, where two participants used only variations of a single tap gesture. The least frequent strategy was to vary which fingers were used; only six participants created distinct gestures by switching their fingers.

	Strategy, varying:			
	Basic gesture	Number of fingers	Specific fingers	Specific landmarks
Same hand	10	7	4	10
Other hand-palm	12	7	3	7
Other hand-back	12	9	3	7
Forearm	12	9	1	4
Face and neck	12	6	4	11

Table 1. Number of participants who used a given strategy to create distinct gestures at each on-body location (*N*=12). Multiple strategies could be used for each location.

4.2 Task 1: On-body Location Preference

The location of a gesture on the body had an impact on the reported ease of use, physical comfort, and social acceptability of that gesture. Overall, of the five locations, participants most preferred *other hand-palm*. We also report on predicted use under physical constraints and for specific tasks.

4.2.1 Ease of Use

Figure 5 shows the rating scale results for ease of use, comfort, and social acceptability. The *other hand-palm* location received the highest average rating at 4.8, while the *same hand* received the lowest rating at 3.2. A Friedman test showed there was a significant effect of on-body location on ease of use ($\chi^2_{(4,N=12)} = 10.46$, $p = .033$). After a Bonferroni adjustment, no posthoc pairwise comparisons with Wilcoxon signed-rank tests were significant. When participants were asked to choose both the easiest and most difficult locations to use, *other hand-palm* was selected as easiest by 5 participants, followed by *other hand-back* (3 participants). The most common reasons for choosing locations on the other hand were that it was natural, offered a relatively wide input space compared to *same hand*, and that it was similar to using a mobile phone. For example: *"I can use my palm as a touchpad. It has enough space to perform any gesture."* (P11). In contrast, eight participants chose the *same hand* as the most difficult location to use, mostly because they found the interaction unfamiliar, for example: *"I'm not used to it. It's different."* (P4).

4.2.2 Physical Comfort

In terms of physical comfort, participants were again positive about *other hand-palm* and *other hand-back*, giving them mean ratings of 4.5 and 4.4 out of 5, respectively; see Figure 5. As with ease of use, the *same hand* was perceived to be least comfortable, at 3.2. A Friedman test showed that the impact of location on physical comfort was statistically significant ($\chi^2_{(4,N=12)} = 10.24$, $p = .037$). After a Bonferroni adjustment, no posthoc pairwise comparisons were significant.

In terms of the single most comfortable location, *other hand-palm* received the highest number of votes (7/12). For least

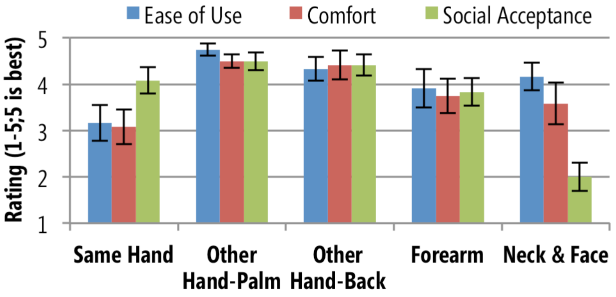


Figure 5. Average ratings for ease of use, comfort, and social acceptance for the on-body locations; 5-point scale, 1-*least*, 5-*most*. Error bars are *standard error*. Locations on the *other hand* (both palm and back) consistently fared well.

comfortable, six participants chose *face and neck* and five chose *same hand*. The most common reasons for finding the face and neck to be uncomfortable were that it is relatively far from where hands natural rest, and that it is curved; three participants preferred flat surfaces for performing gestures. For *same hand*, participants were concerned they would be limited in the number of gestures they could comfortably perform, for example: *"You don't have the freedom to move around. The movements and gestures would be limited"* (P12).

4.2.3 Social Acceptance

For social acceptance, *other hand-palm* and *other hand-back* again fared well, receiving the highest ratings at 4.6 and 4.4 out of 5, respectively; *face and neck* was considered to be unacceptable (Figure 5). A Friedman test showed that there was a statistically significant impact of location on social acceptability ($\chi^2_{(4,N=12)} = 30.31$, $p < .001$); again, due to the Bonferroni adjustment, no posthoc pairwise comparisons were significant.

