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Fast track article

An evaluation of stylus-based text entry methods on handheld devices studied in different user mobility states

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ABSTRACT

Effective text entry on handheld devices remains an important user input problem. On a personal digital assistant (PDA), text entry methods traditionally support stylus-based input performed by the user's dominant hand. In this paper, we present the design of a two-handed software keyboard for a PDA which specifically takes advantage of the thumb in the non-dominant hand. We compare our chorded keyboard design to other stylus-based text entry methods in an evaluation that studies user input in different user mobility states. Our study shows that users type fastest using the mini-qwerty keyboard, and most accurately using our two-handed keyboard. We also discover a difference in input performance with the mini-qwerty keyboard between stationary and mobile states. As a user walks, text input speed decreases while error rates and mental workload increases; however, these metrics remain relatively stable in our two-handed technique despite user mobility.
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1. Introduction

Core applications on Personal Digital Assistants (PDAs), such as calendar, contacts, tasks, notes, and e-mail, require text entry from the user. Text entry is thus a basic interaction in the usage of PDAs, motivating the research and development of a broad range of novel text entry methods. Despite the existing depth in this research space, we observe two research opportunities for further investigation:

- Most of the developed input techniques have been examined only while the users are stationary. However, mobile devices are used not only while the users are sitting or standing still, but also while the users walk. We believe that researchers also should investigate text entry performance with various software keyboard designs for PDAs while users are actually *mobile*.
- Most of the developed text entry techniques support input via only the user's dominant hand. Pen-based text entry techniques on mobile devices require the use of both hands, the dominant hand for using a stylus and the non-dominant hand for holding the PDA. However, we observe that when users hold a PDA, the thumb of the non-dominant hand is still available for secondary input (as shown in Fig. 1). Thus, we believe that there is an opportunity for exploring two-handed text entry methods for mobile use.

Motivated by these two research opportunities, we investigate how existing one-handed text entry techniques designed for PDAs would compare against a two-handed software keyboard design in both stationary and mobile user states. In this article, we describe our implementation of a two-handed chorded software keyboard which uses the thumb of the non-dominant hand to select a part of the alphabet that the PDA then displays in large-sized keys to facilitate stylus-based

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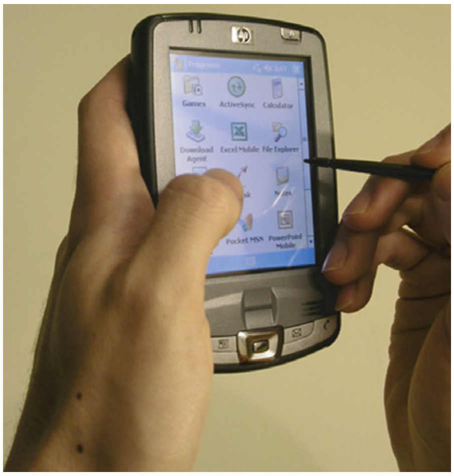

Fig. 1. A user is holding a PDA. Note that the thumb of the non-dominant hand holding the PDA is available for simple manipulations on the screen.

input. We present the details of our keyboard design and the results of the informal user study. Additionally, we discuss an evaluation that compares the speed, accuracy and subjective workload of text input using common one-handed text entry techniques and our two-handed technique in three different mobility conditions: while the user is sitting, walking and climbing stairs. From our study, we learn that users input text the fastest using the mini-qwerty keyboard and the most accurately with our chorded keyboard. However, we show that the user performance with the mini-qwerty keyboard changes with added user mobility, while performance with our two-handed design remains stable. Although the mini-qwerty keyboard was preferred over other techniques, people who are fast walkers while inputting text in our experiment preferred the chorded keyboard. These findings suggest the importance of comparing text entry techniques in different user mobility states beyond just sitting or standing still.

2. Related work

Text entry on mobile devices has been a long-studied problem in the field of Human–Computer Interaction (HCI) [2]. However, most of the proposed text entry methods are one-handed techniques. Furthermore, they have been evaluated primarily while users are stationary (*i.e.*, seated or standing). Despite the growing trend of evaluating input and output techniques on handheld devices in mobile settings, which we will discuss in this section, the performance of various text entry techniques while the user is mobile still has not been studied extensively. The goals of this project are to explore a plausible design for a two-handed software keyboard on a PDA and to compare it against existing one-handed techniques in stationary and mobile settings. As such, we will also review related two-handed interaction research.

2.1. User studies of handheld devices in mobile conditions

Users increasingly operate their handheld devices while mobile. Therefore, we believe that text entry methods need to be studied not only when users are sitting but also when they are in motion. Other researchers also share similar opinions to our belief and have conducted studies of various types of input and output techniques (excluding text entry) on small devices in mobile settings.

Barnard et al. examined the user's reading comprehension and word searching ability while both stationary and mobile [3]. Their experiment included two lighting conditions (low-light level and high-light level) and two mobility conditions (sitting and walking). They revealed that user mobility affected reading performance and subjective workload, and that lighting affected the ability to answer questions. User performance on word searches was found also to be influenced by user mobility and lighting. Mustonen et al. explored alternative measures for studying mobile phone's text legibility while walking [4]. They used natural text and pseudotext (random strings of uppercase and lowercase letters and spaces) in their visual tasks. Their experiment showed that reading normal text was generally faster than searching for a word in pseudotext, and reading velocity is clearly affected by walking. They concluded that the velocity of reading is a more sensitive and useful measure of legibility than the word search task on pseudotext.

