Slide Rule: Making Mobile Touch Screens Accessible to Blind People Using Multi-Touch Interaction Techniques

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ABSTRACT

Recent advances in touch screen technology have increased the prevalence of touch screens and have prompted a wave of new touch screen-based devices. However, touch screens are still largely inaccessible to blind users, who must adopt error-prone compensatory strategies to use them or find accessible alternatives. This inaccessibility is due to interaction techniques that require the user to visually locate objects on the screen. To address this problem, we introduce Slide Rule, a set of audio-based multi-touch interaction techniques that enable blind users to access touch screen applications. We describe the design of Slide Rule, our interaction techniques, and a user study in which 10 blind people used Slide Rule and a button-based Pocket PC screen reader. Results show that Slide Rule was significantly faster than the button-based system, and was preferred by 7 of 10 users. However, users made more errors when using Slide Rule than when using the more familiar button-based system.

Categories and Subject Descriptors:

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Input devices and strategies*, *Voice I/O*. K.4.2.[**Computers and society**]: Social issues – *assistive technologies for persons with disabilities*.

General Terms: Design, Human Factors, Experimentation.

Keywords: Accessibility, blindness, mobile devices, touch screens, multi-touch interaction techniques, speech output.

1. INTRODUCTION

Although touch screens have existed for decades, new advances in touch screen interfaces, as seen in devices such as Apple's iPhone and Microsoft Surface, have renewed interest in touch interfaces. Touch screens are often used to provide information and services to users in places such as museums, airports, and supermarkets. Increasingly, touch screens are also a common interface element of mobile devices such as Tablet PCs, PDAs, and smartphones.

Touch screen interfaces offer users several advantages over interfaces with physical buttons. One advantage is flexibility of presentation and control. A touch screen device can display different interfaces on the same surface, such as a scrollable list, a QWERTY keyboard, or a telephone keypad.

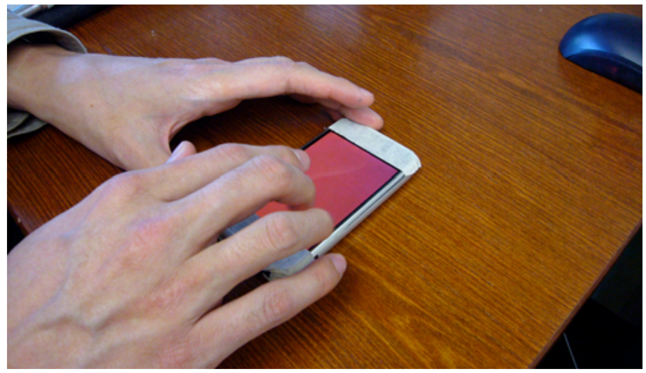

Figure 1. Participant using Slide Rule on a multi-touch smartphone. Slide Rule uses audio output only and does not display information on the screen.

Another advantage of touch screen interfaces is discoverability. Rather than requiring users to remember input commands, touch screens allow users to directly manipulate items on the screen. New multi-touch user interfaces support additional interaction techniques beyond pointing and tapping, allowing users to interact using single- and multi-finger gestures such as flicking, rotating, and pinching [19].

Unfortunately, touch screens can present significant accessibility barriers to blind users. Most touch screens provide no audio or tactile feedback, making it difficult or impossible to locate items on the screen. Because of these difficulties, blind users may need to be shown the locations of on-screen objects by a sighted person, may need to use an alternative accessible interface (if available), or may be completely unable to use a device. Although some assistive technologies can improve touch screen accessibility, these typically require additional hardware buttons (e.g., [18]), or provide only limited use of the touch screen (e.g., Mobile Speak Pocket[1]). Thus, most current touch screen interfaces remain inaccessible to blind users.

In response to these limitations, we developed *Slide Rule*, a set of accessible multi-touch interaction techniques for touch screen interfaces. Slide Rule provides a completely non-visual interface that repurposes a touch screen as a "talking" touch-sensitive surface. Slide Rule uses a set of four basic gesture interactions: (1) a *one-finger scan* to browse lists, (2) a *second-finger tap* to select

ASSETS'08, October 13–15, 2008, Halifax, Nova Scotia, Canada.

[1] http://www.codefactory.es/

items, (3) a multi-directional *flick* gesture to perform additional actions, and (4) an *L-select* gesture to browse hierarchical information. Slide Rule provides access to custom phone book, e-mail, and media player applications that we developed for this evaluation. Slide Rule requires a standard multi-touch screen and audio output, but no additional hardware (Figure 1).

In this paper, we describe the design, implementation, and evaluation of Slide Rule. We present our user-centered design process that included formative interviews with 8 blind mobile device users, followed by iterative prototyping with 3 blind users. We describe a study in which 10 blind people used Slide Rule and a comparable button-based system running the Mobile Speak Pocket screen reader. Our results show that users were faster with Slide Rule and that 7 of 10 participants preferred Slide Rule. However, participants committed more errors with Slide Rule, resulting in a speed-accuracy tradeoff. Finally, we discuss the design implications of this study and possibilities for future work, including the generalization of our techniques to other touch screen-based devices and surface computing platforms.

