An Evaluation of Stylus-Based Text Entry Methods on Handheld Devices in Stationary and Mobile Settings

Koji Yatani and Khai N. Truong
University of Toronto
Department of Computer Science
Toronto, ON M5S 3G4 Canada
+1 (416) 978-4761
{koji, khai} @ dgp.toronto.edu

ABSTRACT
Effective text entry on handheld devices remains a significant problem in the field of mobile computing. On a personal digital assistant (PDA), text entry methods traditionally support input through the motion of a stylus held in 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 both stationary and mobile settings. Our study shows that users type fastest using the mini-qwerty keyboard, and most accurately using our two-handed keyboard. We also discovered a difference in input performance with the mini-qwerty keyboard between stationary and mobile settings. 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.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – Input devices and strategies, Interaction styles; H.1.2 [**Models and Principles**]: User/Machine Systems – Human Factors.

General Terms
Experimentation, Human Factors, Design.

Keywords
Text entry, Two-handed interaction, PDAs.

1. INTRODUCTION
Although recent handheld devices continue to integrate more functionality, such as cameras or presentation material viewers, the primary features of Personal Digital Assistants (PDAs) still remain the calendar, contacts, tasks, notes, and e-mail applications, all of which deeply involve 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 input methods. Despite this already thorough exploration, we observe two opportunities for further investigation:

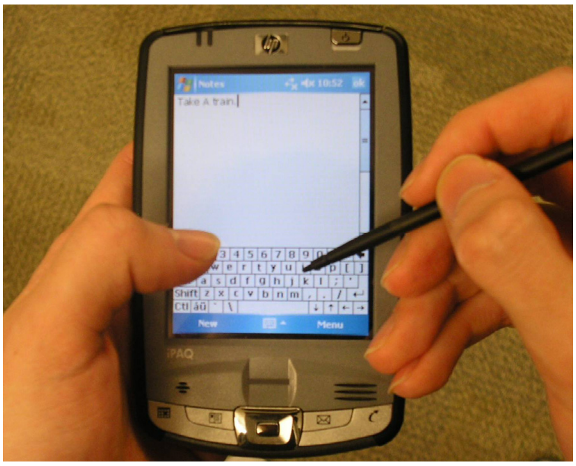

Figure 1. A user is holding a PDA. Note that the thumb of the non-dominant hand holding the PDA is available for simple manipulations on the screen.

1. Most of the developed text entry techniques support input via only the user's dominant hand. These techniques vary in input space, and thus leverage different motor skills. For example, the mini-qwerty keyboard requires users to click small keys, while quikwriting [13] requires users to gesture between a small number of larger-sized zones to input text. We observe however that when users hold a PDA with the non-dominant hand, the thumb of the non-dominant hand is available for secondary input (as shown in Figure 1). We believe that a two-handed keyboard can be designed to support simultaneous input through a stylus and the thumb of the non-dominant hand.
2. Most of the developed input techniques have been examined only while the user is stationary. However, mobile devices are used not only while the user is sitting or standing still, but also while she is walking. We believe that researchers

also should investigate user text entry performance with various software keyboard designs for PDAs while users are actually *mobile*.

Motivated by these two research opportunities, in this study 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 settings. In this paper, we describe our implementation of a two-handed chorded software keyboard which uses the thumb to select a part of the alphabet to display in large-sized keys for easy stylus-based 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 mental workload of text input using common one-handed text entry techniques and our two-handed method in three different scenarios –while the user is sitting, walking and climbing stairs. In our study, we learn that users input text fastest using the mini-qwerty keyboard and most accurately with our chorded keyboard. However, we showed that the users' 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 generally preferred over other techniques, people who walk faster while inputting text preferred the chorded keyboard. These findings suggest the importance of comparing text entry techniques in a mobile setting 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) [7]. However, most of the proposed text entry methods are one-handed techniques. Furthermore, they have been evaluated only when users are stationary (*i.e.*, seated or standing). Despite the growing trend of studying input and output techniques on handheld devices in mobile settings, which we will discuss in the section, these studies have not focused on user performance with various text entry techniques in mobile settings. The goals of this project are to explore how we can design 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 a Mobile Setting