Two projects have previously studied the comprehension of text provided through the audio channel to users who are mobile. Vadas et al. compared reading on the go with a visual display (*i.e.*, where text is displayed on a handheld device) versus with an auditory display (*i.e.*, where text is read aloud by the system using synthesized speech) [5]. Their results showed that the auditory display was more acceptable for comprehension of text in a mobile setting and user performance with the auditory display was comparable to the visual display in the walking condition. Lai et al. has examined text comprehension between synthetic and human speech while driving [6]. Their experiment included three different text types: news, e-mail, and navigation with earcon (a brief sound pattern used to represent an item or event) and three different driving conditions (parked, straight, and curved). They showed that the participants were less accurate in answering questions with synthetic speech than human speech. They also found that message types affected users' ability to accurately answer questions and that the participants answered more accurately in more difficult driving conditions.

As for studies of input behavior on handheld devices while users are mobile, previous work have focused on target selection and navigation tasks. Crossan et al. studied the correlation between the timing of input occurrence on a PDA and the gait phase; they showed that the gait phase influences the accuracy of input in selection tasks [7]. MacKay et al. compared three software-based navigation techniques under different levels of user mobility; they found that conventional scrollbar navigation was less effective and the participants experienced high difficulty in navigation with scrollbars in a mobile setting [8]. Marentakis and Brewster investigated the effect of feedback, mobility and index of difficulty on a deictic spatial audio target acquisition task [9]. They discovered that spatial audio target acquisition abides by Fitts' law models and that audio feedback does not influence users' workload or walking speed. Zucco et al. evaluated user performance on a drag-and-drop task with the four wearable pointing devices while each participant was stationary and walking [10]. This study showed that overall a touchpad and a trackball offer better performance on selection and drag-and-drop tasks than a gyroscopic mouse and a Twiddler mouse.

Although previous work have examined interaction techniques or user experience in a mobile setting, several research problems remain unexplored or have not been investigated thoroughly yet. For instance, interaction techniques for selecting items from a linear list while the user is mobile have not been explored deeply even though they are commonly used in many handheld devices such as a mobile music player. Likewise, with the exception of a few projects, the effectiveness of mobile text entry methods has not been thoroughly examined yet.

Mizobuchi et al. studied the relationship between walking speed and text input task difficulty [11]. Their experiment asked participants to enter text using four different mini-qwerty keyboards which varied in key sizes. Their results showed that users had difficulty with text entry on a keyboard with the key size smaller than 3 mm in terms of both the entry speed and the accuracy. Hoggan et al. evaluated the effectiveness of tactile feedback on mobile touch-screen devices. They compared two kinds of software QWERTY keyboards with tactile feedback against a physical QWERTY and a software QWERTY keyboard without tactile feedback [12]. They conducted their study in a laboratory as a stationary setting and in a subway as a mobile setting. They found that added tactile feedback in software keyboards significantly improves user performance in both stationary and mobile settings. Although their study examined text entry methods like ours, their evaluation was focused solely on the QWERTY layout keyboard.

Our review of the existing work suggests room for further research in mobile text entry methods. Thus, one goal of our work is to evaluate the performance of different text entry methods in different user mobility states. Additionally, we aim to determine specific design features that best support mobile text entry.

2.2. Two-handed interaction techniques

Many human activities involve the use of two hands; thus, it is a straightforward idea to integrate two-handed interaction techniques into the user interface for computers [13]. A good example of user interfaces on mobile devices which enable users to use both hands concurrently is a peephole display [14]. In a peephole display, the information is spread out on a flat virtual workspace larger than the screen of the mobile device. The device can measure its own inertial movements, which allows the user to explore the information space by moving the mobile device physically as if her display was a 'peephole' on the space. Blasko et al. also have integrated spatial awareness into a tablet PC [15]. Their tablet PC detects its orientation relative to the user by a method based on computer vision or the pose of the stylus.

There have been only a few studies of two-handed text entry methods on mobile devices. These previous projects, such as Gopher and Raij's two-handed chorded keyboard [16], have been designed for physical keyboards, which are not available on many PDAs. Additionally, mobile devices do not usually allow users to use both hands concurrently. When the user holds a PDA with the non-dominant hand, this eliminates the free movement of the non-dominant hand. However, as previously mentioned, we believe that simple manipulations or gestures are possible using the available thumb of the non-dominant hand as it holds the PDA. There have been several projects which explore thumb-based interaction on mobile devices [17,18]. One of the most similar research projects to ours is Dual Touch [19]. Dual Touch also allows the user to input with both a stylus and the thumb of the non-dominant hand, and offers several kinds of manipulations on PDAs. However, text entry has not been demonstrated in Dual Touch.

3. Design of two-handed keyboard

In this section, we describe our implementation of a two-handed chorded software keyboard for PDAs. We applied a technique similar to the method used in Dual Touch to support two-handed text entry. Using an iterative design process, we first developed and tested two early prototypes of the two-handed keyboard, as shown in Fig. 2. We use the results of a preliminary evaluation of these prototypes to inform the development of a version that we evaluated against existing stylus-based text entry methods on PDAs.

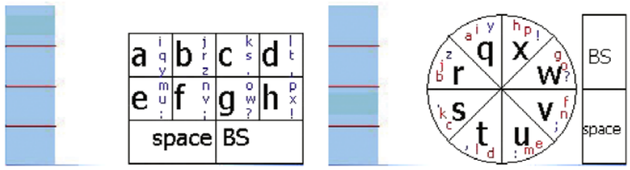

Fig. 2. Our initial prototypes of the two-handed keyboards: (left) square keyboard layout; (right) circular pie layout.