2. RELATED WORK

Slide Rule extends previous research on the accessibility of touch screen interfaces by providing richer methods for interacting with touch screens. Slide Rule also extends research on eyes-free mobile device interfaces by introducing new eyes-free interaction techniques for touch screen-based devices.

2.1 Touch Screen Accessibility

Some past research projects have attempted to increase the accessibility of touch screen-based systems. Vanderheiden's *Talking Fingertip Technique* [18] allowed users to scan a kiosk touch screen with a finger and hear descriptions of the items on the screen, and then activate those items with a hardware button below the screen. The *Talking Tactile Tablet* [8] allowed users to explore a two-dimensional space using a stylus, and used speech and a printed tactile overlay to provide audio and tactile feedback. *Touch 'n Talk* [6] used speech and a tactile overlay to allow users to skim and edit text documents. These systems made traditional touch screen interfaces accessible by providing feedback as the user probed with a finger or stylus. In contrast, Slide Rule provides a specialized touch interface optimized for non-visual browsing. Slide Rule also requires only a multi-touch screen, while these systems required custom hardware or tactile overlays.

Relatively few commercial systems provide touch screen accessibility features. Some touch screens, such as those in supermarket checkout kiosks, provide a tactile overlay template through which users can feel areas of the underlying screen [4]. However, overlays reduce the flexibility of touch screen interfaces, as items on the screen must match the physical overlay.

Some touch screen-based mobile devices may be accessed using a screen reader such as Mobile Speak Pocket (MSP). MSP divides the screen into four quadrants and recognizes taps in each quadrant as button presses. MSP allows blind users to use touch screens, but in a very limited fashion. In contrast, Slide Rule enables a wider range of interactions with a touch screen.

2.2 Eyes-Free Mobile Device Use

Researchers have developed a number of eyes-free interaction techniques for mobile devices that do not use touch screens. These techniques may benefit both blind and sighted users. ADVICE [2] is a prototype mobile device that uses a physical scroll wheel and button to navigate speech-based menus. BlindSight [9] uses a phone keypad to access a speech menu while the user is talking on the phone. Slide Rule performs similar functions to these systems, but uses a multi-touch surface in place of hardware buttons.

Other systems provide eyes-free access to mobile device menus using touch screen gestures. Systems developed by Pirhonen et al. [13], O'Neill et al. [11], and Sánchez and Maureira [16] all use directional gestures to perform basic operations on mobile touch screens. EarPod [21] uses a circular touchpad to provide access to hierarchical audio menus. Slide Rule attempts to improve upon these systems in three important ways: (1) by reducing the user's need to remember arbitrary gesture mappings, (2) by providing access to more complex information, and (3) by using multi-touch gestures to provide richer interactions with the touch surface.

Systems developed by Sánchez and Aguayo [15] and Yfantidis and Evreinov [20] allow users to enter text on touch screens using multi-tap and directional gestures, respectively, and provide audio feedback as the user types. These methods are complementary to Slide Rule, and could be combined with it in the future.

3. FORMATIVE INTERVIEWS

In order to identify usability issues with mobile devices and touch screens, we conducted formative interviews with 8 blind mobile device users. Our questions focused on two primary topics: current use of mobile devices, and breakdowns and workarounds related to touch screens. Each interview lasted about 30 minutes.

Eight informants (4 male, 4 female) participated in the interviews. The average age of informants was 31.4 (*SD*=9.1). All informants were screen reader users and used a computer daily.

3.1 Mobile Device Use

We asked informants about the mobile devices they used regularly. Interestingly, all 8 informants used multiple mobile devices. On average, each informant used 3.6 (*SD*=0.7) mobile devices regularly. Commonly used devices included mobile phones, laptops, Braille PDAs, and audiobook players. All 8 informants had a smartphone or PDA. Two informants had touch screen devices. In many cases, informants carried multiple devices that performed the same function, usually because one had a superior interface for a specific task. For example, some informants carried a portable audiobook reader even though their PDA or portable music player could play audiobooks.

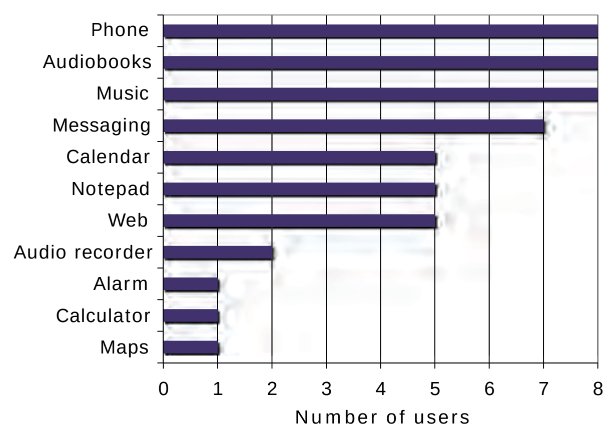

Figure 2. Informants' common mobile device tasks.

We asked informants about the tasks that they currently perform using their mobile devices. This information is shown in Figure 2.