Users increasingly operate their handheld devices in a mobile setting. Therefore, we believe that text entry methods need to be studied not only when users are sitting but also when they are walking and going up/down stairs. 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. Vadas *et al.* compare the users' ability to read on the go using an auditory display (*i.e.,* listening to some text through synthesized speech) and a visual display (a display on a hand-held device) [15]. Their results showed that the auditory display was more acceptable for comprehension of text in a mobile scenario and the performance with the auditory display was comparable to the visual display in the walking condition. Mustonen *et al.* [11] examined alternative measures for studying mobile phone's text legibility while walking. They used reading and pseudo-text as visual tasks and discovered that reading speed is a more sensitive and useful measure of legibility in the mobile scenario.

As for input behavior on handheld devices in a mobile setting, there are several pieces of work 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 [3]. 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 a user experienced high difficulty in navigation with scrollbars in a mobile setting [6]. Marentakis and Brewster investigated the effect of feedback, mobility and index of difficulty on a deictic spatial audio target acquisition task [8]. 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 [18]. This study shows that overall a touchpad and a trackball offer better performance on selection and drag-and-drop tasks.

However, text entry methods in a mobile setting have not been thoroughly examined yet. Mizobuchi *et al.* studied the relationship between walking speed and text input task difficulty [10]. They used four different sizes of keys in the mini-qwerty keyboard. 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. Although their study was focused on text entry methods like ours, their methods were limited to the QWERTY layout keyboard.

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 [2]. A good example of user interfaces on mobile devices which enable users to use both hands concurrently is a peephole display [16]. 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 allow users to explore the information space by moving the mobile device physically as if their display works as a "peephole" on the space. Blasko *et al.* also have integrated spatial awareness into a tablet PC [1]. Their tablet PC detects its orientation relative to the user by a method based on computer vision or a method based on the pose of the stylus.

With the exception of only a few projects, there have been only a few studies on two-handed text entry methods on mobile devices. These previous studies, such as work by Gopher and Raij [4] where a two-handed chorded keyboard was examined, have focused on physical keyboards, which are not available on many PDAs. Additionally, mobile devices do not usually allow users to use both hands concurrently. When a 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

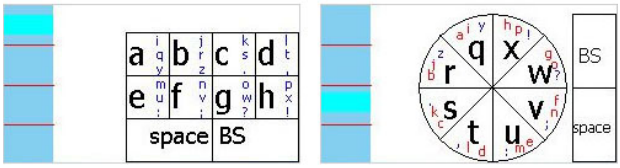

Figure 2. Our initial prototypes of the two-handed keyboards: (left) square keyboard layout; (right) circular pie layout.

interaction on mobile devices [5, 12]. One of the most similar research projects to ours is Dual Touch [9]. Dual Touch also allows users to input with both a stylus and the thumb of the non-dominant hand, and offers several kinds of manipulations on PDAs.

We applied a technique similar to the method used in Dual Touch to support two-handed text entry. Our technique operates under the assumption that input with the thumb always precedes input with a stylus and that the users will only place that thumb within the predefined region (a long and thin rectangle in our system) of the screen. Therefore, when the interface receives input within this region, it interprets these as "thumb placed" events. When the user presses the stylus outside of the region after a "thumb placed" event, the input point jumps out of this region and 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 [17], 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 the stylus.

3. DESIGN OF TWO-HANDED KEYBOARD

In this section, we describe our implementation of a two-handed keyboard for PDAs. Using an iterative design process, we first developed and tested two early prototypes of a two-handed keyboard, as shown in Figure 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. All versions of our keyboard used the same method to recognize concurrent input from the non-dominant hand's thumb and a stylus, which we described in the previous section.

3.1 Initial Keyboard Layouts

Karlson *et al.* showed that it is hard to perform a complicated manipulation or gesture with the thumb while holding a PDA [5]. Moreover, because of the shape of the thumb, it is difficult for users to press precise points on the screen with the thumb. Therefore, we designed the thumb motion interaction to involve only simple movements (*e.g.*, dragging upward or downward). This design controls which text keys to display on the right hand portion of the input widget. Figure 2 shows two ways of displaying the text keys – through a square key layout and through a circular pie layout.

