Understanding Palm-Based Imaginary Interfaces: The Role of Visual and Tactile Cues when Browsing

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ABSTRACT

Imaginary Interfaces are screen-less ultra-mobile interfaces. Previously we showed that even though they offer no visual feedback they allow users to interact spatially, e.g., by pointing at a location on their non-dominant hand.

The primary goal of this paper is to provide a deeper understanding of palm-based imaginary interfaces, i.e., *why* they work. We perform our exploration using an interaction style inspired by interfaces for visually impaired users. We implemented a system that audibly announces target names as users scrub across their palm. Based on this interface, we conducted three studies. We found that (1) even though imaginary interfaces cannot display visual contents, users' visual sense remains the main mechanism that allows users to control the interface, as they watch their hands interact. (2) When we remove the visual sense by blindfolding, the tactile cues of both hands feeling each other in part replace the lacking visual cues, keeping imaginary interfaces usable. (3) While we initially expected the cues sensed by the pointing finger to be most important, we found instead that it is the tactile cues sensed by the *palm* that allow users to orient themselves most effectively.

While these findings are primarily intended to deepen our understanding of Imaginary Interfaces, they also show that eyes-free interfaces located on skin outperform interfaces on physical devices. In particular, this suggests that palm-based imaginary interfaces may have benefits for visually impaired users, potentially outperforming the touchscreen-based devices they use today.

Author Keywords

Imaginary interfaces; mobile; wearable; visual feedback, tactile feedback; non-visual.

ACM Classification Keywords

H5.2 [Information interfaces and presentation]: User Interfaces. - Interaction Styles.

INTRODUCTION

Imaginary Interfaces are spatial non-visual interfaces for mobile devices [13]. Users interact with them by pointing using their dominant hand either in empty space [13] or onto their non-dominant hand (Imaginary Phone [14]). Typically a chest-worn camera observes the user's hands and determines the position of the pointing finger with respect to the other hand. By abandoning the screen, Imaginary Interfaces allow for *ultra-mobile* form factors.

The primary goal of this paper is to provide a deeper understanding of Imaginary Interfaces, i.e., not what they allow users to do, but *why* they allow doing it. We perform our exploration with an example interface: we create a browsing interface (i.e., an interface that enables exploring an unfamiliar system) for imaginary interfaces and then use it to explore which inherent properties of palm-based imaginary interfaces cause it to perform the way it does.

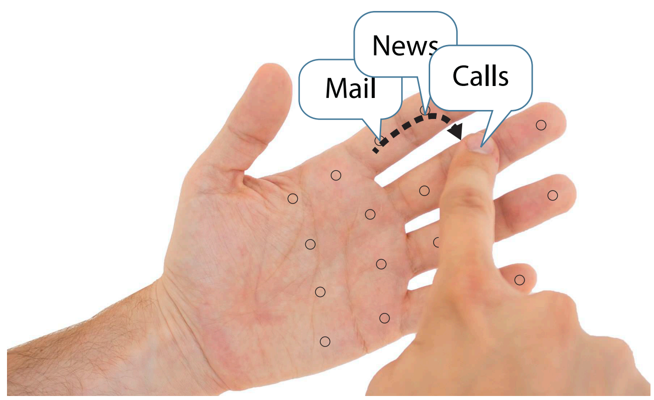

Figure 1: We adapted a non-visual audio interface that announced targets as users touch them, which allow users browse an unfamiliar imaginary interface.

Browsing matters, because one of the key design challenges of Imaginary Interfaces is to enable users to operate an unfamiliar interface. The strongly asymmetric abilities of Imaginary Interfaces make this challenging: input is spatial and precise but, by definition, an imaginary interface cannot show users an overview.

Our previous work restricted users of Imaginary Interfaces to what has been taught offline. For instance, with the Imaginary Phone [14] users are able to learn an imaginary interface by first using a physical device of identical layout and transferring the layout knowledge to the imaginary interface. Unfortunately, this transfer learning is limited to the comparably small number of functions that users use on a frequent basis, such as the home screen launch icons [14] and therefore provide no basis for using the thousands of applications available for today's mobile devices.

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Inspired by touch-and-explore interfaces designed for visually impaired users (Talking Fingertip Technique [35], SlideRule [17] and most recently VoiceOver for iPhone [1]) we created an audio-based interface that announces targets as users scrub across them (see Figure 1). Based on this interface, we investigate which of the particular properties of palm-based imaginary interfaces allows users to operate such interfaces.

CONTRIBUTIONS

The main contribution of this paper is an exploration into the inherent properties of palm-based imaginary interfaces and how the properties are responsible for user performance. We find that (1) visual cues, i.e., observing ones hands performing the interaction; (2) tactile cues sensed by the palm and (3) tactile cues sensed by the pointing finger all contribute to performance, in that order.

These findings deepen our understanding of Imaginary Interfaces and suggest that palm-based imaginary interfaces enable stand-alone eyes-free use, including interfaces for visually impaired users. We investigate this final implication with an exploratory study and interview with one blind participant that confirms our findings.

RELATED WORK

This paper builds on imaginary interfaces and other on-body interfaces; non-visual interfaces including interfaces for visually impaired users; and is grounded in the psychological work of multisensory integration.

Interaction on and around the body

The availability of the user's own body as a surface for mobile interaction has been exploited in many research projects. Sixth Sense [28], Brainy Hand [33], Skinput [16] and OmniTouch [15] all combine on-body interaction with visual feedback from body worn projectors.

In situations that do not afford projection, the user's familiarity with their own body allows for non-visual interfaces that exploit the user's tactile and proprioceptive senses. For instance, BodySpace [32], Point-upon-body [25] and Shoemaker et al.'s body-centric wall interaction [31] assign functions to positions on the user's body that can be activated with differing degrees of visual feedback.