Several informants mentioned that they had tried some task in the past, but ran into difficulties and gave up. This shows that users experience usability and accessibility issues even on devices that they use frequently.

3.2 Difficulties Using Touch Screens

Although our informants were experienced mobile device users, most had not used many touch screens. Informants reported using touch screens on devices such as microwave ovens, supermarket checkout kiosks, voting machines, ATMs, and occasionally, mobile devices, but these were generally rare occasions.

When asked about how they coped with touch screens, informants mentioned several workarounds. When the touch screen was in the informant's home, such as on a microwave or other appliance, he or she often annotated it with adhesive tactile dots or Braille labels. For devices in other locations, informants sometimes memorized the location of on-screen objects, but were often forced to ask a sighted person for help. In some cases, informants simply avoided tasks that required using a touch screen.

Finally, when asked about difficulties that they encountered using touch screens, informants primarily mentioned the difficulty of learning where objects were located on the screen. Some informants also mentioned that they were concerned about accidentally activating certain features on the touch screen, for example accidentally deleting a file or withdrawing money from an ATM.

3.3 Implications for Design

Our interviews were helpful in identifying key issues to address in the development of Slide Rule. We identified three common themes that guided the development of Slide Rule and further motivate the development of accessible touch screen interfaces.

First, informants favored devices that featured familiar interface layouts. Several informants praised devices that used a mini-QWERTY keyboard or phone keypad because of their familiar layout. Therefore, accessible touch screen interfaces should allow users to interact with familiar spatial layouts when possible.

Second, all informants carried multiple mobile devices, and often carried functionally redundant devices. Multiple devices can be difficult to manage. One informant stated, "I always have so much with me now, so if I'm having to take all these pieces of technology, it gets to be a little much." Touch screen devices offer the potential to incorporate the functions of several devices into a single mobile device. However, reusable commands and gestures are needed to ensure consistent interactions across applications.

Finally, while many of our informants were intrigued by the possibility of using an accessible touch screen, some were concerned about being unable to find objects on touch screens or accidentally activating incorrect features. Thus, it is important that touch screen interfaces are easy to explore and minimize the need to search for on-screen items through trial-and-error.

4. DESIGN OF SLIDE RULE

Results from the interviews described above were used to shape the development of Slide Rule. We begin this section with our motivating principles, followed by an overview of the interaction techniques and their realization in Slide Rule.

4.1 Design Principles

Before developing Slide Rule, we extracted a set of design principles based on our interviews and interactions with early prototypes. These principles allowed us to develop an efficient and cohesive set of interaction techniques.

Risk-free exploration. The user must be able to scan the screen with one finger without performing any action. Slide Rule reads the names of items as they are touched. Operations that alter state (e.g., deleting items) are activated by multi-finger taps or gestures, and cannot be activated by simply touching the screen.

Operate at finger resolution, not screen resolution. Audio feedback has been shown to improve pointing accuracy for small targets [3]. Using speech feedback allows for even smaller targets to be used, as labels can be spoken rather than written. Slide Rule uses targets that are small and close together in order to maximize the number of items per screen.

Reduce demand for selection accuracy. Users should not have to accurately tap on an object, but should be able to find the object with their index finger and then perform a tap gesture *anywhere* on the screen with their middle finger. This technique reduces the need to accurately tap on objects.

Quick browsing and navigation. Users should be able to quickly scan through each page by running their finger down the screen, and flip between pages of items using flick gestures.

Intuitive gestural mappings. Slide Rule avoids arbitrary gestures and instead uses natural gesture mappings (e.g., flicking to the right will forward a message, flicking to the left will reply).

Enable users to query location and return home at any time. Users should be able to identify the current screen they are on or return home by performing quick flicking gestures.

4.2 Screen Layout

Slide Rule's interface is entirely speech-based and has no visual representation. Slide Rule displays a solid color on the screen to indicate that it is running, but provides no other visual feedback.

Despite its non-visual interface, Slide Rule lays out objects on the screen spatially using linear lists. Users navigate through lists of items by scanning their fingers down the device surface, and use gestures to interact directly with on-screen objects. For example, rather than finding and tapping a 'Forward' button in the Mail application, users forward a message by locating the message with their finger and performing a *right-flick* gesture. This style of interaction is uncommon in systems designed for blind users, but reduces the need to constantly locate targets on the touch screen.

In most cases, screen objects are placed in a single column with no dead space between objects, reducing the need to hunt for objects. Objects are ordered logically: for example, in the Phone application, contacts are ordered alphabetically, while in the Mail application, messages are ordered chronologically.

4.3 Target Size

Because Slide Rule does not display item labels, targets can be made small and densely packed. In the Phone and Mail applications, the size of each item is 50.8 mm by 7.62 mm, slightly smaller than the size recommended by Parhi et al. [12]. Targets in the Music application are narrower, at 3.91mm by 7.62mm. This target size allows up to 130 objects to be placed on the screen at any one time. After a brief practice session, all study participants were able to select these small targets during the evaluation. Rather than require users to manage scrolling windows, Slide Rule uses paging when there are too many targets to fit on one screen. Left and right flick gestures are used to switch between pages.