We asked four users to use and compare our prototypes against the mini-qwerty keyboard while seated. We obtained several insights from this preliminary evaluation.

- **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 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 this usage of the thumb in our particular design.
- **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 strongly 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.

3.2 Revised Keyboard Design

Using the findings above, we developed another version of the two-handed chorded software keyboard as shown in Figure 3. The blue rectangle on the left-bottom of the screen represents the input region for the thumb of the non-dominant hand. A portion of the mini-qwerty keyboard is displayed on the right side of the screen. Initially, the interface shows the left portion of the mini-qwerty layout. The position of the thumb of the non-dominant hand in the blue region determines the portion of the mini-qwerty keyboard that should be displayed. For example, when the user places the thumb in the right-most region of the blue box, the right portion of the mini-qwerty keyboard is shown, like in Figure 3 (c). The interface highlights where it detects the thumb has been placed and which key is pressed. For the left-handed users, the interface displays the blue region on the right-bottom of the screen and text keys on the left side of the screen.

4. USER STUDY

To gain a deeper understanding of the appropriateness of our two-handed keyboard as a potential text entry technique for PDAs, we

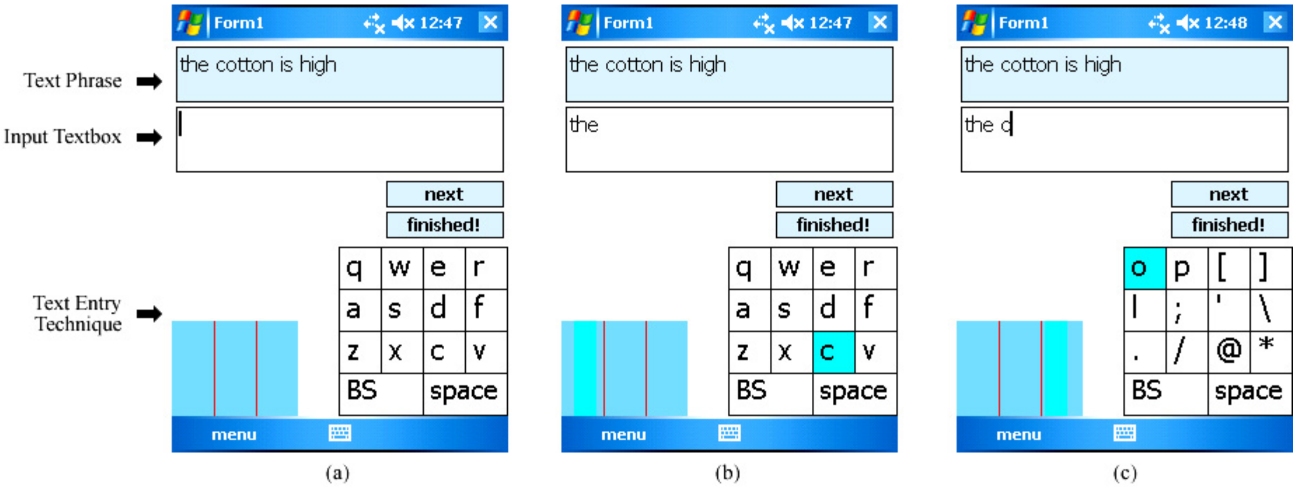

Figure 3. (a) Screen shot of the PDA screen of our two-handed chorded keyboard (for right-handed users); (b) While the user inputs 'C' on the two-handed chorded keyboard the interface highlights the position of the non-dominant hand's thumb and the 'C' key; (c) The user enters an 'O'. Note that the keys change with the new location of the thumb.

conducted a structured evaluation of our design in comparison to three other existing text entry methods:

1. mini-qwerty (a one-handed key-based text entry method),
2. hand-writing recognition, and
3. quikwriting (a gesture-based text entry method).

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

- S1-sitting: We asked the participants to input text input while remaining seated.
- S2-walking: We asked the participants to input text while walking along a designated path within a lab.
- S3-stairs: We asked the participants to input text while going up or down stairs.

For scenario S1-sitting, the participants sat at a table in a laboratory. We instructed them to remain seated until they completed all given tasks.

