INVESTIGATING RETROSPECTIVE INTEROPERABILITY BETWEEN THE ACCESSIBLE AND MOBILE WEBS WITH REGARD TO USER INPUT

A thesis submitted to the University of Manchester
for the degree of Doctor of Philosophy
in the Faculty of Engineering and Physical Sciences

2011

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Abstract

The World Wide Web (Web) has become a key technology to provide access to on-line information. The Mobile Web users, who access the Web using small devices such as mobile phones and Personal Digital Assistants (PDAs), make errors on entering text and controlling cursors. These errors are caused by both the characteristics of a device and the environment in which it is used, and are called situational impairments. Disabled Web users, on the other hand, have difficulties in accessing the Web due to their impairments in visual, hearing or motor abilities. We assert that errors experienced by the Mobile Web users share similarity in scope with those hindering motor-impaired Web users with dexterity issues, and existing solutions from the motor-impaired users domain can be migrated to the Mobile Web domain to address the common errors.

Results of a systematic literature survey have revealed 12 error types that affect both the Mobile Web users and disabled Web users. These errors range from unable to locate a key to unable to pin-point a cursor. User experiments have confirmed that the Mobile Web users and motor-impaired Web users share errors in scope: they both miss key presses, press additional keys, unintentionally press a key more than once or press a key too long. In addition, both small device users and motor-impaired desktop users have difficulties in performing clicking, multiple clicking and drag selecting. Furthermore, when small device users are moving, both the scope and the magnitude of the errors are shared. In order to address these errors, we have migrated existing solutions from the disabled Web users domain into the Mobile Web users domain. We have developed a typing error correction system for the Mobile Web users. Results of the user evaluation have indicated that the proposed system can significantly reduce the error rates of the Mobile Web users.

This work has an important contribution to both the Web accessibility field and the Mobile Web field. By leveraging research from the Web accessibility field

into the Mobile Web field, we have linked two disjoint domains together. We have migrated solutions from one domain to another, and thus have improved the usability and accessibility of the Mobile Web.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Acknowledgements

I would like to express my deep appreciation to my supervisor Dr. Simon Harper, whose kind guidance helped me throughout this PhD project. I also would like to thank Dr. Yeliz Yesilada who helped me on every little details of this project. I would like to express my sincere appreciation to both of them, especially for their help during the writing-up period. This thesis was written in very difficult time. Without their extreme patience and continuous encouragement, this PhD will never be complete.

I am very thankful to all the Web Ergonomics Lab (WEL) members: Dr. Darren Lunn, Dr. Eleni Michailidou, Dr. Caroline Jay, Dr. Andrew Brown, Grace Mbipom and Alex Chen. I would like to thank them for all their support through discussions, user evaluations and statistics.

Many people volunteered during the user evaluations, for which I would like to thank. I appreciate their time and effort in helping me complete this project. My WEL colleagues are thanked for assisting me in conducting the experiments and for participating in all pilot experiments providing valuable comments.

I am grateful to my family and friends for all their encouragement during my time completing this thesis. Special thanks and this thesis dedication go to my parents, Jie and Fengju, for all their endless love, support and belief in me through my years in the UK.

Chapter 1

Introduction

World Wide Web (Web) technologies have become the key enablers of access to the Internet through desktop and laptop computing platforms; and are becoming extremely popular in playing the same role for Internet access from small devices (such as smart-phones and PDAs) [Lewis, 2006]. Many smart-phones and PDAs [1] provide functionality to access the Internet and e-mail apart from the traditional voice call and text message services. Very different from desktop or laptop computers, the flexibility and mobility of small devices now allow people to access the Web in various contexts. Traditional desktop computers are designed for indoor usage. Laptop computers provide a certain extent of flexibility; but they still need to be placed on a flat surface and operated in stable conditions. On the contrary, smart devices, which integrate computing power into palm size devices, grant users much more freedom in terms of where and how the devices are used. Thanks to their small size and light weight, small devices can be put into pockets or handbags and taken almost anywhere. They do not need a flat surface operate on, and can be used while the user is on the move. Consequently, small devices can be used to access the Web in many contexts.