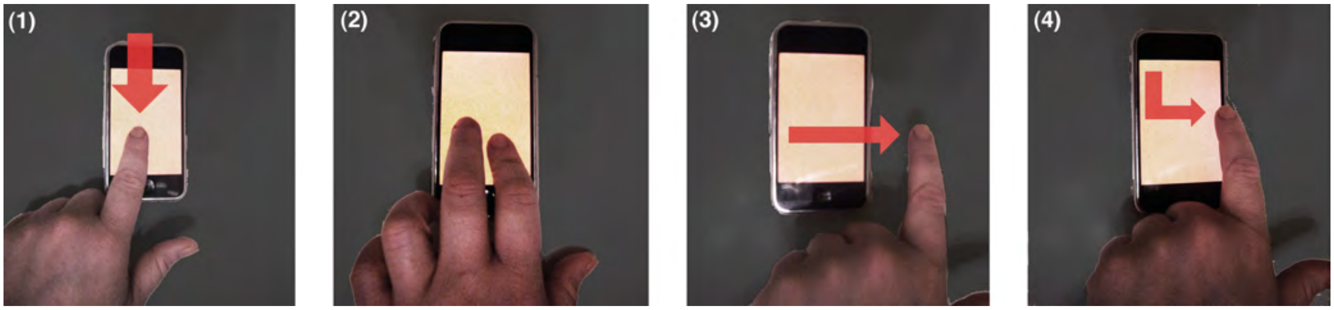

Figure 3. Slide Rule uses multi-touch gestures to interact with applications. (1) A *one-finger scan* is used to browse lists; (2) A *second-finger tap* is used to select items; (3) A *flick* gesture is used to flip between pages of items or a currently playing song; (4) An *L-select* gesture is used to browse the hierarchy of artists and songs in the music player.

4.4 Interaction Techniques and Applications

Drawing on the design principles above, we developed a set of new interaction techniques for eyes-free use of touch screens (Figure 3). To illustrate their usability and flexibility, these techniques were implemented in three prototype applications: a phone book (Phone), an e-mail client (Mail), and a music player (Music). Table 1 summarizes how the interaction techniques are used in each application.

Table 1. Slide Rule interaction techniques and their functions.

Application	Interaction techniques
All applications	*Flick up:* Return to Home screen *Flick down:* Read screen contents *Flick left or right:* Previous/next page
Home screen	*One-finger scan:* Browse applications *Second-finger tap:* Select application
Phone	*One-finger scan:* Browse contacts *Second-finger tap:* Call contact
Mail	*One-finger scan:* Browse message headers *Second-finger tap:* Read message body *Flick left:* Reply to message *Flick right:* Forward message
Music	*One-finger scan:* Browse artists *L-select:* Browse songs for artist *Second-finger tap:* Play song *Flick left:* Play previous song *Flick right:* Play next song *Double tap:* Pause current song

4.4.1 One-finger Scan

The user may browse the contents of the screen using a one-finger scan gesture. Because objects are stacked vertically, a user can slide their finger from the top of the screen to the bottom to read all of the items in the current view. When the user's finger touches a new object, Slide Rule announces the name and a summary of that object. For example, Slide Rule speaks the first and last name of a contact in the phone book when the user touches the area for that contact. Each item's name is prefaced by a preview sound, either the first letter of a name or the number of an item in a list, to enable fast scanning using the finger. For example, the name Bob Jones is read as "B, Bob Jones." This allows users to quickly scan the list of names to find the one that they are looking for without having to listen to lengthy readouts.

4.4.2 Second-Finger Tap Selection

Prior research has shown that tapping targets on a touch screen can be difficult, especially when targets are small [17]. Target selection techniques like *first-contact* and *take-off* [14] make it difficult for users to explore the screen without activating targets.

In Slide Rule, targets are selected by holding one finger down over a target, which has already been read aloud, and then tapping *anywhere* on the screen with a second finger. This selects the target beneath the *first* finger, thereby lessening the accuracy demands of the second-finger tap. During our pilot study, we observed that a user's first finger would occasionally slip when tapping. For this reason, a slip timer was added to the second-finger tap gesture: if the target changed within 400 ms of a second-finger tap event, the prior target was used.

During our pilot study, some users attempted to hold the device in one hand and touch the screen with their thumb, thus making the second-finger tap gesture difficult to perform. For this reason, we added the *lift-then-tap* gesture [10] for selecting targets with one hand, although this gesture was not used in the experiment. With the lift-then-tap gesture, the target beneath the lift is activated when the tap occurs, regardless of where the tap itself lands.

4.4.3 Flick

Slide Rule implements a flicking gesture similar to the gesture supported by the Apple iPhone and the flick gesture described by Wu and Balakrishnan [19]. A user performs the flick gesture by quickly flicking their finger in one of four directions. Flicking upward in any application returns the user to the Home screen, while flicking downward provides a speech overview of the current screen. Left and right flicks are used differently depending on the application (Table 1).