Other projects have used the user's palm as an interaction surface due to its abundant tactile features and natural divisions: as a number pad [11], television remote control (PalmRC [6]), for text entry (KITTY [19]) and for elaborate input/output such as with the Mobile Lorm Glove [12].

Other interface concepts have exploited users' intimate familiarity with their peripersonal space and their proprioceptive abilities. Chen et al.'s collection of body-centric interaction techniques [4] shows how the space on and around the body can be combined to offer compelling interactions. Folmer et al.'s proprioceptive displays [8] combine proprioception with spatially triggered vibrotactile feedback to allow eyes-free exploration of the featureless space in front of the user. Similarly, Motion Marking Menus [29] use proprioception to enable eyes-free input for handheld devices and Virtual Shelves [23, 24] allow users to invoke mobile phone functions by pointing at representative locations in the hemisphere in front of them.

Imaginary Interfaces [13] allow users to perform spatial interaction despite the lack of visual feedback. Imaginary Phone [14] allows users to interact on their palms, by mimicking the layout of a familiar mobile device (i.e., by *transfer learning*).

Mobile interfaces for visually impaired users

Many systems have been developed to help visually impaired users operate the predominately visual interfaces present on modern computing devices.

Visually impaired users rely heavily on tactile cues but modern touchscreen-based devices lack the tactile discoverability of button-based devices. To address this, McGookin et al. [27] investigated tactile overlays and gesture-based interfaces to increase the usability of touchscreen phones. The Talking Tablet [20] uses tactile and audio feedback to complementarily reinforce learning through dual modalities. EarPod [37] and BlindSight [22] combine liberal amounts of audio feedback with a tactile-rich form factor to enable eyes-free operation.

Touchscreen-based interfaces allow for highly dynamic interfaces where the user cannot predict where a given function will be located. To address this, researchers have turned to audio feedback to "explain" the interface to the user. For instance, Pirhonen et al. [30] investigated combining audio output with gestural input, and Brewster et al. [3] followed up on the work by improving the audio feedback with 3D spatiality and a more dynamic nature.

Beyond research prototypes, visually impaired users regularly employ mobile technology to gain more independence [18]. Commercially available mobile phone interfaces come in two categories: *cursor-based* and *touch-and-explore* interfaces. Cursor-based interfaces, such as Mobile Speak [5], have a cursor that announces the current function as the user moves around the interface in single steps, allowing the user traverse the interface in a predictably way. Alternatively, touch-and-explore interfaces allow users to navigate the interface by dragging freely on the touch screen and listening to the auditory feedback in response (as in the Talking Fingertip Technique [35], SlideRule [17] and VoiceOver for iPhone [1]). The touch-and-explore interaction mode allows users to access familiar items faster than the linear effort imposed by a cursor-based list. However, to do this, they must build up spatial memory to be able to target a memorized location.

Psychological foundations of non-visual interfaces

When interacting spatially in the world, humans gather information from many senses (visual, tactile, proprioceptive, etc.) that must be combined (using a process called *multisensory integration*) to produce a general understanding of the environment [7]. Because of this, even though modern touchscreen interfaces rely heavily on vision, proprioception and taction also play an important role.

For instance, proprioception alone is not precise enough to enable fine-grained interaction (targeting can be off by 8cm on average [9]). Instead, eyes-free interaction typically involves proprioception and taction working together since taking either away degrades performance substantially [36]. Similarly vision and taction work in concert, at least for the hand [21].

Touch itself is multi-faceted and has three distinct flavors: *active touch* (the person touching something); *passive touch* (something touching the person); and *intra-active touch* (the person touching him or herself) [2]. Each has its own capabilities: active touch is a scanning mechanism that allows the actor to build up an understanding of the scene over time [10], while passive is limited to "being touched". However, this is mitigated by the high spatial resolution of the hand (tactile discrimination ranges from 7.7mm on the palm to 1.6mm on the index finger tip [34]). On the other hand, intra-active touch, as is used in palm-based imaginary interfaces, combines the capabilities of both, allowing users to actively explore the interface while passively noting the location of discovered targets.

BROWSING INTERFACE FOR IMAGINARY INTERFACES

In order to create an appropriate interaction style for browsing imaginary interfaces we searched the related work for appropriate concepts. Interfaces for visually impaired users display some obvious similarities with Imaginary Interfaces in that neither relies on visual feedback. Narrowing down our search to spatial interfaces led us to focus on the touch-and-explore interaction style described in the previous section.

We adapted this interaction style for use with imaginary interfaces. Figure 2 shows the resulting interface based on the Imaginary Phone [14]. As users drag their fingers across the palm surface, they enter different buttons and the system responds by announcing the name of the target, such as "clock". If users continue further, the auditory feedback is immediately interrupted and the new name is announced. Users familiar with the layout can shortcut this exploration and acquire a target by tapping directly on it.

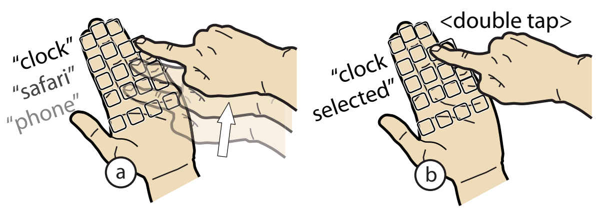

Figure 2: We adapted the touch-and-explore style interaction to imaginary interfaces – (a) as users scrub along their palm, the system announces the name of the function at each location. When users find what they are looking for (b) they double tap to perform the selection.

Prototype implementation

To provide high tracking accuracy, we created a simple prototype using an OptiTrack motion capture system that tracks reflective markers. As shown in Figure 3, users wear a set of markers on the back of their non-dominant hand and one on the index finger of their dominant hand. Users calibrate the system with a 23-point calibration procedure: 3 points are used to find the plane of the hand and the remaining 20 to find the precise location of each finger segment that will be mapped to imaginary button locations. We were careful to leave the users' palm and pointing finger unobstructed in order to not interfere with the interaction between the two hands.