Other hand-palm was selected as the single most socially acceptable location by 8 participants, who appreciated that it allows for discreet use thanks to its similarity with everyday activities, for example: *"It doesn't draw a lot of attention"* (P2). Not surprisingly, all participants considered the *face and neck* to be the least socially acceptable, most commonly because it attracts too much attention, or interferes with other activities. For example, P1 said: *"You would be considered as rude or have bad manners [if gesturing on face] during conversations."*

We further investigated social acceptability in terms of place of use and audience (Tables 2 and 3). All three hand input locations had high acceptance rates regardless of place—private, crowded public, non-crowded public, and workplace; across the four places their average acceptance rates ranged 85–96%. The *forearm* had a somewhat lower acceptance rate (M = 71%), while the *face and neck* was generally unacceptable except in private. In terms of audience—alone, partner, friends, family, colleagues, and strangers—again, the *neck and face* had a much lower acceptance rate than other on-body locations. It was also interesting to note that *forearm* was again considered to be not as acceptable as the hand locations. One participant even said, while scrubbing his forearm: *"They may say I might have fleas"* (P12).

	Private	Crowded Public	Non-crowded Public	Workplace	Acceptance Rate (%) *(SD)*
Same hand	12	9	11	9	85.5 (12.5)
Other hand-palm	12	10	12	12	95.8 (8.3)
Other hand-back	11	8	12	10	85.4 (14.2)
Forearm	11	6	9	8	70.8 (17.3)
Face, neck	9	1	4	3	35.4 (28.4)

Table 2. Number of participants who would perform on-body gestures in different contexts, with average acceptance rates across contexts (*N*=12).

	Alone	Partner	Friends	Family	Coll-eagues	Stran-gers	Acceptance rate (%) *(SD)*
Same hand	12	11	12	12	10	8	90.3 (13.4)
Other hand-palm	12	12	12	12	12	10	97.2 (6.8)
Other hand-back	12	12	12	11	11	9	93.1 (9.74)
Forearm	11	10	9	9	7	5	70.8 (18.1)
Face, neck	9	8	6	8	3	1	48.6 (26.6)

Table 3. Number of participants who would perform on-body gestures in front of different audiences, with average acceptance rates across audiences (*N*=12).

4.2.4 Physical Constraints

We expected that pose (seated, standing, or walking) and whether one hand is holding a cane or dog leash would be critical factors affecting on-body input for people with visual impairments. Table 4 shows the number of participants who were willing to perform gestures at each on-body location under these physical constraints. With two hands free, the majority of participants were willing to perform gestures at all on-body locations, whether seated, standing, or walking. For one hand holding a cane or leash, however, only the *same hand* location was popular, with 9 participants willing to use *same hand* whether they were seated, standing, or walking. For two hands free, the responses suggest that participants may be less likely to want to make on-body gestures while walking than seated or standing, although further work is needed to confirm this possibility.

	Two-hands Free			One-hand Busy			Acceptance rate (%) *M (SD)*
	Seated	Standing	Walking	Seated	Standing	Walking	
Same hand	11	10	9	9	9	9	79.2 (7.0)
Other hand-palm	12	12	8	2	3	3	55.6 (38.6)
Other hand-back	11	12	8	3	5	5	61.1 (30.1)
Forearm	10	9	7	1	3	3	45.8 (30.6)
Face, neck	10	8	6	6	4	4	52.8 (19.5)

Table 4. Number of participants who would perform on-body gestures under different physical constraints, with average acceptance rates across constraints (*N*=12).

4.2.5 Input Type

To understand how participants would want to use each on-body location, we asked about five input types previously evaluated with sighted users by Weigel *et al.* [33]; see Table 5. *Other hand-palm* was seen as particularly flexible for supporting a range of input types. It was the most popular for handwriting, keyboard, number pad, and sketching, and was tied with *other hand-back* for touchpad-style input (*e.g.*, taps, swipes). *Same hand* and *face and neck* were the least likely to be used; for example, no one was willing to use the *same hand* as a keyboard.