4.4.4 L-Select

To browse hierarchical data such as music, users can perform an L-shaped selection gesture. In the Music application, this gesture allows the user to select any song with a single gesture (Figure 4). A user begins this gesture by scanning his finger down the left edge of the screen. Slide Rule reads the name of each artist as the user scans down the edge of the screen. Once the user finds the desired artist, he scans his finger to the right to move through songs by that artist. The user selects a song with a second-finger tap. As the user begins to scan to the right, the screen areas representing that artist's songs expand to fill the entire height of the screen, so that the user's finger can drift up or down without accidentally selecting another artist's songs. In the end, the user has made an L-shaped gesture to select the song.

4.4.5 Double Tap

Slide Rule can also detect a quick one-finger double-tap gesture. This gesture, performed anywhere on the screen, is currently used to pause and resume the music player.

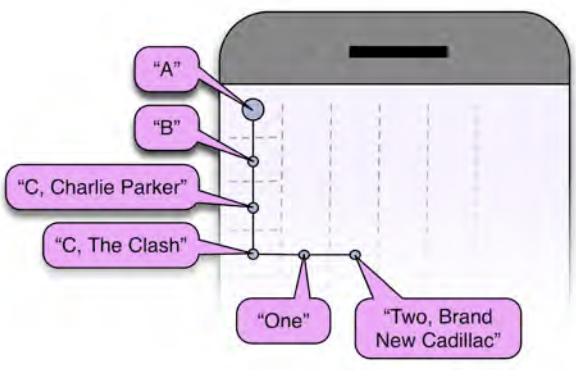

Figure 4. User performs an L-select gesture by scanning their finger down a list of artists, then across a list of songs. Slide Rule says the first part of each item to enable quick scanning.

5. SYSTEM EVALUATION

We conducted an experimental evaluation of Slide Rule to validate these interaction techniques and discover possibilities for improving the prototype. We first performed a pilot study with 5 users (3 blind, 2 sighted) to identify major usability issues with our prototype. Following the pilot, the results of which are not reported here, we conducted a usability and performance evaluation in which 10 blind people used Slide Rule and a comparable Pocket PC device running equivalent applications with Mobile Speak Pocket.

5.1 Participants

Ten blind computer users (8 men, 2 women) participated in our study. Participants were recruited through university email lists and local community centers for the blind. For the purposes of this evaluation, we defined *blind users* as "desktop screen reader users." We recruited participants who were screen reader users and who had the dexterity to use a mobile device. The average age of the participants was 41.2 (*SD*=11.5). All participants had 10 years or more of screen reader experience. Four participants were smartphone users, and 6 users had some residual vision.

5.2 Apparatus

Two devices were used during the experiment. Slide Rule was developed on an Apple iPhone. The iPhone has a 3.5-inch capacitive touch screen that operates at 320×480 resolution. Slide Rule was implemented as a custom Objective-C application. Because the iPhone does not natively support speech synthesis, all speech was pre-rendered on a Windows XP computer using Acapela Ryan. Slide Rule operates using the touch screen only, and does not require use of any of the iPhone hardware buttons.

For comparison to Slide Rule, we developed a Pocket PC application suite using the Mobile Speak Pocket (MSP) screen reader. These applications were implemented on an ASUS MyPal A730 Pocket PC running the Windows Mobile 2003 operating system. MSP also used Acapela Ryan for speech synthesis. Figure 5 shows the devices used.

The Pocket PC test applications (Phone, Mail, Music) were implemented using C# and duplicated the functionality of Slide Rule. These applications were developed using standard Windows Mobile design guidelines and controls. Standard MSP input settings were used to interact with the Pocket PC applications. Users navigated through application menus using the four-way navigation control below the touch screen. Users also performed simple tapping gestures using the device's touch screen. MSP divides the touch screen into four quadrants, which are used as discrete input areas. Participants were taught two required touch screen gestures: (1) tapping the top-right corner to read the current screen contents, and (2) double-tapping the bottom-left corner to close an active window.

Both devices used the same sample data set, which consisted of 10 phone book contacts, 10 e-mail messages, and 10 albums containing a total of 105 songs. We chose a small data sample set to reduce the duration of the experiment, and included the music task as a demonstration of Slide Rule's extension to larger data sets. Small data sets correspond to the kinds of tasks that a typical user might perform while "on the go," such as calling someone on a favorites list or reading recently received e-mail messages.

Both devices recorded a tab-delimited log of all button presses, touch screen interactions, and application events. All events were time-stamped to the nearest millisecond. These logs were parsed by a Python script and analyzed using statistical software.

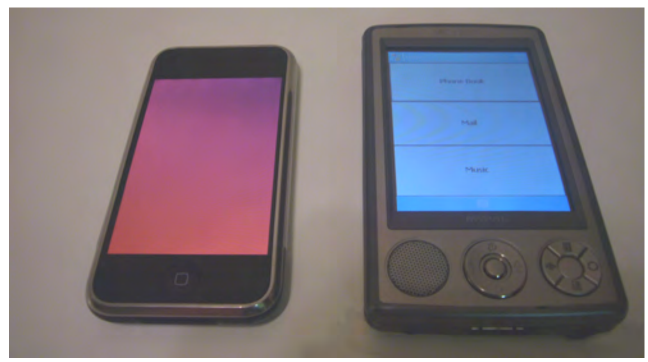

Figure 5. Devices used in the evaluation. Apple iPhone (left), ASUS MyPal A730 Pocket PC (right).