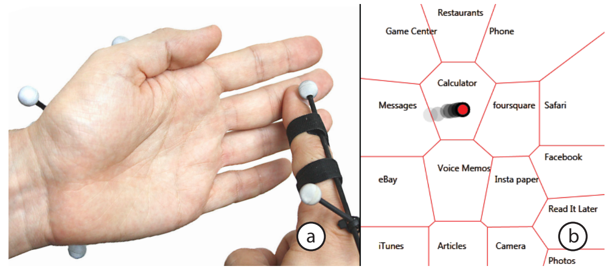

Figure 3: As users (a) move their pointing finger across the palm and finger, the system (b) determines the closest target.

When the user's finger is within 3mm of the hand's plane it is in the touching state and the system uses a space-filling Vornoi layout (shown in Figure 3b) to snap selection to the closest target. Users can freely move their finger around the interfaces and listen to the audio feedback. We stabilized selection by adding a small amount of hysteresis. To activate a target, users double tap their hand.

OVERVIEW OF STUDIES

During early testing, the palm-based touch-and-explore interface performed better than expected. Encouraged by this, we went a step further and not only formally evaluated the technique's performance but investigated *what caused* it to perform so well. We conducted three user studies with the goal to determine which properties of Imaginary Interfaces are responsible for their performance. Asking this question allowed us to learn more not only about browsing with an imaginary interface but also about the very nature of Imaginary Interfaces themselves.

While Imaginary Interfaces share properties with interfaces for visually impaired users—neither relies on visual feedback—it has extra cues that are potentially relevant:

1. *Visual cues:* While the lack of a screen prevents imaginary interfaces from providing actual dynamic feedback, they do offer a very particular style of visual feedback from users watching their hands interact.

2. *Tactile cues:* During interaction users' hands touch. This provides them with tactile cues in both directions: the pointing finger feels the palm and the palm feels the pointing finger.

To explore the role of these cues we ran three user studies:

Study 1: Visual Cues. Does watching ones own hands interact support browsing? We explored this by comparing blindfolded with sighted use (neither with visual screen feedback) on the phone and the palm.

The results of Study 1 showed that watching ones hands interact improves performance and we received first insights about tactile cues: blindfolded interaction did better on the palm than on the phone. However, it remained unclear if the extra tactile cues on the palm were responsible. To explore this we ran two more studies: the first focused on the tactile sensation in the pointing finger, the second on the tactile sensation on the palm.

Study 2: Tactile Cues Sensed by Pointing Finger. We created three versions of the phone interface, all of which participants operated while blindfolded. The first was a plain touchscreen phone and the second was the same with an engraved tactile grid. In addition, we were wondering whether the phone was really featureless or whether touching the bezel and the supporting hand helped users orient. To investigate this we added a third condition that embedded the phone interaction surface into a large clear piece of acrylic, thereby preventing participants from using the bezel to obtain tactile cues. We included sighted use as an additional baseline.

Study 3: Tactile Cues Sensed by Palm. To study this, we created another three interfaces that participants used while blindfolded. We compared interaction on the palm to interaction on a silicone cast of a hand and to interaction on the palm with a covered pointing finger that minimized fine tactile cues sensed by the pointing finger. Again, we included sighted use as an additional baseline.

Figure 4 summarizes the six different form factors participants used throughout the three studies.

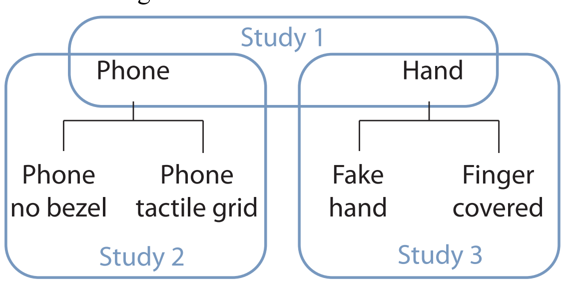

Figure 4: The form factors used in the three user studies.

STUDY 1: THE IMPACT OF VISUAL CUES

With this study we tested whether watching ones own hands interact supports browsing. We compared sighted to blindfolded use of our browsing interface on the phone and the palm. At the same time, we used this first study to formally evaluate our interface.

Task and procedure

The study used a within subjects 2×2 factorial design with these independent variables (shown in Figure 5):

- Sightedness: SIGHTED vs. BLINDFOLDED
- Interaction surface: PHONE vs. PALM

In each trial participants searched for and selected a prompted target. They started the trial by pressing a footswitch and the system spoke the target name and showed it on a screen. The participants touched the interaction surface with their finger and as they moved it around the system announced the name of each target (as described previously). When participants found the required selection they pressed the footswitch to complete the trial. We measured task time from the start of the trial until the participant made a selection. If the selection was incorrect, the trial was discarded and the participant was required to repeat the trial.

Before beginning the experiment, participants received instructions on how to use the system and performed a series of practice trials with each interaction surface until they indicated they understood the interaction style and were comfortable with the system.

During each of the four blocks (each tested one combinations of variables) participants had to repeatedly locate five targets out of the 20 available targets in the interface. The five targets (chosen randomly) were presented to the participants eight times in random order.

Figure 5: Study 1 conditions – (a) SIGHTED vs. (b) BLINDFOLDED, using a partial blindfold that only obscures the participants' view of their hands; (c) PHONE vs. (d) PALM.

We presented the conditions in a counter-balanced order using a balanced Latin square. Each condition used a different set of target names derived from a survey of the most popular iPhone apps used by local students.

At the end of the experiment participants completed a short questionnaire to gather their preference of interaction surface when blindfolded and not.