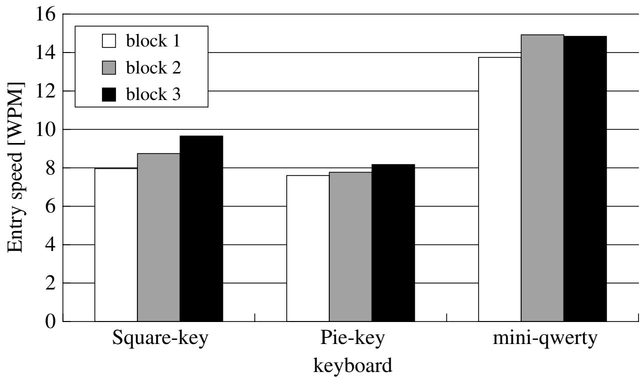

Fig. 3. Text entry speed in the pilot study.

3.1. Initial keyboard designs

Karlson et al. have previously shown that it is hard for the user to perform a complicated manipulation or gesture with the thumb while holding a PDA [17]. Moreover, because of the shape of the thumb, it is difficult for the user to press precise points on the screen with the thumb. Therefore, we designed the interactions required of the thumb to be only simple movements (*e.g.*, dragging upward or downward). Furthermore, our technique operates under the assumption that input with the thumb always precedes input with a stylus and that the user will only place that thumb within the predefined region (a long and thin rectangle) on the screen. By sliding the thumb up and down this region, the user controls which text keys to display on the right-hand portion of the input widget. Fig. 2 shows two ways of displaying the text keys through a square key layout and through a circular pie layout.

All versions of our keyboard used the same method for recognizing concurrent input from the non-dominant hand's thumb and a stylus. When the interface receives input within this region, it interprets these actions as "thumb placed" events. When the user presses the stylus outside of the region after a "thumb placed" event, the PDA reports the midpoint between the thumb and the stylus. Our system recognizes that the user has performed a concurrent input and estimates the point where the stylus is placed. As Yee reported in his method for recognizing simultaneous input from the stylus and a finger [20], the PDA does not always report the actual midpoint between the two points selected during concurrent input. Therefore, we gathered examples of simultaneous input and manually calibrated our system based on these samples to estimate more precisely the point of input by the stylus.

3.2. Pilot study

We asked four users to use and compare our prototypes against the mini-qwerty keyboard while seated. Our goal in this pilot study was to get user feedback about using both hands for text entry and to learn what we should avoid in designing the interface for our technique. The order of the three text entry techniques was randomly presented to each participant. For each input technique, the participants were given a practice block followed by three real blocks in which they were asked to type four short phrases as quickly and accurately as possible. The short phrases of text were selected randomly from MacKenzie's English phrase dictionary [1]. After the user study, an interview with the participants was held.

3.3. Results

Fig. 3 shows the entry speed on the three keyboards used in the pilot study. As shown in Fig. 3, the participants were faster with mini-qwerty keyboard than the proposed two-handed methods. However, three of the participants preferred the square key method the most. The post-experimental interview revealed additional insights.

- The participants found that the concurrent usage of the stylus and the thumb of the non-dominant hand to be generally acceptable. The intended movement of the non-dominant hand's thumb in our keyboard designs may not have been a

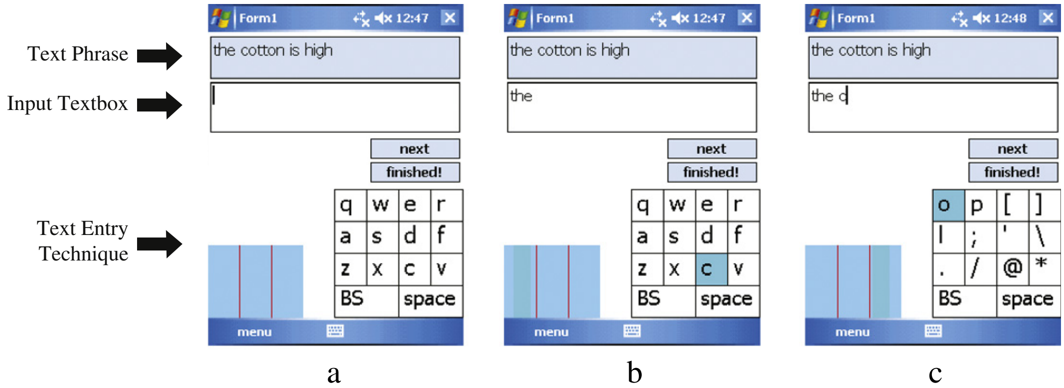

Fig. 4. (a) Screen shot of the PDA screen of our two-handed chorded keyboard (for right-handed users); (b) While the user inputs ‘C’ on the two-handed chorded keyboard the interface highlights the position of the non-dominant hand’s thumb and the ‘C’ key; (c) The user enters an ‘O’. Note that the keys change with the new location of the thumb.

familiar action for our participants; however, all the subjects reacted positively to this use. They commented that complex or fine-grained manipulations with their thumbs would be difficult to perform, but accepted the usage of the thumb required by our two-handed keyboards.