In scenario S2-walking, we defined a path similar to the one used by Vadas *et al.* in their reading experiment [14], as shown in Figure 4. The path was approximately 38.8*m* long and 50*cm* wide. We asked the participants to follow the path and to stay inside the path as much as possible. They were instructed to keep walking as much as possible but they were allowed to slow down or speed up at any point.

For scenario S3-stairs, we used a curved stairway which spanned across two stories in our building. In total, there were 36 steps. The participants were asked 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. We included this scenario because we observed that sometimes people must also devote additional attention to the environment. This includes when users climb stairs, walk along uneven surfaces or move through crowded places.

4.1 Hardware & Software Platform

We used an HP iPAQ hx2790 Pocket PC as the base platform for all the software techniques studied in our evaluation. In each trial of this study, the PDA displayed a short phrase (consisting of three to six words) 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.

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 for 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 [14], which are designed to assess subjective workload in terms of the six indices. We asked them to complete the NASA-TLX forms after each trial. 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. For the mini-qwerty technique and hand-writing, the participants could skip the practice session if they already felt comfortable with them.

After the participants completed the practice sessions, they began the actual experiment. We used a within-subjects experimental

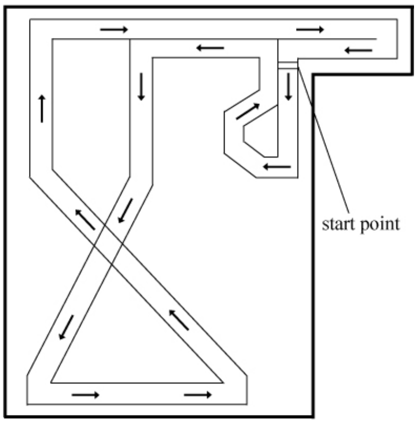

Figure 4. The path used in the walking scenario.

Figure 5. Scenario S2-walking (left): The participants walked around our lab along a path while entering text phrases; Scenario S3-stairs (right): The participants went up/down stairs while entering text phrases.

design, where all the participants used all the four text entry techniques in all three scenarios. The order of the scenarios was counterbalanced and the order of the text entry methods for each scenario was randomly determined.

For each scenario, 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 as quickly and accurately as possible. 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 had completed all three scenarios. Thus, each participant entered 72 different text phrases in total. The short phrases of text were selected randomly from MacKenzie's English phrase dictionary [20].

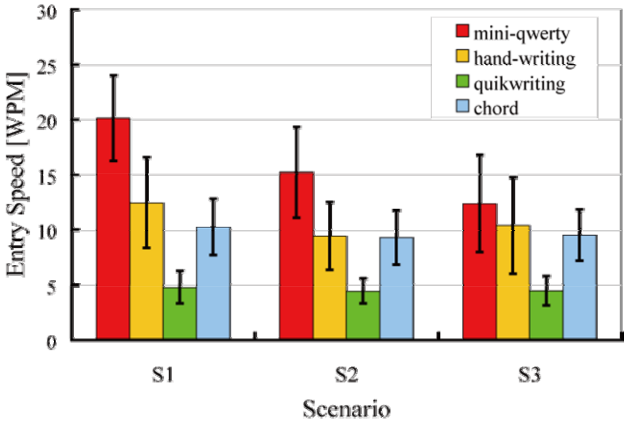

Figure 6. Entry speed for the four input methods in the different scenarios.

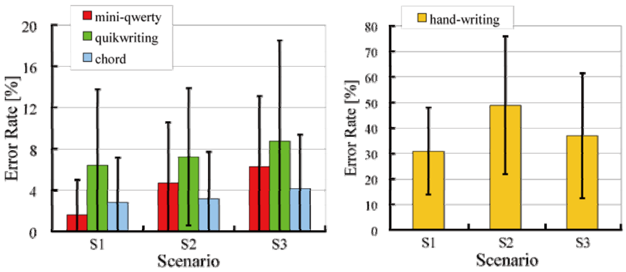

Figure 7. Average error rate for each text entry across the three scenarios.

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

5. RESULTS

In this section, we present findings from our study, including the participants' 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 methods studied.