Apparatus

As shown in Figure 6, the participant sat in front of a table with a monitor showing instructions located directly in front of them. A footswitch was used to confirm selection.

For the palm condition, participants used the prototype system described earlier. Their non-dominant hand was placed in a fixture molded to the back of their hand. This allowed the participant to replace their hand in the same position when switching between the PHONE and PALM conditions while maintaining a consistent calibration.

For the PHONE condition, we tracked interaction with the same optical tracker system used in the palm condition. This kept any potential tracking errors consistent across conditions. The phone used in the study was a non-functional replica of an iPhone 3G with identical surface area but thinner (at 5.5 mm).

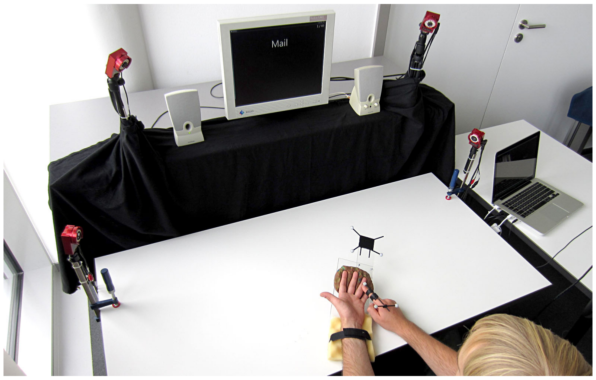

Figure 6: Study 1 apparatus – the participant's non-dominant hand was fixed to a brace to ensure consistent calibration and the participant's pointing finger was tracked with reflective markers. A footswitch (not shown) was used for confirmation.

During the BLINDFOLDED conditions, a partial blindfold was used (shown in Figure 5b). Due to its shape, it obscured the participants' view of their hands but not of the display in front of them.

Hypotheses

First of all, since vision and taction work together [21], we expect that the sighted conditions (that combine both visual and tactile cues) will outperform the conditions where only taction is available. Therefore, in our first hypothesis we wish to confirm this idea:

H1: Participants will be faster when SIGHTED.

However, since taction far outperforms proprioception [9], we believe that the tactile cues available on the palm are more likely to be able to fill in for visual cues when they are not present, compared to the mostly featureless phone surface. Therefore our second hypothesis is:

H2: When BLINDFOLDED, using the hand as an interaction surface will result in faster search times.

Participants

We recruited 12 participants (2 female) from our institution. They ranged in age from 22 to 30 (M=26.0, SD=2.63). All were right-handed and all had normal or corrected to normal vision and hearing.

Results

We collected 1938 data points and removed 18 error trials (0.9%) and 43 outliers (2.2%), leaving 1877 trials in this analysis. We defined outlier response times as three standard deviations above the mean for each condition and repetition. Participants completed the study within 30 min.

We ran a 2×2×8 (SIGHTEDNESS × INTERACTION SURFACE × repetition) repeated-measures ANOVA on completion time. There was no overall significant difference between PHONE and PALM (p=0.11) but when participants were BLINDFOLDED they were 50% slower than when SIGHTED (5.39s vs. 3.59s, $F_{1,11}$=99.90, p<0.001, η^2=0.08), which confirms our first hypothesis that watching your hands improves interaction.

As shown in Figure 7, there is a clear learning effect ($F_{1,11}$=85.55, p<0.001, η^2=0.54) and by inspection one can see that participants' selection times steadily decrease in the first three or four repetitions then level off in the remaining repetitions.

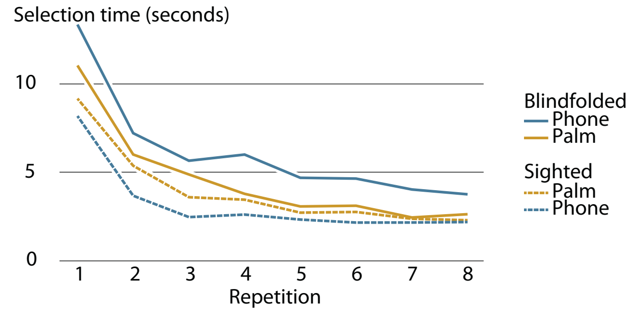

Figure 7: Study 1 results showing performance over time.

To investigate these results further we aggregated the repetitions into two equal blocks: *learning phase* (the first four repetitions where participants acquired knowledge of the target locations, shown in Figure 8a) and *trained phase* (the last four repetitions where participants had acquired good knowledge of the target locations and response time have leveled off, shown in Figure 8b) and analyzed each with a separate 2×2 repeated-measures ANOVA.

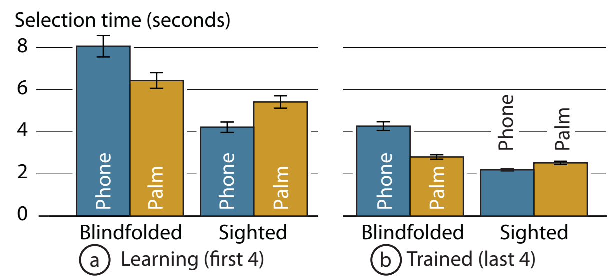

Figure 8: Study 1 results showing (a) first and (b) last half of the repetitions. Error bars are +/- one std. error.

Learning phase (Figure 8a):

In this phase participants took approximately 6 seconds on average to find and select each target and the difference between the PHONE (6.15s) and PALM (5.92s) was not significant.

When BLINDFOLDED, participants were 50% slower than SIGHTED (7.25s vs. 4.82s, $F_{1,11}$=66.26, p<0.001, η^2=0.41) and there was an interaction effect between SIGHTEDNESS and INTERACTION SURFACE ($F_{1,11}$=9.72, p=0.01, η^2=0.14).