- The participants preferred our prototype to the QWERTY keyboard despite the slightly slower text entry speed. All the participants regularly use desktop or laptop computers and have a strong familiarity with the QWERTY. As a result, they entered text fastest using the mini-qwerty keyboard, second fastest using the two-handed square keyboard, and slowest using two-handed circular pie keyboard. However, most of the participants preferred our prototypes to the mini-qwerty keyboard despite the slower entry speed. Because the participants were more familiar with square layouts than circular pie layouts, more preferred the two-handed square keyboard than any other design. Moreover, the participants also preferred the backspace and the space keys at the bottom on the square keyboard design than the right edge of the screen in the circular pie layout because they commented that they sometimes hit the backspace key inadvertently when they moved the stylus back to the edge.
- The participants’ familiarity with the QWERTY layout can be integrated into the square keyboard design. As mentioned above, people who use desktop or laptop computers regularly already have a mental model of the QWERTY layout. Furthermore, one participant suggested adopting the QWERTY layout in our two-handed keyboard. Such a design could potentially reduce the time to learn this technique.

3.4. Revised keyboard design

Using the findings from the pilot study, we developed another version of the two-handed chorded software keyboard as shown in Fig. 4. The new keyboard splits the mini-qwerty layout into three parts. Initially, the interface displays the left part of the mini-qwerty layout on the right side of the screen. The left side of our two-handed keyboard contains a blue rectangular input region also divided into three sub-regions. Each sub-region in the blue rectangle is associated with a part of the mini-qwerty layout. To change the part of the mini-qwerty layout displayed on the right side of the interface, the user slides the thumb of the non-dominant hand along this blue rectangle. For example, when the user wants to enter the letter ‘O’, she slides the thumb to the rightmost sub-region of the blue rectangle. Then, the right part of the mini-qwerty keyboard is shown. She then taps the key with the letter ‘O’ with the stylus. The interface highlights where the thumb is placed and which key is pressed, as shown in Fig. 4 (c). As we mentioned before, this interface emulates multi-touch detection; thus, the user does not need to release the thumb before tapping the letter ‘O’ with the stylus. For the left-handed users, our two-handed keyboard displays the blue region on the right side of the interface and the text keys on the left.

4. User study

In this section, we describe our study evaluating the performance of different text entry techniques for the PDA in different user mobility states. This study included four different text entry methods:

1. mini-qwerty (a one-handed key-based text entry method, Fig. 5 (a)),
2. hand-writing recognition (Fig. 5 (b)),
3. quikwriting [21] (a gesture-based text entry method, Fig. 5 (c)), and
4. our two-handed chorded keyboard described above.

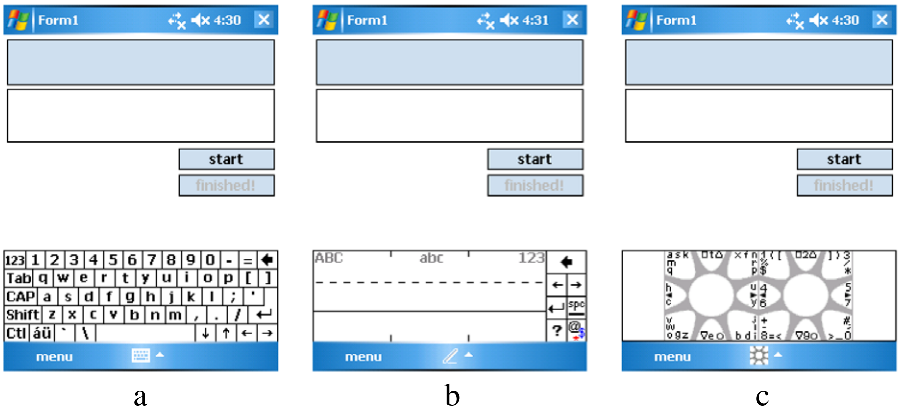

Fig. 5. Text entry methods used in the experiment: (a) mini-qwerty, (b) hand-writing, and (c) quikwriting.

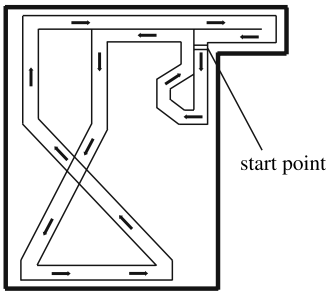

Fig. 6. The path used in *Walking* condition.

Although our chorded keyboard is still in its early exploratory stage, we include it in this study as the means for gaining an initial understanding of the advantages and problems involved in a two-handed technique in comparison to one-handed techniques. These findings in turn can inform the future design of improved two-handed techniques.

We evaluated all four text entry techniques in each of the following three mobility conditions:

- *Sitting*: We asked the participants to input text while remaining seated.
- *Walking*: We asked the participants to input text while walking along a designated path within a single room in our laboratory.
- *Stairs*: We asked the participants to input text while going up or down some stairs.

In the *Sitting* condition, the participants sat at a table in our laboratory. We instructed them to remain seated until they completed all given tasks.

In the *Walking* condition, we asked participants to follow a path (38.8 m long and 50 cm wide) drawn with colored tape on the floor, as shown in Fig. 6. Our path is similar to the one used by Vadas et al. [5]. At the start of this condition, we explained to participants how to follow the path. We asked them to try to maintain a comfortable pace, and should keep walking while staying inside the path as much as possible. Participants were allowed to slow down or speed up at any point.