5.1 Text Entry Speed

Figure 6 shows the entry speed for the four input methods in the three scenarios. The entry speed was calculated based on the standard WPM (words-per-minute), which is generally calculated as [characters per second] x 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 miniqwerty keyboard and the other entry methods, between handwriting and quikwriting, and between the chorded keyboard and quikwriting in scenario S1-sitting and S2-walking. There are significant differences ($p<0.05$) between quikwriting and the other entry methods, and between the mini-qwerty keyboard and the chorded keyboard in scenario S3-stairs.

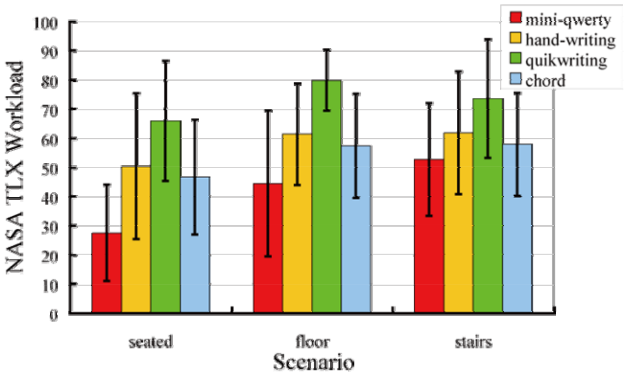

Figure 8. NASA TLX Workload for the four input methods in the different scenarios.

5.2 Error Rate

We measure errors in each given 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 phrase. Figure 7 shows the error rate for each condition. Although the mini-qwerty keyboard is the least error-prone technique in scenario S1-sitting, the two-handed chorded technique was the least error prone in the mobile scenarios.

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 scenarios. Furthermore, statistically significant differences ($p<0.05$) exist between the mini-qwerty keyboard and quikwriting in scenario S1-sitting, and between the chorded keyboard and quikwriting in scenario S2-walking.

5.3 NASA TLX Workload

Figure 8 shows the overall workload ratings. Here, we also used 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 scenario S1-sitting. Statistically significant differences ($p<0.05$) exist between the mini-qwerty keyboard and quikwriting, and between the chorded keyboard and quikwriting in scenario S2-walking. However, no significant difference exists in scenario S3-stairs.

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 a high workload demand for that technique.

5.4 Walking Speed

Based on the measured distances and times recorded during the S2-walking scenario, we calculate the approximate walking speed of the participants. Figure 9 shows the participants' normal walking speed and their walking speed in scenario S2-walking. We defined fast walkers as the seven participants who walked

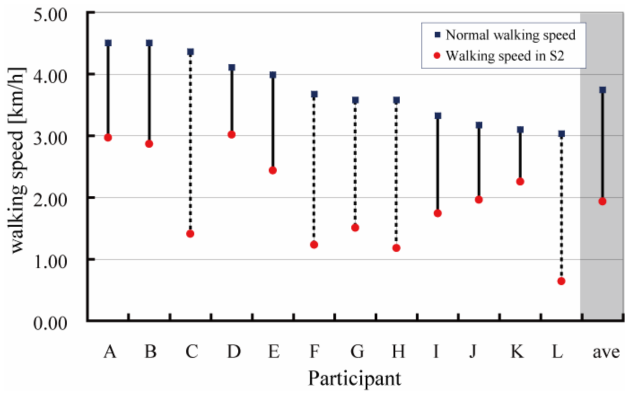

Figure 9. The walking speed for each participant in scenario S2-walking. A blue square and a red circle represent the average normal walking speed and the average walking speed in S2, respectively. A rigid line stands for a fast walker and a dashed line stands for a slow walker.

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.

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 1 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 scenarios, the mini-qwerty keyboard was preferred the most. However, the preference was varied in S3-stairs; fast-walkers split between mini-qwerty and chorded, and slow walkers for hand-writing

Table 1. Preferences on the text input methods.

	fast walkers			slow walkers			All		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
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

6. DISCUSSIONS

Entering this study, we had two goals.

1. We wanted to investigate how a two-handed text entry technique would be different from existing one-handed stylus-based techniques. In addition to the question of how the participants would perform with a two-handed technique in comparison to existing techniques, this required an understanding of how the dominant and non-dominant hand could be used in text-entry. Our preliminary evaluation suggested that the participants felt 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.