5.3 Procedure

After the introduction, participants were given the first of two devices (either Slide Rule or the Pocket PC) and guided through its operation by the experimenter. The experimenter demonstrated each application, describing the operations needed to perform each of the tasks. After being walked through each task, the participant was prompted to verbally describe how to complete the task and then to perform three practice tasks. Once the participant successfully demonstrated the task three times, the experimenter moved to the next task. At the end of the practice session, the participant was given an opportunity to perform any additional practice tasks that he or she wished. The practice period lasted about 15 minutes per device.

Once the practice session was completed for a device, the experimenter began the experiment. During the experiment, the participant performed 5 trials for each of the following experimental tasks: (1) placing a phone call, (2) reading an e-mail message, and (3) playing a song. Participants were instructed to complete the task quickly and accurately. At the end of each trial, participants were instructed to return to the Home screen. Each trial began when the participant entered the correct application for the current task, and ended when the participant performed the correct operation. Participants continued the task until completion, regardless of any errors that they made.

Each participant completed both the practice and evaluation sessions with the first device before moving to the second device. The order of devices was counterbalanced across participants. A test of *Device Order* on task time was non-significant ($F(1,9)=0.549$, $p=.56$), indicating adequate counterbalancing.

5.4 Design and Analysis

The experiment was a 2×3×4 within-subjects factorial design with the following factors and levels:

- *Device* {Slide Rule, Pocket PC with MSP}
- *Application* {Phone, Mail, Music}
- *Trial* {1, 2, 3, 4}[2]

The total number of trials in the experiment was 240. The dependent variables were task completion time, task completion errors, and listening time per item. Errors were defined as activating an incorrect target area (e.g., phone book contact, e-mail message, or song) or accidentally triggering a gesture. Listening time per item was measured as the average time spent listening to each item on screen per application.

Time and time per item were analyzed using repeated-measures ANOVA. Errors and questionnaire responses were analyzed using nonparametric Friedman and Wilcoxon tests.

6. RESULTS

6.1 Adjustment of Data

As explained in Footnote 2, we excluded the first trial from our analysis due to significant learning effects we observed between the first and second trials. Furthermore, as is common with time measures, the observed time data were not normal (Shapiro-Wilk $W=0.90$, $p<.0001$). Instead, the data conformed to a lognormal distribution (Kolmogorov's $D=0.05$, $p>.15$). Therefore, we transformed our time data with a log transformation as is customary [1]. The time per item variable also did not fit a normal distribution ($W=0.95$, $p<.0001$), but did conform to a lognormal distribution ($D=0.05$, $p=.15$), so we also log-transformed. Where times are reported, they are in untransformed values.

6.2 Task Completion Time

Overall, Slide Rule was significantly faster than the Pocket PC. The mean time for tasks using Slide Rule was 11.69 seconds ($SD=5.77$), while the mean time for the Pocket PC was 12.79 seconds ($SD=7.58$). These differences resulted in a significant effect of *Device* on completion time ($F(1,9)=5.68$, $p<.05$). Time results are shown in Figure 6.

Because Slide Rule's interaction methods varied somewhat between applications, we also compared performance across applications. There was also an effect of *Application* on time ($F(2,18)=59.80$, $p<.001$), indicating that some application tasks were faster to complete than others. A pairwise comparison using Holm's sequential Bonferroni procedure [7] shows speed differences between all 3 applications: Mail was faster than Music ($F(1,18)=17.14$, $p<.01$), and Phone was faster than both Mail ($F(1,18)=17.14$, $p<.01$) and Music ($F(1,18)=28.77$, $p<.0001$).

There were no other significant effects or interactions with task completion time. Overall, Slide Rule was the faster technique for 6 of 10 participants.

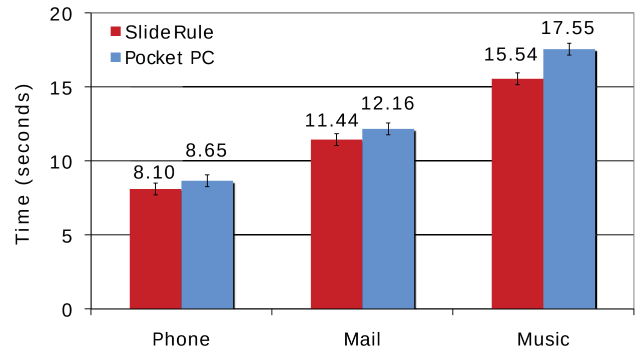

Figure 6. Time in seconds for each level of *Device* and *Application*. Lower is better. Error bars show ±1 SE.