However, the size of small devices does not always bring advantages to the users. Small devices are born with several limitations which make them hardly as easy to use as desktop or laptop computers. Compared with a desktop computer keyboard, the keys on a small device keyboard are much smaller and the layout is more compact. This causes difficulty in keying: a user can easily miss the target key or hit the key that is adjacent to the target key. In addition, a small device keyboard normally contains fewer keys than a desktop keyboard due to the size

[1] In the rest of this thesis, we use the term small device to represent smart phones and PDAs.

limitation. As shown in Figure 1.1, a numeric keyboard only has 12 keys, and 10 of them are used for text entry. The 26 letters of the English alphabet are located on keys '2' through '9', and the SPACE character is normally on the '0' key. Since several characters are located on each key, ambiguity arises. A user needs to either press the key several times to specify a target character (known as *multi-tap*) or use prediction and select a key combination from a list of suggestions (e.g., T9 [2]) [MacKenzie and Soukoreff, 2002]. However, these methods can still lead to difficulty in selecting characters as a user may press the correct key but fails to select the correct characters. The difficulty in entering text on a small device accelerates when the input contains both characters and numerical or punctuation symbols (e.g., forms and URLs). In addition, reducing ambiguity also increase keying time and thus reduce the typing rates. In laboratory environment, small device users typing with both hands can reach a typing rate of 27.2 words per minute (wpm) using multi-tap, and 45.7 wpm using T9 [Silfverberg et al., 2000]. However, in reality people's typing rates are much slower.

In addition to text entry, controlling cursor on a small device is also less efficient. Traditional pointing methods on small devices use joy sticks, trackballs and touch-screen to recreate the functionality of a mouse. However, the performance of these alternatives is no better than a mouse. Mackenzie [1991] compared the performance of a mouse, a trackball and a stylus with a tablet and concluded that trackball and stylus was no better than a mouse on processing on-screen information: a stylus was faster than a mouse on pin-pointing a on-screen item but slower on dragging an item; a trackball was slower than stylus and mouse on both tasks. As demonstrated in [MacKenzie and Jusoh, 2001], a mouse is better than a trackball, a joystick and a touch-screen in that the cursor movement of a mouse is more fluent and thus it requires the least cursor adjustment. Recently, evolution of mobile devices is adding new pointing methods to the Mobile Web context. With the new touch-screen technologies, a user can produce a lot more functionalities with finger gestures. For example, on a iPhone [3] a user can scroll up and down a page by sliding the screen using one finger. These new pointing methods are not only used for traditional text entry and pointing tasks, but also used for new functionality such as game control [Zaman et al., 2010]. Although these new pointing methods improve the pointing performance of small device

[2]See `http://www.t9.com`

[3]See `http://www.apple.com/uk/iphone/index.html`

Figure 1.1: Standard 12-key telephone keypad [Mackenzie and Tanaka-Ishii, 2007].

users, they are by no means perfect [Haywood and Boguslawski, 2009]. Apart from text entry and cursor control, small devices also have presentation issues due to the screen-size. For example, a 240×320 pixels display of a PDA can only show less than 1/6 of a 1280×1024 desktop screen [Jones et al., 2005]. The limited screen size restricts the context and overview a user can get, and also increase the dependency upon scrolling through materials. As Kim [2003] indicates, due to the screen size limitation, a small device user has to do more horizontal and vertical scrolls to "obtain a full picture", which imposes heavy burden on information search [Kim and Albers, 2003].

The limited input bandwidth and presentation issues of small devices set usability challenges to device manufacturers, Web designers and researchers. World Wide Web Consortium (W3C)'s "Mobile Web Initiative" (MWI)[4] seeks to address these issues through a concerted effort of key players in the mobile production chain, including authoring tool vendors, content providers, handset manufacturers, browser vendors and mobile operators. The current work in the MWI focuses in two main areas: (i) Developing "best practices", which include developing a