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 scenario S1-sitting.

Overall, this study shows that mobility can impact 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.

As shown in Figure 6, the mini-qwerty keyboard was the fastest entry method in the all the scenarios. All the participants use desktop or laptop computers regularly. Therefore, they are familiar with the layout of the QWERTY keyboard, which allowed them to use the mini-qwerty keyboard more efficiently. However, in scenario S3-stairs, 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 steadily. Furthermore, the small key size in the mini-qwerty keyboard resulted in an increase in occurrence of errors while the user is mobile (see Figure 7).

The two-handed chorded keyboard was the best entry method in terms of the accuracy although there was not a statistically significant difference. Additionally, no statistically significant difference was found in accuracy between mini-qwerty and two-handed chording; this result is promising for two-handed chording, considering that several of the users had significant prior experience with mini-qwerty. In particular, the chorded keyboard supported less error-prone text entry in the mobile scenarios. The chorded keyboard provides larger keys than the mini-qwerty keyboard, which allowed the participants to target 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 made them more frustrated.

Hand-writing was the most error-prone text entry method in all the scenarios. Four participants experienced great difficulty entering specific characters, such as 'f', 'i' or 't'. Therefore, hand-writing often required that the participants enter the same character several times. Furthermore, in the mobile scenarios, written characters became more ambiguous, which were difficult to be recognized correctly.

However, hand-writing was preferred by the slow walkers in the S3 scenario. Hand-writing uses a user's actual writing as input, which requires less visual attention than the mini-qwerty or our chorded keyboard. This allowed them to pay more attention to the environment in the mobile scenarios, which enhanced their mobile experiences. Another reason is that their walking styles allowed them to hold the PDA more steadily, which resulted in the fact that the preference of the slow walkers between S1 and S2 were almost the same.

The quikwriting technique was not as successful as the other entry methods. Participants had more difficulty learning to quikwriting than the other methods. Most participants commented that they could not memorize the quikwriting layout. As a result, participants spent more effort on visual search. In mobile scenarios, visual search became even harder to perform. However, some of the participants told us that they would prefer to use an easier stroke-based text-entry method in a mobile setting. This comment implies that a stroke-based text entry method would provide better experiences for expert users because it would require no visual search and less visual attention. However, recognition errors would still remain an important design consideration.

The chorded keyboard tied with mini-qwerty as the preferred input method of fast walkers while walking up stairs. In these cases, their walking speed leads to a more unstable condition for text entry compared to a stationary situation. Despite the advantage in visual search, hand-writing became less robust in their cases because it required the attention of the fast walkers for confirming whether characters had been entered correctly. The mini-qwerty keyboard was much more robust, but the text keys were too small for the users to hit while walking. Our chorded keyboard offered larger keys than the mini-qwerty keyboard and the same layout as the mini-qwerty keyboard. This gave the fast walkers a better experience in the mobile scenarios.

The chorded keyboard had a lower input speed 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. We believe that we can apply a layout based on the frequency of characters to the two-handed keyboards, such as FrogPad [19] in order to solve this problem.

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 and discussed so 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 scenarios.

This study shows that our chorded keyboard gives a user more accurate text entry in the mobile settings. 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 situation. Overall, the participants found the idea of our two-handed chorded keyboard generally acceptable even in the mobile scenarios. 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 in terms of 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 the inputting of a small number of words per tasks (such as adding context information or calendar events). We did not focus on the performance by expert users of the different input techniques in the three scenarios. We plan to study this issue further in future work.

8. ACKNOWLEDGEMENTS

We would like to appreciate Kurt Partridge from PARC and Dynamic Graphics Project (DGP) members at University of Toronto for giving us comments on our paper. We also thank participants of this study for their time and comments. This work is covered under the Ethics Review Office protocol reference #19532 at the University of Toronto.