	Hand-writing	Keyboard	Number pad	Sketching	Touchpad	Acceptance rate (%) *M (SD)*
Same hand	2	0	5	2	7	26.7 (23.1)
Other hand-palm	9	6	10	7	11	71.7 (17.3)
Other hand-back	7	4	8	5	11	58.3 (22.8)
Forearm	6	5	7	6	9	55.0 (12.6)
Face, neck	0	2	3	1	7	21.7 (22.5)

Table 5. Number of participants who would perform different types of input at each on-body location, with average acceptance rates across types of input (*N*=12).

4.2.6 Overall Preference

In terms of overall preference, and in line with the results above, the majority of participants favored *other hand-palm* (8 responses). *Same hand* and *other hand-back* also received two votes each. The *face and neck* was the least preferred location by 10 participants, while *same hand* received two votes. This overwhelming selection of *face and neck* as least preferred is particularly interesting given that its raw scores on ease of use and physical comfort were higher than *same hand* (Figure 5). This result suggests that the social unacceptability of *face and neck* overrode ease and comfort concerns.

4.3 Task 2: Touchscreen *vs.* On-hand Input

For Task 2, recall that participants performed the same input tasks on a smartphone as well as on their body. Overall, subjective preference for phone versus on-hand input depended on whether both hands were available.

4.3.1 Overall Preference and Perceived Trade-Offs

The majority of the participants preferred the two-handed on-phone condition (8 responses); three preferred one-handed on-hand input, while one preferred two-handed on hand input. The least preferred condition was one-hand with the phone (8 responses). Below, we summarize participants' perceived advantages/disadvantages for touchscreen *vs.* on-hand input.

While conventional touchscreen input (two-handed) was overall the most preferred, perhaps due to its familiarity, participants valued the advantages of on-hand interaction as well. A primary reason was that it allowed the phone to be safely stowed away, for example: *"You don't have to take out iPhone, you don't have to worry about getting it wet"* (P8). Some participants also commented that eliminating the need for the screen positively impacted ease of access and efficiency. For example, P9 said: *"You can just go right to your hand, you don't have to take the phone out. It could eliminate the screen."* Related, P7 commented on the aesthetic feel of the on-hand interaction, saying that it feels better not to have to interact with a piece of metal or glass.

All participants appreciated one-handed input for mobile computing because it can be important to have a hand free. For one-handed use, the on-hand input won out over the phone. One hand made it difficult to hold the phone and control it at the same time. P6, for example, commented that there was increased risk of dropping the phone, while P3 said: *"[It's] very uncomfortable, certain gestures can be mistaken for other gestures."* In comparison, two-handed use was considered easier, more accurate, and more stable. Four participants also noted that two hands allows for a greater variety of gestures. For example: *"It's easier because I have a free hand to maneuver the phone… do whatever you want to gesture"* (P11).

In general, all 12 participants felt it would be difficult to use their phone with both hands at times, particularly when they are walking. For example, P11 said: *"I have to stop walking and do the gestures and continue walking, or I have to wait until I get to the place where I can use it."* However, only six participants expressed the same concern with two-handed on-hand input. At the same time, even on-hand input with one hand was not always considered to be good, with five participants commenting on physical limitations of using the thumb for input with the one-handed use case. Two participants did not wish to interact with their phone at all when walking because of safety.

4.3.2 Ease of Use, Comfort, and Social Acceptability

Ratings on ease of use, comfort, and social acceptance are shown in Figure 6. To assess the effect of *device* and *hand count* on ease of use ratings, we ran a two-way repeated measures ANOVA with ART. The interaction effect between input methods (on-phone, on-hand) and number of hands was statistically significant ($F_{1,11} = 37.66$, $p < .001$, $\eta^2 = .77$). Posthoc pairwise comparisons using Wilcoxon signed rank tests showed that the phone was easier than the hand for two-handed use ($Z = -2.31$, $p = .021$). The opposite was true for one-handed use, with on-hand input being easier than the phone ($Z = -2.36$, $p = .018$). There was also a significant main effect of hand count ($F_{1,11} = 16.01$, $p = .002$, $\eta^2 = .59$) but the main effect for device was not significant.