The *Walking* condition allows us to evaluate text entry while the user is mobile. However, in a real walking situation, the user must sometimes devote some attention to the environment. Examples of situation where the user must pay attention to their path includes users walking along uneven surfaces, moving through crowded places, and climbing stairs. As a result, we included the *Stairs* condition which involved a curved stairway which spanned across two stories in our building. In total, there were 36 steps. We asked the participants to walk only up or down stairs for each trial (that is, three trials involved going up stairs and three trials involved going down stairs). They could slow down or speed up at any point, and they could stop if they perceived danger (Figs. 7 and 8).

4.1. Hardware and software platforms

We used an HP iPAQ hx2790 Pocket PC as the base platform which ran all the software techniques studied in our evaluation. In each trial of this study, the PDA displayed a short phrase (explained later) at the top of the screen. We asked participants to input the phrase into a second textbox as accurately as possible. The text entry technique was shown at the bottom of the screen. The software recorded the participants' input (including backspaces) with timestamps.

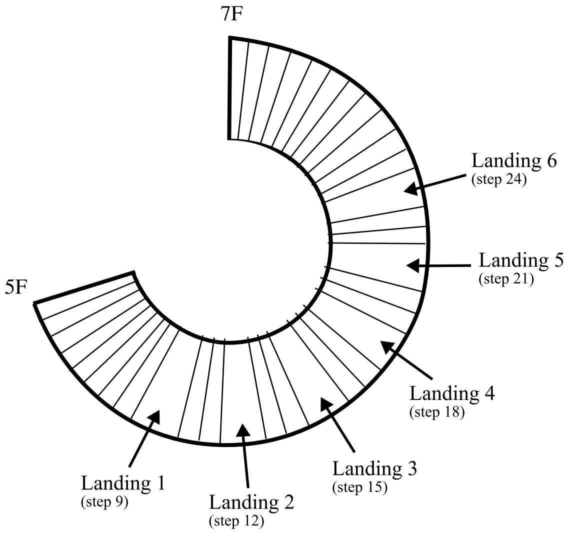

Fig. 7. The stairs used in the *Stairs* condition. There were six small landing spaces at the 9th step, the 12th step, the 15th step, the 18th step, the 21st step, and the 24th step.

Fig. 8. (left) A participant walking inside a path while entering text phrases during the *Walking* condition; (right): A participant climbing up/down stairs while entering text phrases during the *Stairs* condition.

4.2. Participants

We recruited twelve participants for this study and paid each with a $10 gift certificate after the experiment. We did not control any demographic factors (*e.g.*, gender or age). The participants ranged from 20 to 35 years; 11 were male and 1 was female. All the participants were right-handed.

Of the 12 participants, 3 had never used a PDA before this study. Of the nine people who previously had used a PDA, seven were familiar with inputting text using either the mini-qwerty keyboard or hand-writing recognition. Additionally, five participants who had used a PDA occasionally do so while walking. Two participants had experience with quikwriting before this study.

4.3. Procedure

The study began with an explanation of the experimental procedure. We also explained the NASA-TLX forms [22] which would be given to them after each trial to assess subjective workload. We then administered a questionnaire to gather background information on their familiarity and use of mobile devices. Next, we let the participants practice the four text entry methods on the PDA until they became comfortable with each technique. For the mini-qwerty technique and handwriting, the participants could skip the practice session if they already felt comfortable with these methods.

After the participants completed the practice sessions, they began the actual experiment. We used a within-subjects experimental design, where all the participants used all four text entry techniques in all three mobility conditions. The

Table 1
Examples of the phrases (taken from MacKenzie's English phrase dictionary [1]) which were used in the experiment.

He is just like everyone else
The world is a stage
The power of denial
The force is with you
The facts get in the way

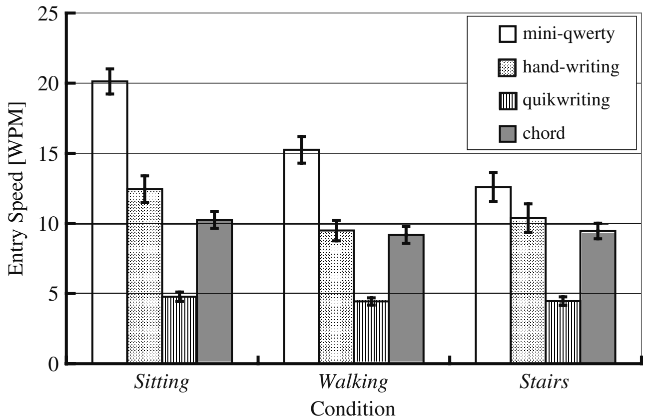

Fig. 9. Entry speed for the four input methods in the different mobility conditions. In this and all later charts, the error bars represent 95% confidence intervals.

order of the mobility conditions was counterbalanced and the order of the text entry methods for each mobility condition was randomly determined.

For each mobility condition, we asked the participants to use one of the four text entry methods to enter six text phrases, displayed one at a time, at the top of the screen. They were instructed to type the phrases such as the ones shown in Table 1 as quickly and accurately as possible. The short phrases of text were selected randomly from MacKenzie's English phrase dictionary [23,1]. These phrases are designed to be used in the evaluation of various text entry methods; they are moderate in length (16–43 letters with 28.6 letters in average), easy to remember, and representative of English sentences. Once a participant had finished entering the six text phrases, we administered a NASA-TLX questionnaire. Then, we asked the participant to enter the six different text phrases with the next entry technique until she had used all the four methods. The participant then repeated the same procedure until she has completed all three mobility conditions. Thus, each participant entered 72 different text phrases in total.