9. REFERENCES

[1] G., Blaskó, W. Beaver, M. Kamvar, S. Feiner: Workplane-Orientation Sensing Techniques for Tablet PCs. In *UIST '04: Proceedings of the 17th annual ACM symposium on User interface software and technology*, 2004. (poster)

[2] W. Buxton, M. Billinghurst , Y. Guiard, A. Sellen and S. Zhai: Human Input to Computer Systems: Theories, Techniques and Technology. 2002. http://www.billbuxton.com/inputManuscript.htm

[3] A. Crossan, R. Murray-Smith, S. Brewster, J. Kelly, and B. Musizza: Gait phase effects in mobile interaction. In *CHI '05 extended abstracts on Human factors in computing systems*, page 1312–1315, 2005.

[4] D. Gopher and D. Raij: Typing with a two-hand chord keyboard: Will qwerty become obsolete. *IEEE Transactions on Systems, Man, and Cybernetics*, 18(4):601–609, 1988.

[5] A. K. Karlson, B. B. Bederson, and J. SanGiovanni: Applens and launchtile: two designs for one-handed thumb use on small devices. In *CHI '05: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 201–210, 2005.

[6] B. MacKay, D. Dearman, K. Inkpen, and C. Watters: Walk 'n scroll: a comparison of software-based navigation techniques for different levels of mobility. In *MobileHCI '05: Proceedings of the 7th international conference on Human computer interaction with mobile devices & services*, pages 183–190, 2005.

[7] I. S. MacKenzie and R. W. Soukoreff: Text entry for mobile computing: Models and methods, theory and practice. *Human-Computer Interaction*, 17:147–198, 2002.

[8] G. N. Marentakis and S. A. Brewster: Effects of feedback, mobility and index of difficulty on deictic spatial audio target acquisition in the horizontal plane. In *CHI '06: Proceedings of the SIGCHI conference on Human Factors in computing systems*, pages 359–368, 2006.

[9] N. Matsushita, Y. Ayatsuka, and J. Rekimoto: Dual touch: a two-handed interface for pen-based pdas. In *UIST '00: Proceedings of the 13th annual ACM symposium on User interface software and technology*, pages 211–212, 2000.

[10] S. Mizobuchi, M. Chignell, and D. Newton: Mobile text entry: relationship between walking speed and text input task difficulty. In *MobileHCI '05: Proceedings of the 7th international conference on Human computer interaction with mobile devices & services*, pages 122–128, 2005.

[11] T. Mustonen, M. Olkkonen, and J. Hakkinen: Examining mobile phone text legibility while walking. In *CHI '04: CHI '04 extended abstracts on Human factors in computing systems*, pages 1243–1246, 2004.

[12] P. Parhi, A. K. Karlson, and B. B. Bederson: Target size study for one-handed thumb use on small touchscreen devices. In *MobileHCI '06: Proceedings of the 8th conference on Human-computer interaction with mobile devices and services*, pages 203–210, 2006.

[13] K. Perlin: Quikwriting: continuous stylus-based text entry. In *UIST '98: Proceedings of the 11th annual ACM symposium on User interface software and technology*, pages 215–216, 1998.

[14] S. Rubio, E. Díaz, J. Martín, and J. M. Puente: Evaluation of Subjective Mental Workload: A Comparison of SWAT, NASA-TLX, and Workload Profile Methods. *Applied Psychology*, 53(1):61–86, 2004.

[15] K. Vadas, N. Patel, K. Lyons, T. Starner, and J. Jacko: Reading on-the-go: a comparison of audio and hand-held displays. In *MobileHCI '06: Proceedings of the 8th conference on Human-computer interaction with mobile devices and services*, pages 219–226, 2006.

[16] K.-P. Yee: Peephole displays: pen interaction on spatially aware handheld computers. In *CHI '03: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 1–8, 2003.

[17] K.-P. Yee: Two-handed interaction on a tablet display. In *CHI '04 extended abstracts on Human factors in computing systems*, pages 1493–1496, 2004.

[18] J. E. Zucco, B. H. Thomas, and K. Grimmer: Evaluation of Four Wearable Computer Pointing Devices for Drag and Drop Tasks when Stationary and Walking. In *ISWC'06: Proceedings of the Tenth International Symposium on Wearable Computers*, pages 29–36, 2006.

[19] FlogPad http://www.frogpad.com/

[20] MacKenzie's English phrase dictionary http://www.yorku.ca/mack/phrases2.txt.