Looking at BLINDFOLDED and SIGHTED trials separately, we see that when using the PHONE being BLINDFOLDED resulted in a 91% worse task time (4.22s vs. 8.06s; t_{11}=8.84, p<0.001, Cohen's d=5.33) and when using the PALM being BLINDFOLDED only led to 19% worse performance (5.41s vs. 6.43s). This last difference was not significant (p=0.14).

Trained phase (Figure 8b):

In this phase, participants took 3.23s to select the target on the PHONE and slightly faster at 2.66s on the PALM, a significant difference ($F_{1,11}$=15.33, p=0.002, η^2=0.07).

When BLINDFOLDED participants were 50% slower than when SIGHTED (3.53s vs. 2.36s), also a significant difference ($F_{1,11}$=66.54, p<0.001, η^2=0.29). Like in the learning phase there was a significant interaction effect between INTERACTION SURFACE and SIGHTEDNESS ($F_{1,11}$=21.55, p=0.001, η^2=0.159).

This interaction occurred because when using the PHONE, participants who were BLINDFOLDED were 94% worse than when SIGHTED (2.19s vs. 4.27s; t_{11}=6.27, p<0.001, Cohen's d=3.78) but were not significantly worse when using their PALM (2.51s vs. 2.80s, p=0.136).

Questionnaire:

When BLINDFOLDED, 11 participants preferred to use their PALM (one had no preference) and 10 participants rated the PALM faster than the PHONE with the remaining two rating the PHONE faster. When SIGHTED, the preference was split with five participants for each interface (one had no preference) but eight indicated the PHONE was faster and two that the PALM was faster (two reported neither).

Participants commented that when blindfolded the palm offered more tactile cues and the phone lacked a "reference system". One said, "There are more features on the hand. On the hand you can relate terms to fingers." However, many commented that when not blindfolded the straightforward grid of targets on the phone was easier to traverse: "When not blindfolded the grid helps to be more efficient." One participant noted that the tactile cues were sufficient even when not blindfolded, stating, "Even in 'sighted' mode I'd rarely look at the phone/hand anymore once I learned the positions."

Discussion

First of all, this study shows that our proposed browsing interface works. The interface functioned reliably and as participants familiarized themselves the task time dropped to 2.66s for locating a target on the palm.

This has implications as a browsing interface that users can operate reliably could one day form the basis of a standalone imaginary interface. Previous work assumed that users were already familiar with the interface before using it, thus offered no solution when encountering an unfamiliar interface in the "wild".

The results also show that participants performed better when they could see their hands interact and we gathered first insights into how tactile cues on the palm contribute to eyes-free use. However, we did not know which tactile cues were responsible for this.

To explore this we ran another two studies. The first study focused on the tactile cues sensed by the pointing finger and the second on the tactile cues sensed by the palm.

STUDY 2: TACTILE CUES SENSED BY THE FINGER

In this study, we explored how far tactile cues sensed by the pointing finger contribute to browsing an imaginary interface. We used three phone-based conditions: a normal phone; a phone with tactile cues added in the form of a tactile grid; a phone with all cues removed by placing the interaction surface in a large featureless sheet of acrylic. We were interested in blindfolded use but included sighted use as an additional baseline.

Apparatus, task and procedure

The apparatus and task are identical to Study 1 except that the experimental conditions were changed. This study used a within-subjects 2×3 design with these factors:

- Sightedness: BLINDFOLDED vs. SIGHTED
- Interaction surface: PHONE vs. LARGE PHONE vs. TACTILE PHONE, shown in Figure 9.

We fabricated the phone prototypes in three layers: a 4mm base of acrylic, a printed sheet of paper for phone screen and a 1.5mm acrylic top layer. The tactile grid on the surface of the phone used in the TACTILE PHONE condition (close-up shown in Figure 9d) was etched using a laser cutter. The interaction area of each phone was identical (5 × 7.5cm) but for the LARGE PHONE the interaction area was centered on a 22.5cm × 16.5cm panel to prevent the participants from orienting using the device's bezel.

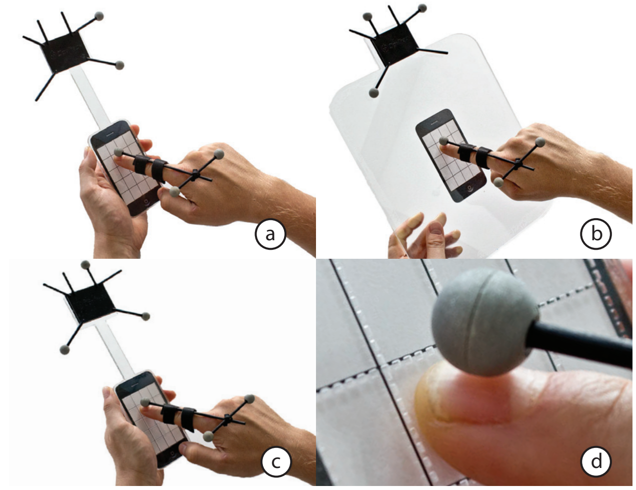

Figure 9: Study 2 conditions – (a) PHONE vs. (b) LARGE PHONE vs. (c) TACTILE PHONE; (d) close up of the tactile grid.

Hypotheses

By observing participants in pilot studies we noticed they regularly orient using the device's bezel when blindfolded. We therefore believe this is an important tactile cue and we wished to confirm that depriving participants of it would result in worse performance.

H1: When blindfolded, participants will be slower with the LARGE PHONE than with the PHONE.

Based on Study 1, where the palm, with its rich tactile cues, performed better than the smooth phone surface, we expected that adding tactile cues to the surface of the phone would also enable more efficient interaction.

H2: When blindfolded, participants will be faster with the TACTILE PHONE than with the PHONE.

Participants

We recruited a new set of 12 participants from our institution (4 female, 10 right-handed). They were between the ages of 23 and 30 (M=25.2, SD=2.55) and all had normal or corrected to normal vision and hearing.