At the end of the study, we asked the participants to fill out a questionnaire. At this time, participants also shared any comments they had about their experience during this study.

5. Results

In this section, we present the findings from our study, including the participants' input speed and error rates for each entry technique. We also describe how the different techniques affected the users' mental workload and walking speed. Finally, we discuss the users' preference of the text entry methods studied.

5.1. Text entry speed

Fig. 9 shows the entry speed for the four input methods in the three mobility conditions. The entry speed was calculated based on the standard WPM (words per minute), which is generally calculated as [characters per second] times 60/5.

In order to know whether there exists any significant difference among multiple elements, we used an analysis of variance (ANOVA), followed by Tukey's pairwise comparison test. There are statistically significant differences ($p < 0.05$) between the mini-qwerty keyboard and the other entry methods, between hand-writing and quikwriting, and between the chorded keyboard and quikwriting in the *Sitting* and *Walking* conditions. There are significant differences ($p < 0.05$) between quikwriting and the other entry methods, and between the mini-qwerty and the chorded keyboard in the *Stairs* condition.

5.2. Error rate

We measure errors in each phrase as the number of backspace key presses and the number of the remaining errors in the entered phrase. Then we calculate the error rate as the number of occurrence of errors divided by the length of the given

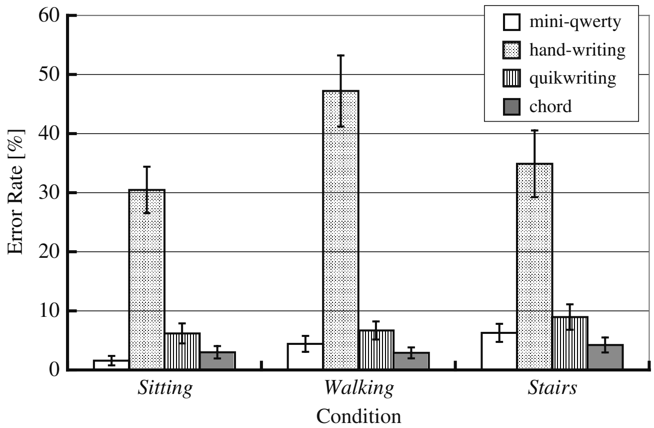

Fig. 10. Average error rate for each text entry across the three mobility conditions.

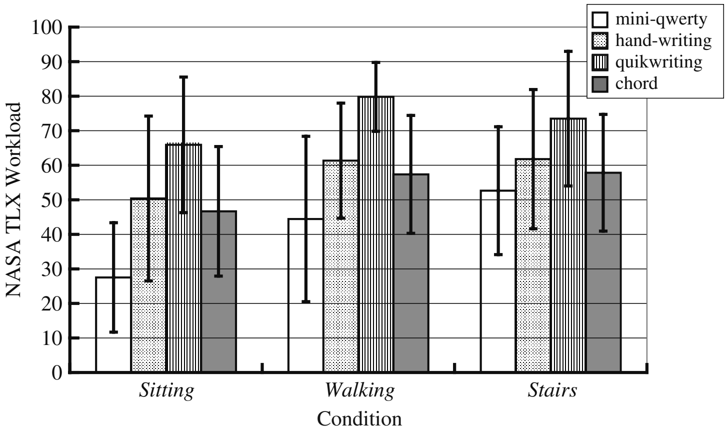

Fig. 11. NASA-TLX workload for the four input methods in the different mobility conditions.

phrase. Fig. 10 shows the error rate for each mobility condition. Although the mini-qwerty keyboard is the least error-prone technique in the *Sitting* condition, the two-handed chorded technique was the least error prone in the mobile conditions.

The ANOVA test followed by Tukey's test showed statistically significant differences ($p < 0.05$) between hand-writing and the other text entry methods in all three mobility conditions. Furthermore, statistically significant differences ($p < 0.05$) exist between the mini-qwerty keyboard and quikwriting in the *Sitting* condition, and between the chorded keyboard and quikwriting in the *Walking* condition.

5.3. NASA-TLX workload

Fig. 11 shows the overall workload ratings. Here, we also used the ANOVA test followed by Tukey's test for the pairwise comparisons. Statistically significant differences ($p < 0.05$) exist between the mini-qwerty keyboard and quikwriting in the *Sitting* condition. Statistically significant differences ($p < 0.05$) exist between the mini-qwerty keyboard and quikwriting, and between the chorded keyboard and quikwriting in the *Walking* condition. However, no significant difference exists in the *Stairs* condition.

Overall, this reveals that quikwriting required a higher workload than the other three techniques while the mini-qwerty keyboard and then our two-handed chorded keyboard involved the lowest amount of mental workload. This is perhaps due to the users' familiarity with the QWERTY layout and lack thereof with the quikwriting interface. The problems often associated with hand-writing recognition led to the high workload demand for that technique.

5.4. Walking speed

Based on the measured distances and times recorded during the *Walking* condition, we calculate the approximate walking speed of the participants. Fig. 12 shows the participants' normal walking speed and their walking speed in the *Walking* condition. We defined fast walkers as the seven participants who walked faster than the group's average and defined slow walkers as the five remaining participants. Overall, however, we observed that everyone walked slower while inputting text.