Physical comfort ratings mirrored the ease of use results. A two-way repeated measures ANOVA with ART revealed a statistically significant interaction effect between input location and hand count ($F_{1,11} = 63.15$, $p < .001$, $\eta^2 = .852$). Again, posthoc pairwise comparisons using Wilcoxon signed rank tests showed that participants felt more physically comfortable using two hands on the phone ($Z = -2.77$, $p = .006$), but that on-hand interaction was more comfortable for one-handed use ($Z = -3.07$, $p = .002$). There was no statistically significant main effect of input method, however, there was a main effect of number of hands ($F_{1,11} = 49.65$, $p < .001$, $\eta^2 = .82$).

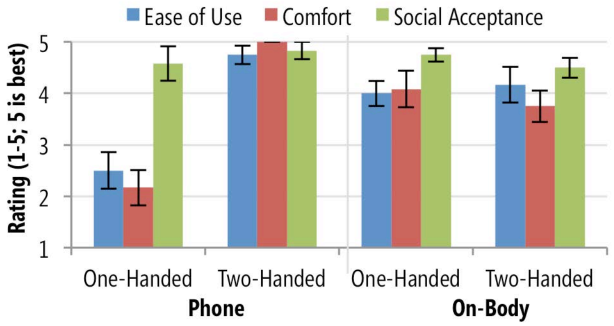


Figure 6. Average ratings for ease of use, comfort, and social acceptance for Task 2; 5-point scale, 1-*least*, 5-*most*. Error bars are *standard error*.

	Two-hands Free			One-hand Busy			Acceptance rate (%) *M (SD)*
	Seated	Standing	Walking	Seated	Standing	Walking	
Phone One	6	6	6	6	6	6	50.0 (0.0)
Phone Two	12	12	8	1	2	2	51.4 (43.0)
Hand One	11	11	10	10	11	11	88.9 (4.3)
Hand Two	10	9	5	0	0	0	33.3 (39.1)

Table 6. Number of participants who would use on-body input under different physical constraints, with mean acceptance rates across constraints (*N*=12).

Social acceptance ratings were high across all four conditions, ranging on average from 4.5 to 4.8 out of 5. A two-way repeated measures ANOVA with ART revealed no significant main or interaction effects of device and hand count on these ratings. While we asked about use of the input methods in different places and in front of different audiences as with Task 1, no clear trends emerged based on either contextual factor.

Table 6 shows the popularity of the four input conditions under different physical constraints—that is, seated, standing, or walking, and two hands free versus one holding a cane or dog leash. These results again reflect the tradeoffs between on-hand and phone input when only one hand is free. While the two-handed input conditions were both popular when two hands are free and the participant is seated or standing, these numbers quickly drop off for walking, and drop even further when only one hand is available. One-handed on-hand input, however, was perceived to be the most versatile, with 10 or 11 participants out of 12 willing to use it regardless of the physical constraints.

5. DISCUSSION

Based on findings from the study, we provide design implications for accessible on-body interaction for people with visual impairments, and reflect on our findings.

5.1 Design Implications

Dominance of hands. When combining results from both tasks, the hand-based locations (same hand, and other hand palm and back) were better received by participants than the forearm or face and neck areas. Participants appreciated, among other factors, the discreet and natural aspects of hand-based interaction compared to the relatively socially unacceptable forearm or face/neck input. We thus recommend supporting body input on the hand for people with visual impairments. This finding contrasts Weigel *et al.*'s [33] study with non-visually impaired users, which found the forearm to be the easiest and most comfortable location to use, although the palm also performed well.

Providing complementary input techniques. The preference for touchscreen input when two hands are available and on-body input when one hand is available suggests that on-body input should be used as a *complement* to the phone itself. A downside of one-handed on-body input as identified by some participants is that it does not offer the same kind of input flexibility as other locations. Even so, as a complementary form of input, it could be used to support a specific set of tasks more easily and quickly than pulling out and using a phone (*e.g.*, controlling navigation instructions, notifications, and audio).

Considering physical constraints. Relatedly, blind mobile phone users often have one hand busy with a cane or dog leash. Support for one-handed input is thus critical for supporting accessible information access on the go, a need that came out in participant comments. An issue that two participants commented on was that they hold their cane with their dominant hand, which was the same hand we had tested in our study. A system to support people with visual impairments would need to either allow for input on the same hand while also holding the cane or would need to easily support switching control to the non-dominant hand temporarily.