6.3 Task Completion Errors

Although users were faster on average with Slide Rule, they made more errors per trial than with the Pocket PC. The average errors per trial for Slide Rule was 0.20 ($SD=0.56$). No participants made any errors using the Pocket PC. A nonparametric Wilcoxon test showed this difference to be significant ($z=-3.80$, $p<.001$). A total of 17 out of 120 (14.1%) Slide Rule tasks contained errors. Error results are shown in Figure 7.

Number of errors differed between applications, but not significantly. For Slide Rule, the average errors per trial was 0.10 ($SD=0.38$) for Phone, 0.18 ($SD=0.55$), for Mail, and 0.33 ($SD=0.69$) for Music. A Friedman test showed no significant main effect of *Application* on errors ($\chi^2(2,N=40)=3.67$, $p=.16$).

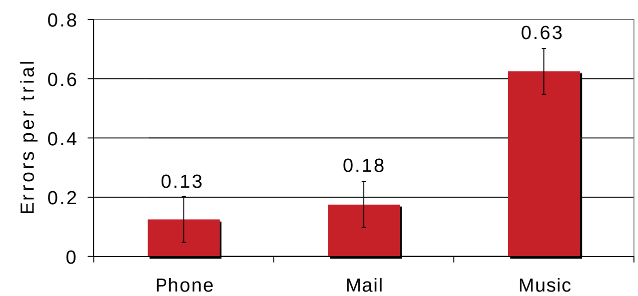

Figure 7. Average errors per trial for Slide Rule applications. Lower is better. Error bars show ±1 SE.

6.4 Listening Time per Item

The mean time spent listening to each item was 0.95 seconds ($SD=0.43$) for Slide Rule and 1.42 seconds ($SD=0.46$) for the Pocket PC. This difference was statistically significant ($F(1,8)=68.88$, $p<.001$). This suggests that users of Slide Rule were able to more quickly scan through items, which may account for part of the observed speed advantage with Slide Rule. There was also a significant overall effect of *Application* on time per item ($F(2,18)=4.12$, $p<.05$), although there were no significant pairwise differences between applications.

6.5 Questionnaire Results

Following the experiment, participants completed a questionnaire about the two devices. Participants indicated their agreement with

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[2] Although 5 trials were performed, our analyses indicated that significant learning occurred from the first to the second trial ($p<.05$), but not thereafter. Therefore, we excluded trial 1 from our analysis, leaving 4 trials for each subject within each *Device* × *Application* condition.

a series of statements about each device using a 5-point Likert scale (1=Disagree strongly, 5=Agree strongly). The statements used, along with their mean values, are listed in Table 2.

Using a Wilcoxon test, the following items were significant: Easy to use (z=–2.39, p<.05), Felt in control (z=–2.35, p<.05), Easy to learn (z=–2.53, p<.05), and Familiar (z=–2.55, p<.05). There were no significant differences in the other items. Together, these results confirm that our participants, who were mobile device users and screen reader users, felt more comfortable and were more familiar with the *de facto* standard, rather than the novel design. Surprisingly, however, participants responded differently when asked to indicate their favorite of the two devices. In fact, 7 of 10 participants preferred Slide Rule to the Pocket PC. Taken together, these results show that users may not always be most successful with the designs with which they feel most comfortable.

Table 2. Results of the questionnaire (1-5). Higher is better. Starred items were rated significantly higher for Pocket PC.

Statement	Pocket PC	Slide Rule
Easy to use*	4.6 (0.52)	3.2 (1.40)
Fun to use	3.9 (1.20)	4.4 (0.52)
Fast to use	3.8 (0.92)	4.3 (0.82)
Felt in control*	4.7 (0.48)	3.3 (1.16)
Easy to learn*	4.9 (0.32)	4.1 (0.57)
Intuitive	4.6 (0.52)	4.3 (0.95)
Familiar*	3.8 (1.48)	2.2 (1.03)
Features clear to me	4.8 (0.42)	4.7 (0.48)
Improve with practice	3.4 (1.58)	4.5 (0.71)
Would use on phone	4.4 (0.52)	4.1 (1.45)
Would use on other touch screens	3.9 (1.05)	4.7 (0.99)
Makes touch screens accessible	3.4 (1.20)	4.5 (0.48)

6.6 Qualitative Feedback

Participants commented positively about Slide Rule's speed and ability to randomly access lists. Participants also felt that Slide Rule was more "natural" than the Pocket PC, and enjoyed interacting more fully with the touch screen. One participant stated, "I've never seen a touch screen that accessible before, and that was pretty cool."

While 7 participants preferred Slide Rule, 3 preferred the Pocket PC. Negative comments about Slide Rule focused largely on the uncertainty involved in using a touch screen and the relatively small size of the targets, especially in the Music application. One participant said, "I preferred [the Pocket PC] … [Slide Rule] was more frustrating." Some participants expressed the opinion that touch screens could *never* be useful to blind users. One participant stated, "Flat screens without a grid—a real tangible grid—are difficult for blind people … I think that flat screens are not really accessible." These comments suggest an existing bias or resistance to touch screens among some blind users. Such a bias would not be surprising given the current inaccessibility of touch screens, but we are optimistic that Slide Rule has demonstrated that touch screens can be a viable option for blind users.