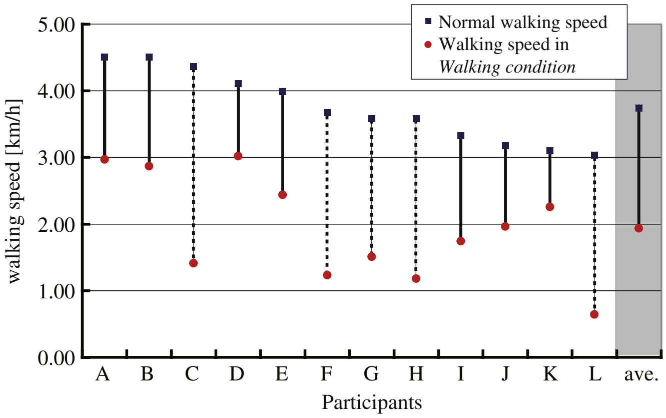

Fig. 12. The walking speed for each participant in the *Walking* condition. A blue square and a red circle represent the average normal walking speed and the average walking speed in the *Walking* condition, respectively. A rigid line stands for a fast walker and a dashed line stands for a slow walker.

Table 2
Preferences on the text input methods. (C1 = *Sitting* condition, C2 = *Walking* condition, C3 = *Stairs* condition).

	Fast walker			Slow walker			All		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
Mini-qwerty	3.9	3.4	3.3	3.8	3.4	3.0	3.8	3.4	3.2
Hand-writing	2.7	2.7	2.1	3.2	3.2	3.6	2.9	2.9	2.8
Quikwriting	1.1	1.1	1.3	1.0	1.0	1.2	1.1	1.1	1.3
Chorded	2.3	2.7	3.3	2.0	2.4	2.2	2.2	2.6	2.8

5.5. *Preference*

In the questionnaire at the end of the study, we asked the participants to rank the four input methods according to preference, with 4 being best, and 1 being worst. Table 2 shows the preferences of the four text entry methods. The bold values means that the method was preferred the most. Averaged over all participants and all the conditions, the mini-qwerty keyboard was preferred the most. However, the preference was varied in the *Stairs* condition; fast walkers split between mini-qwerty and chorded, and slow walkers preferred hand-writing.

6. Discussion

Entering this study, we had two goals.

(1) We wanted to explore how a two-handed text entry technique would compare to existing techniques. Using rapid prototyping and iterative design, we learned from a preliminary evaluation that participants were comfortable with a two-handed technique in which the thumb of the non-dominant hand would not be used for complex or fine-grained selection tasks. The preliminary evaluation also helped us identify an appropriate layout for a two-handed design that could be used in a more structured comparison study against existing techniques. However, we wanted to learn further the advantages and problems users would have with a two-handed text entry technique in order to inform the design of future methods.
(2) We wanted to study if user performance differed between conditions where the participants were stationary or mobile; this finding would reveal if text entry techniques for mobile devices could be evaluated only in a stationary setting.

Overall, this study shows that mobility impacts the user's text entry ability with respect to input speed, accuracy, and mental workload. As a user walks, input speed generally decreases while the error rate and mental workload increases. Although this finding is not surprising, it suggests that it is important to evaluate a text entry technique for a handheld device in a mobile setting. In the following sections, we will discuss each of the text entry methods in the experiment.

6.1. *Discussion on mini-qwerty*

As shown in Fig. 9, the mini-qwerty keyboard was the fastest entry method in all mobility conditions. All the participants use desktop or laptop computers regularly. Therefore, they are familiar with the QWERTY keyboard layout, which allowed them to use the mini-qwerty keyboard more efficiently. However, in the *Stairs* condition, no significant difference exists between the mini-qwerty keyboard, hand-writing and our chorded keyboard. Climbing stairs required the participants to pay more attention to the environment and made it difficult to hold the PDA steady.

Participants commented that it was difficult for them to use the mini-qwerty keyboard in the mobile conditions because the keys were too small to press accurately. Text entry using the mini-qwerty method while the user was mobile resulted in a significant increase in occurrence of errors in comparison to the sitting condition (see Fig. 10). Some of the participants rested their hands at the corner of the device to try to achieve a more accurate pointing (we will discuss this point further in the *Other Design Implications* section).

6.2. Discussion on hand-writing

Hand-writing was the most error-prone text entry method across all the mobility conditions. In particular, four participants experienced great difficulty entering specific characters, such as 'f', 'i' or 't'. These participants often must enter the same character several times. Furthermore, while they were mobile, their hand-written characters typically became more ambiguous and harder for the recognizer to interpret correctly.

Interestingly, hand-writing was preferred by the slow walkers in the *Stairs* condition. This technique employs the user's actual hand-written text as input, which requires less visual attention than the other methods used in this study. This allowed them to pay more attention to the environment in the mobile conditions, which enhanced their mobile experience.

6.3. Discussion on quikwriting

The quikwriting technique was not as successful as the other entry methods. Participants had more difficulty learning to use quikwriting than the other methods. Most participants commented that they could not memorize the layout. As a result, they exerted a significant effort performing visual searches for letters required to enter the specified text. In the mobile conditions, visual search became even harder to perform because participants also needed to pay attention to the environment. However, some of the participants told us that they would like to use an easier stroke-based text entry method while they are mobile. This comment implies that a stroke-based text entry method would provide better experiences for expert users if it would require less visual attention. However, recognition errors would still remain an important design consideration.