[4]See `http://www.w3.org/2005/MWI/`

set of technical best practices and associated materials in support of the development of websites that can be easily viewed and interacted with on small devices; and (ii) Identifying device information required for content adaptation which includes the development of services that provide device descriptions in support of Web–enabled applications. However, current study only looks at the Mobile Web as a stand-alone field and fails to integrate research from other domains to help addressing usability problems of the Mobile Web. In fact, anecdotal evidence has suggested that small device users and disabled desktop users experience common accessibility and usability problems [Trewin, 2006, Sloan et al., 2000]. Problems caused by limited input bandwidth are similar to problems caused by deficiency or impairments in hand or finger control. For example, a mobile phone user sending text messages while walking in freezing wind may make as many typing errors as a user with finger control impairment due to the dexterity problems caused by low temperature. A user typing on a mobile phone on a bumpy car may make as many typing errors as a disabled user who's hand trembles unintentionally. In addition, the screen size of small devices and lighting conditions of the environment may also cause the Mobile Web users problems as if they were visually impaired. For example, when using outdoor, the screen will sometimes reflect sun light and make it very difficult to read. In general, small device users' behaviors are affected, sometimes impaired, by the devices they use and the contexts they use the devices in, and thus experience *situational impairment* [Sears and Young, 2003a] It is suggested that there are strong similarities between physical usability issues in mobile and accessible desktop Web browsing scenarios: they share the need to support various input techniques; they both benefit from flexibly authored and Accessible Web pages; text entry and navigation in both scenarios are slow and error-prone [Trewin, 2006]. This being the case, available research can be leveraged between disabled desktop user domain and small device user domain, and existing techniques can be transferred between the two in order to address the common problems.

1.1 Problem Statement

The PhD work presented in this thesis aims to shed the light on integrated research between the Accessible Web and the Mobile Web. We [5] investigate the

[5] In all cases I mean 'I', but I feel that 'we' is more in-keeping with the usual academic style.

common accessibility problems experienced by both disabled Web users [6] and the Mobile Web users. If common problem exist, we will search for opportunities to migrate existing solutions from one domain to another. Since the Mobile Web is a relatively younger field compared with the Accessible Web, more solutions exist in the former domain. Therefore, in this thesis we will look at migrating solutions from the Accessible Web to the Mobile Web and thus contribute to the development the Mobile Web. As the Mobile Web develops, new solutions may be also migrated to the Accessible Web domain.

In particular, the work focuses on accessibility problems on text entry [7] and cursor movement [8]. We assert that small device users and motor-impaired desktop users share the same types of errors in text entry and cursor movements, and solutions can be migrated between user domains to address the common problems. To take a close look, existing research suggests that motor-impaired desktop users who have problems in finger or hand control suffer from various accessibility problems in using keyboard and mouse. For instance, Trewin and Pain [1999] studied the input problems of motor-impaired desktop users. Participants of their experiments suffered from impairments in hand and finger control due to stroke, radial palsy, muscle loss or wrist stiffness. Trewin and Pain found that these users experienced 6 types of typing errors and 3 types of pointing errors. For example, a user unintentionally pressed a key longer than the default key repeat delay, causing a key repeating itself. This is called a *long key press error*. A user also failed to press two keys simultaneously, which generated a *dropping error*. Other typing errors include *additional key error* where a key adjacent to the intended key is activated; *bounce error*, where a user unintentionally presses the intended key more than once; *missing key error*, where the user failed to activate the intended key; and *remote key error* which occurred when a user accidentally pressed a key that was remote from any key the user intended to activate. Mouse control wise, participants of Trewin and Pain's study also had difficulties in performing pointing, clicking and dragging. On first looking into these typing and pointing errors, they are also likely to affect the Mobile Web users who use small devices under various conditions. However, there is no empirical study to investigate this assumption.

[6] In all cases the term 'disabled Web users' and 'the Accessible Web users' mean disabled Web users who access the Web from desktop computers.

[7] Referred as typing errors in the rest of this thesis

[8] Referred as pointing errors in the rest of this thesis

The work presented here attempts to investigate common typing and pointing errors of the Mobile Web users and the Accessible Web users. A three-step approach was used during the research: (i) Identifying gaps and overlaps between research on disabled Web user domain and mobile Web user domain in the literature; (ii) conducting user evaluation to investigate and confirm the common problems between the two domains; and (iii) proposing solution migrations from one domain to another in order to address the common problems. We started drawing similarities between disabled desktop users and small device users by replicating the original controlled experiments with small device users. Having established the basic understanding of scope of errors affecting the two domains, we then moved on and investigated the typing and pointing errors of small device users in more realistic settings. Particularly, we focused on the error rates of small device users under different mobility conditions. We then sourced existing Web Accessibility research for available solutions, and migrated one solution to the Mobile Web domain. This pilot study of solution migration enabled us to understand whether direct solution migration from the Accessibility domain benefit the Mobile Web users.

1.2 Research Questions

Based on the problem statement presented in previous section, following questions motivate this work and outlines the remaining of this thesis.