Results

From the 2943 data points collected during the experiment we removed 63 error trials (2.1%) and 72 outliers (2.4%), leaving 2808 trials for analysis. As in Study 1 the results were analyzed using repeated measures ANOVA. All post hoc comparisons used Bonferroni corrected confidence intervals. Each participant took approximately 45 minutes.

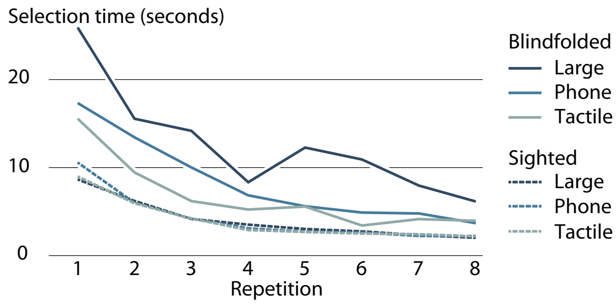

Figure 10: Study 2 performance of each condition over time.

The overall trend of the data, shown in Figure 10, matches the data from Study 1. We therefore took the same approach and divided the repetitions into two even groups of four repetitions each and performed separate analyses.

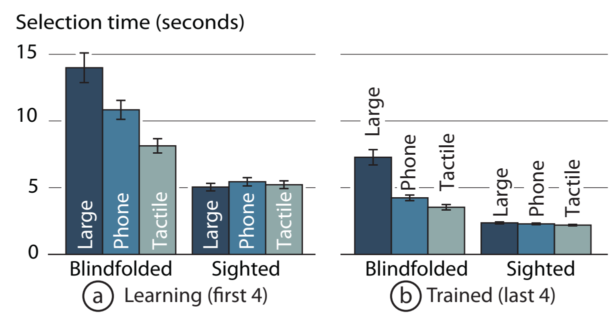

Figure 11: Study 2 results showing the (a) first and (b) last half of the repetitions. Error bars are +/- one std. error.

Learning phase (Figure 11a):

There was a significant main effect ($F_{2,22}$=11.51, p<0.001, η^2=0.08) of INTERACTION SURFACE and pairwise tests show that participants were significantly faster with the TACTILE PHONE than both LARGE PHONE (30% faster, p=0.009) and PHONE (18% faster, p=0.036). Although the PHONE was faster than LARGE PHONE by 17% the difference was not significant (p=0.061).

When BLINDFOLDED participants were 110% slower than when SIGHTED ($F_{1,11}$=65.89, p<0.001, η^2=0.48) and there was a significant interaction between SIGHTEDNESS and INTERACTION SURFACE ($F_{2,22}$=12.21, p<0.001, η^2=0.09).

The differences between interaction surfaces were not significant (p=0.76) when participants were SIGHTED but they were when BLINDFOLDED ($F_{2,22}$=14.136, p<0.001, η^2=0.36), which explains the interaction effect. When blindfolded, participants using the TACTILE PHONE were significantly faster than both LARGE PHONE (42% faster, p=0.003) and PHONE (25% faster, p=0.015) but although the PHONE was faster by 23% than LARGE PHONE the difference was not significant (p=0.060).

Trained phase (Figure 11b):

As in the learning phase, there was significant main effect of INTERACTION SURFACE ($F_{2,22}$=18.18, p<0.001, η^2=0.14). Participants using the LARGE PHONE were significantly slower than when using the PHONE (48%, p=0.015) and the TACTILE PHONE (41%, p<0.001).

Overall in this phase BLINDFOLDED participants were 120% slower than when SIGHTED ($F_{2,22}$=54.675, p<0.001, η^2=0.36). There is also a significant interaction between SIGHTEDNESS and INTERACTION SURFACE ($F_{2,22}$=15.99, p<0.001, η^2=0.12).

Breaking these results down further and looking at SIGHTED and BLINDFOLDED trials separately can help explain the interaction: when SIGHTED there is no significant difference between interaction surfaces (p=0.73) but when BLINDFOLDED there is ($F_{2,22}$=17.836, p<0.001, η^2=0.42). Participants using the LARGE PHONE were significantly slower than those using the PHONE (72%, p=0.016) and the TACTILE PHONE (106%, p<0.001). The TACTILE PHONE was 17% faster than the PHONE but this difference was not significant (p=0.596).

When blindfolded, in both phases the LARGE PHONE performed significantly worse than regular PHONE (and the TACTILE PHONE), which confirms our first hypothesis that depriving the participant of the bezel negatively affects performance. However, the TACTILE PHONE only significantly improves interaction during the learning phase and not once the participants have learned the target locations. Therefore our second hypothesis regarding the benefits of added tactile cues is only partially confirmed.

Discussion

Our results suggest that, although a touchscreen phone appears featureless, some features exist to guide interaction: the presence of a bezel provides a substantial benefit to the unsighted user. It allows users to find the extent of the interaction area and concentrate their searching within that area. It also brings the participant's non-dominant hand near the interaction area, allowing it to be used as an additional tactile cue.

Based on the results from Study 1 we expected that adding tactile cues to the surface of the phone would lead to a large improvement. However, this was not entirely the case: adding additional tactile cues only improved performance during the learning phase. Once the participants had learned where the targets were, they performed similarly with and without the extra tactile cues. This indicates that it is important to have some passive tactile cues that can be sensed by the pointing finger but they are only effective up until a point.

STUDY 3: TACTILE CUES SENSED BY THE PALM

To understand the precise nature of tactile cues sensed by the palm, this study removed the sensing of tactile cues from the palm. For comparison, we also added a condition that removed the sensing of cues by the pointing finger.