6.4. Discussion on two-handed chorded keyboard

The two-handed chorded keyboard was the best entry method in terms of the accuracy although we could not find any statistically significant difference between it and the other techniques. However, this result is promising for the two-handed chorded keyboard because several of the participants had extensive prior experience with mini-qwerty. In particular, the two-handed chorded keyboard supported less error-prone text entry in the mobile conditions. It provides larger keys than the mini-qwerty keyboard, which allowed the participants to select keys more accurately. Furthermore, the workload of the chorded keyboard was comparable to that of hand-writing. The chorded keyboard required the participants to use both hands actively; thus, the physical demand was higher than hand-writing. However, hand-writing was more error prone, which frustrated the participants more.

Participants had a slower input speed using the two-handed chorded keyboard than the mini-qwerty keyboard and hand-writing. This contributed to the lower overall preference for the chorded keyboard for the rest of our participants. However, the two-handed chorded keyboard tied with mini-qwerty as the preferred input method of fast walkers in the *Stairs* condition. For these participants, their walking speed makes text entry on the PDA challenging in general. For example, despite the advantage of not requiring users to perform visual search to enter text, hand-writing became less robust and required the attention of the fast walkers to confirm whether characters had been entered correctly. The keys in the mini-qwerty keyboard were too small for the users to hit while climbing stairs. Our chorded keyboard offered larger keys than the mini-qwerty keyboard and a familiar layout to the common QWERTY keyboard. Thus, fast walkers had a better experience with the two-handed chorded keyboard than with other methods in the *Stairs* condition.

Overall, we did not give the participants enough practice with our two-handed chorded keyboard in order to be experts with the technique in this study. However, we expect that users would input text using our keyboard better than that observed in the experiment when given a sufficient amount of practice. Still, we expect that users would input text slightly slower with this method compared to the mini-qwerty keyboard because our keyboard requires an additional movement of the thumb to enter a letter. Nevertheless, input using our keyboard could be faster than the mini-qwerty keyboard in mobile conditions because the input rate with our keyboard would be similar across the different mobility conditions. Alternatively, the input rate using mini-qwerty becomes slower in mobile conditions as shown in Fig. 9. We also believe that we can apply a layout based on the frequency of characters to the two-handed keyboards, such as FrogPad [24] in order to optimize the input rate.

6.5. Other design implications

We observed that some of the participants often rested their dominant hand on the PDA below the screen (specifically, at the bottom-right corner of the device for right-handed users, or the bottom-left corner for left-handed users) to stabilize their hand while they used the device. In the hand-writing condition, the input region lies in the middle of the bottom part of the screen. The specific size and position of this input region allowed users to easily point at it using a stylus held in their dominant hand (rested at the bottom corner of the device). Furthermore, without needing to lift their hand from the PDA, users would then simply slide the stylus within this input region to input text. These participants commented that keeping their dominant hand steady on the PDA while they were walking was important. This finding implies that the input region for a text entry method should be an appropriate size within the reach of the stylus held in the dominant hand which most likely would be rested at a bottom corner of the device. The input region also should be large enough for a user to input characters accurately as well.

We also observed during our study that the PDA's slippery surface may affect the performance on text entry with a stylus in mobile conditions. The current surface of the display of a handheld device may have been designed so that the user can move the stylus on the surface smoothly. However, while the user is in motion, this property makes input more unstable, which would lead to the decrease in the performance for the mini-qwerty and hand-writing methods. One possible solution to this problem is to add physical constraints to the input region, such as with EdgeWrite [25], so that the user can stabilize their input easily even when they are mobile.

7. Conclusions and future work

Text entry methods on mobile devices remain a challenging issue in the field of HCI. A broad range of text entry methods have been developed thus far; however, the design of two-handed keyboards on mobile devices has not been investigated thoroughly. We explore the design of a two-handed software keyboard for a PDA and compare it against existing one-handed text entry techniques. Our two-handed chorded keyboard supports concurrent input using a stylus and the thumb of the non-dominant hand. Whereas previous studies have evaluated many techniques in a stationary situation, we compared our technique to others also in the two mobile conditions.

This study shows that participants were able to more accurately perform text entry with our two-handed chorded keyboard while they were mobile than the other studied techniques. Additionally, this study shows that mobility impacts user's input speed, accuracy and mental workload. This suggests that text entry techniques must be evaluated in more than just the sitting condition. Overall, the participants found the idea of our two-handed chorded keyboard generally acceptable even in the mobile conditions. We also discovered that people with different walking speeds preferred different input techniques. Specifically, the chorded keyboard was preferred by the fast walkers although improvements on the design of the chorded keyboard remain necessary to produce faster entry speed. We also believe that our two-handed interaction technique can be extended to other tasks, such as selection or navigation.

In this study, we used short text phrases because most of the text entry tasks on handheld devices involve inputting of a small number of words per tasks (such as adding contact information or calendar events). We did not focus on the performance by expert users of the different input techniques in the three mobility conditions. We plan to study this issue further in future work. Additionally, although our chorded keyboard is still in its early exploratory stage, its evaluation still enabled us to gain an initial understanding of the advantages and problems involved in a two-handed technique in comparison to one-handed techniques. These findings provide insights for the future design of improved two-handed techniques.

Finally, we measured participants' subjective workload using the NASA-TLX indices, but objective estimation of physical workload might be possible through sensors, such as accelerometers or motion trackers. However, sensors usually must be placed on participants' body, which might be intrusive to the experiment. We will explore more practical methods for measuring users' physical workload while they are mobile.

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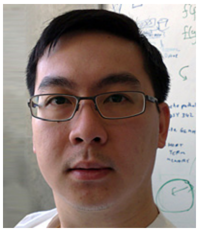

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