Creating gesture sets. Based on the user-defined gestures created in Task 1, we recommend that designers primarily utilize the basic gestures now well-established with modern touchscreens (*e.g.*, tap *vs.* swipe) for common on-body interactions. Varying the number of fingers and using specific landmarks on the body can broaden the set of distinguishable gestures. Landmarks, in particular, such as pointing to different parts of the hand, may be useful for rapid mode switching or to respond to a notification (as is done in *Imaginary Phone* [7]). These findings confirm Rico *et al.*'s [27] recommendation to create gestural interfaces that are similar to existing interfaces, and provide further support for an approach like *Imaginary Phone*, which transfers the standard phone interface to the palm. Finally, participants rarely varied their gesturing finger (*e.g.*, index *vs.* thumb), a finding that also mirrors touchscreen input preferences by sighted users [34].

Social acceptability. As with mainstream wearable research (*e.g.*, [37]), social acceptability plays an important role for on-body input for people with visual impairments. Our Task 1 findings suggest that participants prioritized social acceptability over ease of use and physical comfort by choosing the face and neck location as least *preferred* even while input on one hand was considered relatively hard to use and uncomfortable. Thus, participants preferred input locations that were discreet. This finding is in direct conflict with the dominant interaction model for Google Glass, so it will be interesting to see how heads-up display input evolves over the next few years.

5.2 Reflections and Future Work

As the first work on on-body interaction for people with visual impairments, our study was purposely exploratory, focusing on subjective responses rather than input performance. It will be important for future work to quantitatively assess performance of on-body input for people with visual impairments (*e.g.*, pointing accuracy, gesturing accuracy). A comparison to touchscreens, similar to Gustafson *et al.*'s study with sighted users [7], would characterize the degree to which the increased proprioception of on-body pointing can aid users with visual impairments. We hypothesize that there will be a larger benefit here than for sighted users, which Gustafson *et al.* have already shown.

Participants' preferences changed between Task 1 and Task 2, from being largely positive about two-handed on-body input to more negative. This change highlights the importance of having users interact with working systems rather than assigning too much weight to subjective responses collected in the largely imaginary scenarios that the user-defined gestures method traditionally employs (*e.g.* [33,34]). Directly comparing on-body input to a touchscreen on the phone provided additional insight.

Our study identifies potential advantages of on-body input, even compared to the ubiquitous smartphone. One question, however, is how feasible it is to support on-body input for people with visual impairments. Sensing systems to date, including our own, have primarily used depth and color cameras [3,7,13,14,21]. The camera itself would need to be mounted on the body, perhaps as a pendant or on a pair of glasses. Ensuring the hands are in the camera frame could be an issue for eyes-free use although the appropriate lens would mitigate this problem. We did not encounter such framing issues in our study, but this could be because the camera was in a fixed location. Alternatively, tangible wearable devices should be further explored as a means of always-available input for this population (*e.g.* [37]).

In terms of limitations, the primary shortcoming is the disparity in how familiar participants were with touchscreens versus on-body input in Task 2, likely leading to a bias toward the touchscreen input; a multi-session study with more in-depth tasks with the interactive system could partly address this issue. Additionally, while on-body input is meant to support mobile information access, we conducted the study in a controlled lab setting and participants were seated while using the system. Different contexts of use may impact participants' reactions to the input. Finally, while most past work on wearable and on-body input has focused on sighted users, we did not include sighted users in our study. A direct comparison would be useful to understand the differences between sighted and visually impaired users' needs.

6. CONCLUSION

We conducted an exploratory study with 12 participants with visual impairments to better understand how to design accessible on-body input and to identify potential impacts of such input compared to touchscreen mobile devices. Finally, tradeoffs were seen in preferences for touchscreen versus on-body input, with on-body input considered useful for contexts where one hand is busy (*e.g.*, holding a cane or dog leash)—such as when the user is holding a cane or dog leash. The results also suggest that participants may be prioritizing social acceptability over ease of use and physical comfort when assessing the feasibility of input at different locations of the body. As such, the least preferred areas were the face and neck, and the forearm; in contrast, locations on the hands were considered to be more discreet and natural. Finally, we provided implications to inform the design of future accessible on-body input systems.

7. ACKNOWLEDGMENTS

We thank our participants, Nancy Pack, and the Maryland State Library for the Blind and Physically Handicapped. This work was funded by Nokia.

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