Most participants were either neutral or positive about the Pocket PC. Participants noted that using buttons was more familiar and less error prone than using a touch screen. Negative comments about the Pocket PC focused primarily on its slower response speed, although some users also had difficulty tapping the touch screen. A number of users were pleased with both devices, and suggested building interfaces that combined the quick access of Slide Rule with the accuracy of a button-based interface.

7. DISCUSSION

We observed qualitative differences between how people used Slide Rule and the Pocket PC with Mobile Speak Pocket. The primary difference between the two systems was in how users navigated lists. On the Pocket PC, users were required to step through lists one item at a time, starting at the first item. This method was somewhat slow, although some users began to navigate lists quickly by rapidly tapping the down arrow. In the end, Pocket PC users were less likely to make errors, and less likely to miss an item on the list.

In Slide Rule, users are able to navigate lists in a non-linear fashion. This allowed users to jump to an area near their intended target and locate it from there. However, users would sometimes skip over items or navigate randomly until they found the target item. This suggests that Slide Rule might benefit from a method of stepping through lists sequentially, although users' ability to search lists might also improve with practice.

Although participants were faster overall with Slide Rule, they made more errors with Slide Rule than with the Pocket PC. In fact, participants made no errors with the Pocket PC during the experiment. The higher number of errors is not surprising, as touch screens may be less accurate than physical buttons. Most of the participants in this study were not touch screen users, and none had used a multi-touch device before. It is possible that users would perform fewer errors as they learned to use the device. Also, note that devices such as the iPhone are popular despite the lower accuracy of touch screens, suggesting that touch interfaces may provide benefits that outweigh their increased error rate.

Note that we adopted a strict and unforgiving definition of errors in Slide Rule. Errors included accidentally tapping the screen with a second finger and incorrectly activating the swipe gesture, even if there were no undesirable effects. One important consideration when comparing speed and accuracy is the cost of making an error. In the Mail and Music applications, making an error has relatively low cost, either reading an unintended message or playing an unintended song, respectively. Errors in the Phone application were somewhat more costly, and could result in calling an unintended contact. Fortunately, these errors were rare in our experiment, occurring in only 3 of 40 Phone trials. Adding confirmation gestures to actions with greater consequences, such as when making a phone call, could reduce the impact of errors.

In the end, we were generally pleased with the performance of Slide Rule for our blind participants, especially when we keep in mind that they were long-time screen reader users who were accustomed to mobile devices with physical buttons. Even further, 4 of 10 participants were already existing mobile screen reader users, giving the Pocket PC every advantage over Slide Rule in terms of familiarity and potential for users' favor. Despite participants' initial skepticism about multi-touch interactions, they preferred Slide Rule in the end, recognizing its potential. If participants spend as much time with Slide Rule as they have with conventional screen readers, their speed advantage would probably improve, and errors would likely be reduced.

8. FUTURE WORK

The results of this study suggest that Slide Rule's techniques are potentially useful and worthy of further exploration. A longer study is necessary in order to better understand the strengths and limitations of this method. However, we have identified a number of areas in which the current implementation can be extended to handle additional tasks and usage scenarios.

*Composite interaction techniques***.** We might extend Slide Rule's interaction to handle additional hardware keys, or use additional parameters such as device orientation to augment touch screen input [5]. We might also extend Slide Rule with haptic feedback.

*Text entry methods***.** The current prototype provides text entry through a QWERTY soft keyboard. Text entry might be improved using gesture-based text entry or a Braille chording soft keyboard.

*Support for larger displays***.** We might extend Slide Rule to support larger touch screen displays, such as airport kiosks, voting machines, or large shared multi-touch displays. Extending Slide Rule to larger displays may require modifications to the current set of gestures or the creation of additional gestures.

Applicability to sighted users in eyes-free contexts. Slide Rule may have applications for sighted users operating mobile devices with limited visual attention, such as when using a device while walking down a crowded street. A future study could compare the performance of Slide Rule between blind and sighted users.

9. CONCLUSION

We introduced Slide Rule, a set of multi-touch interaction techniques that improves the accessibility of touch screen-based mobile devices, and that can be used on a multi-touch screen without any additional hardware buttons. Slide Rule's design is based on interviews with blind mobile device users and on user-centered design with blind people. Our study shows that users are able to complete tasks more quickly with Slide Rule than with a button-based mobile screen reader, although they make more errors. Users also prefer Slide Rule to the button-based system despite reservations about the feasibility of using touch screens and despite greater familiarity with conventional screen readers.

The results of this study indicate that Slide Rule's interaction techniques may be used to improve the accessibility of current and future touch screens. Furthermore, the performance benefits suggest that touch screens have promise as an additional input technology for blind users, and that blind users need not be cut off from this important and widespread technology.

10. ACKNOWLEDGMENTS

The authors thank Sunny Consolvo, Intel Research, and the Washington Research Foundation for equipment used in the study, and Hesham Kamel for his feedback on early prototypes.

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