Apparatus, task and procedure

The apparatus and task are identical to Study 1 and 2 but the interaction surface conditions were changed. This study used a within subjects 2×3 design with these factors:

- Sightedness: SIGHTED vs. BLINDFOLDED
- Interaction surface: PALM vs. FAKE PALM vs. PALM WITH FINGER COVER, as shown Figure 12.

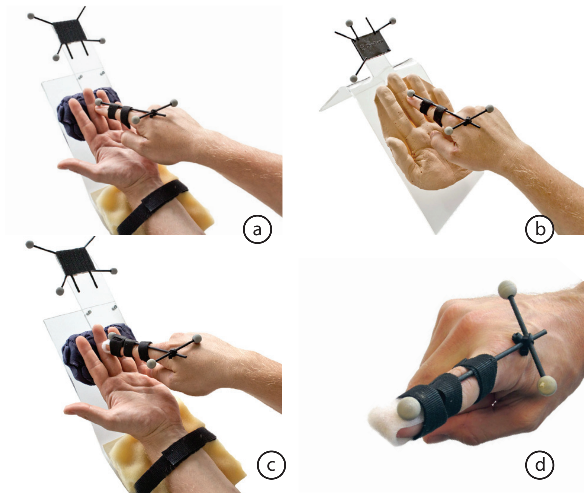

Figure 12: Study 3 conditions – (a) PALM vs. (b) FAKE PALM vs. (c) PALM WITH FINGER COVER; (d) close up of finger cover.

As in Study 1, for the PALM-based conditions we placed the participants' non-dominant hand in a fixture (shown in Figure 12a,c) that provided a consistent reference for calibration.

For the FAKE PALM condition, we built a realistic replica of one author's left hand (shown in Figure 12b) formed with liquid silicone. The replica has all of the fine ridges and features of a real hand and remains slightly compliant.

For the PALM WITH FINGER COVER condition we covered the tip of the participants' pointing finger a piece of Velcro backing. The cover removed the fine cutaneous sensation from the participants' fingers but the participants could still sense pressure and large features like the palm outline.

Hypotheses

First, since the PALM condition allows the participants to use both palm and finger taction (i.e., intra-active touch [2]) we expect it would outperform the other conditions when blindfolded:

> H1: When BLINDFOLDED, participants will be faster with the PALM than with the other interface conditions.

Secondly, we expect the FAKE PALM, which only involved active touch, to be comparatively worse to the PALM WITH FINGER COVER, which is dominated by passive touch. Passive tactile discrimination on the palm is very good [34], allowing the participants to directly localize the sensation instead of integrating the position while scanning with the finger tip. Therefore our second hypothesis is:

> H2: When BLINDFOLDED, participants will be slower with the FAKE PALM than with the PALM WITH FINGER COVER.

Participants

We recruited a new set of 12 participants from our institution (3 female, all right-handed) between the ages of 21 and 30 (M=24.3, SD=2.67). All had normal or corrected to normal vision and hearing.

Results

We collected 2941 data points and removed 61 error trials (2.0%) and 72 outliers (2.4%). This left 2808 trials for our analysis, which used the same procedure as Study 1 and 2.

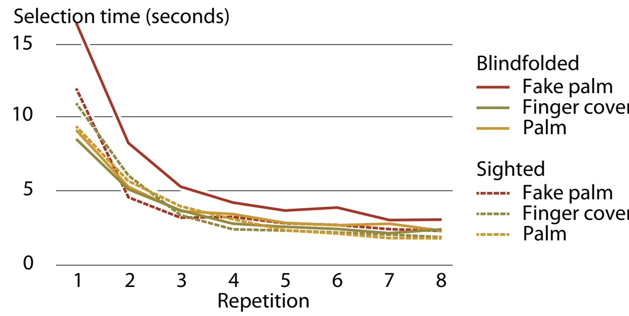

Figure 13: Study 3 performance for each condition over time.

Learning phase (Figure 14a):

There was no significant main effect of INTERACTION SURFACE (p=0.083) but there was for SIGHTEDNESS: when BLINDFOLDED participants were 20% slower than SIGHTED ($F_{1,11}$=9.13, p=0.012, η^2=0.07). There was also an interaction between INTERACTION SURFACE and SIGHTEDNESS ($F_{2,22}$=10.54, p=0.001, η^2=0.18).

Only when BLINDFOLDED were the differences between interaction surfaces significant ($F_{2,22}$=8.145, p=0.002, η^2=0.34) with the FAKE PALM being significantly slower than both the PALM (38%, p=0.019) and the PALM WITH FINGER COVER (33%, p=0.054).

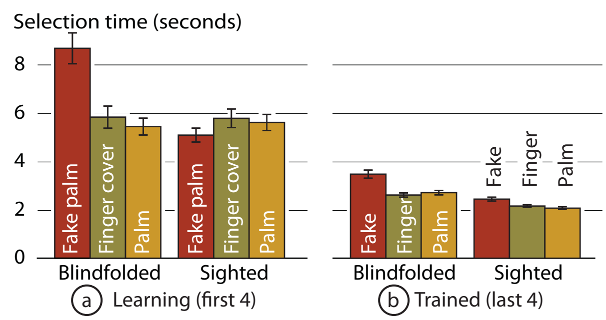

Figure 14: Study 3 results showing the (a) first and (b) last half of the repetitions. Error bars are +/- one std. error.

Trained phase (Figure 14b):

Unlike in the learning phase, this phase had a significant main effect of INTERACTION SURFACE ($F_{2,22}$=12.08, p<0.001, η^2=0.14) with the FAKE PALM being significantly slower than both the PALM (25%, p=0.024) and the PALM WITH FINGER COVER (24%, p=0.007).

By breaking these numbers down further and only looking at BLINDFOLDED trials, there is still a significant main effect ($F_{2,22}$=12.173, p=0.001, η^2=0.26) and the differences are more pronounced with the FAKE PALM being 30% slower than the PALM (p=0.024) and 33% slower than the PALM WITH FINGER COVER (p=0.003).

Overall, the FAKE PALM clearly performs the worst when BLINDFOLDED but surprisingly for both interaction phases, the PALM and PALM WITH FINGER COVER conditions perform similarly, which partially confirms H1 (that PALM outperform the others) and fully supports H2 (that FAKE PALM is slowest).

Discussion

The results indicate that it is the passive touch on the palm that contributes most to browsing an imaginary interface. The active touch feedback received by the tip of the pointing finger, in contrast, contributes comparatively little.

Although the FAKE PALM condition contained equivalent tactile cues to be sensed by the finger, participants performed substantially worse using it as an interaction surface compared to the user's own hand. We cannot say equivocally that the pointing finger contributes nothing to the interaction as in the PALM WITH FINGER COVER condition, large-scale tactile features (such as the edges of the hand and fingers) could still be felt but it is apparent that the fine tactile cues on the surface of the palm contribute very little.

We believe the difference occurred because the high touch discriminability of the palm makes it inherently spatial—touch occurs at an easily resolvable location—whereas tactile cues sensed by the pointing finger are inherently ambiguous as all fingers provide similar tactile cues. Users are apparently able to resolve this by integrating tactile information over time to develop an understanding of where they are located on the palm. However, this integration process takes time and is prone to error, which would explain the longer interaction times in our studies.

The same reasoning can also explain the limited performance improvement of the TACTILE PHONE in Study 2. Since only the pointing finger could sense the added tactile cues, they contribute less than if the participant's palm could be used for sensing.

CONCLUSIONS OF STUDY 1, STUDY 2 AND STUDY 3

First, the three studies combined show that imaginary interface browsing works well. This is an important finding because it suggests that future imaginary interfaces may use such an interaction technique to allow for stand-alone use.

Furthermore, the three studies provide an understanding of what enables palm-based imaginary interfaces:

1. Even though these interfaces cannot display visual content, users' visual sense remains the main mechanism that allows users to control the interfaces because it allows users to watch their hands interact. In conditions where users are able to watch their hands interact, this overrides the other cues we studied, i.e., all tactile cues.

2. In the absence of visual cues, the tactile cues available when the pointing finger touches the palm fill in for the lacking visual cues. As a result, palm-based imaginary interfaces remain usable even when operated eyes-free.

3. While we initially expected the pointing finger to sense the majority of tactile cues, we found the opposite to be the case, as the passive tactile sensing by the palm allows users to orient themselves. The most likely explanation is that the cues sensed by the pointing finger are ambiguous, while the cues sensed by the palm are unique and easy to locate spatially.

Potential implications for blind and eyes-free use

The second point in this list, i.e., the fact that tactile cues between pointing finger and supporting hand can in part fill in for the absence of visual cues has an additional implication: it suggests that the palm-based interaction from imaginary interfaces might be relevant for eyes-free use and in particular for visually impaired users.

We showed that when the interaction surface is located on the user's body, additional passive tactile sensing becomes available that increases performance compared to an eyes-free interface on an ordinary surface (such as a mobile phone). Thus, while this project started by borrowing from the related work on interfaces for visually impaired users, we propose exporting our findings back to that community. More concretely, the Imaginary Interface hardware, e.g., sensing the hands with a chest-mounted camera, might allow visually impaired users to perform better than with the touchscreen-based devices they use today. While such a claim obviously requires a substantial amount of additional research, we want to conclude this paper with a one-user pilot study we conducted to inspire this discussion.

One blind participant performing the task from Study 1

We recruited one blind person to perform the experiment task of Study 1 and to supply feedback.

Our participant was a 33 year-old male, right-handed, and a musician by trade. He had been blind since age two and has zero sensitivity to light. In his daily life, he uses screen-reading software on his PC and on his non-touchscreen Nokia mobile phone. He was familiar with the VoiceOver for iPhone interaction style but has not used it regularly.

The participant performed the task from Study 1. He performed four blocks (two for each interaction surface condition) of 40 trials each. We used ABBA counterbalancing to balance learning effects. His results are shown in Figure 15.

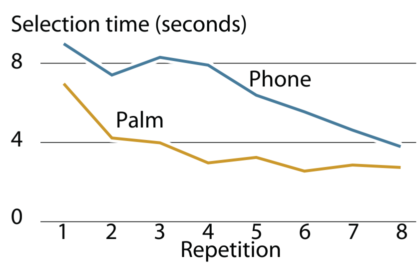

Figure 15: Blind participant's selection times with the PALM and PHONE interfaces.

Overall, his performance matched the results from the blindfolded participants in that he was faster both phases with the palm interface. In the learning phase he was 44% faster with the palm (4.54s) than phone (8.15s) and also 44% faster in the trained phase (2.85s vs. 5.09s).

Following the study, we conducted an informal interview. He was overall very positive about the palm interface and preferred it to the phone, saying that he preferred "the material of [his] palm." Assuming the sensing technology was reliable, he said that he could imagine himself using such an interface. He also commented that using the palm might actually have less social stigma in public because it wouldn't appear out of the ordinary, especially compared to specialized equipment like Braille readers.

Clearly we must be careful generalizing from the outcome of one participant but the results here are promising and will hopefully inspire future work in the area of imaginary interfaces for visually impaired users.

CONCLUSION

In this paper, we explored which inherent properties of palm-based imaginary interfaces are responsible for user performance. We conducted our exploration using the example of an interface that allows users to browse unfamiliar imaginary interfaces. We learned that visual cues, tactile cues sensed by the palm and tactile cues sensed by the pointing finger all contribute to the performance of imaginary interfaces, in that order. In addition, we obtained good results with the browsing interface, suggesting that this interaction technique has the potential for forming the basis of future stand-alone ultra-mobile devices.

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