1. *What are the common input problems shared by disabled Web users and the Mobile Web users?*
   This question lays the foundation of this work. It allows us to identify gaps and overlaps between the Web Accessibility domain and the Mobile Web domain. The gaps motivate further empirical studies on "linking" similar problems, and the overlaps promote solution migrations between domains. We do this so that users from the two domains can benefit from existing solutions of each other and thus improve the accessibility and usability of both areas. In order to answer this question, we have integrated existing research on Web Accessibility and the Mobile Web. To start with, a systematic literature review was conducted to reveal problems experienced by specific user domains along with the corresponding solutions. In order to provide a wide coverage on different types of impairments, the review included accessibility

research on motor-impaired users, visual-impaired users, hearing-impaired users, cognitive-impaired users, aged users and able-bodied small device users. We then summarized the common problems across the domains. We facilitated this process by building a matrix where the x-axis listed the user domains and the y-axis listed the problems. Intersections of the two axes were filled with references that supported the existence of a problem in a particular user domain (see Table 2.1 and Table 2.2 in Chapter 2). On the other hand, an empty cell on the matrix suggested that there was no existing research supporting the existence of an accessibility problem.

2. *How do these problems affect text entry and cursor movement of the Mobile Web users?*
   Answers to the first research question gave us links between the two domains. However, details of how each problem affects the Web users only exist within their own user domain. There is no cross-domain empirical study to verify whether certain problems are common across the board. Indeed, controlled experiments across different user domains help us better understanding the problems faced by both disabled Web users and the Mobile Web users and thus facilitate solution migrations. To answer this research question, we first looked at the problems experienced by motor-imparied desktop users and investigated whether they also affected the Mobile Web users. We did this by rerunning an existing motor-impaired desktop user evaluation with small device users. We first conducted the user evaluation in a laboratory environment. After that, we conducted a field study to investigate the patterns of usage of small devices in real life. This helped us to design a realistic experiment to study the typing and pointing errors of the Mobile Web users in scenarios closer to their daily life. Based on the patterns obtained from the field study, we then conducted a third user evaluation and investigated the input errors of the Mobile Web users in naturalistic settings.

3. *Can existing solutions to one user domain also benefit another user domain given that they experience the same problem?*
   After identifying the common problems, the next step is to investigate whether it is possible to migrate solution between domains to address the problems. If solution migration from Web Accessibility to the Mobile Web

is possible, device manufacturers and Web developers can directly apply existing techniques available in the Web Accessibility domain to the Mobile Web, and thus improve the usability of it. To answer this question, several existing techniques were proposed to address the common problems. Possibility of migration were analyzed. We then picked up one proposed technique and implemented it in the Mobile Web domain. Then we evaluated the migrated solution by rerunning the same experiment that we used to investigate the input errors of small device users in naturalistic settings, and compared users' performance with and without applying the migrated solution. The comparison revealed whether existing solution could be directly migrated from Web Accessibility domain to the Mobile Web domain, and therefore support or destroy our hypothesis.

1.3 Thesis Structure

The rest of this thesis is structured in the following manner:

Chapter 2: Background and Related Work

Chapter 2 will present a systematic literature review on similar accessibility problems experienced by the Accessible Web users and the Mobile Web users. The aim of the review is to answer the first research question by comparing existing research on the Accessible Web and the Mobile Web and identifying common problems which motivate potential solution migrations. The review focused on five categories of disabled Web users, including motor-impaired users, visual-impaired users, hearing-impaired users, cognitive-impaired users, and aged users. A matrix was built to facilitate identifying overlaps and gaps between different user domains. Overall the review suggested 12 common input problems between different domains.

Chapter 3: Small Device User Evaluations While Seated

Chapter 3 will present a user study that investigated typing and pointing errors of small device users while seated. The aim of this study is to find out whether typing and pointing errors experienced by motor-impaired desktop users also affect small device users who use small size QWERTY keypad and touch-screen. To achieve this, an existing study that investigates typing and pointing errors of motor impaired desktop users was reproduced with able-bodied small device users. Results showed that small device users and motor impaired desktop users shared 5 common typing errors and 3 common pointing errors, however, the error rates did not overlap: small device users under sitting conditions had much lower error rates than motor-impaired desktop users.

Chapter 4: Investigating Use Patterns of Small Device Users

To answer the third research question, it is crucial to understand how small devices are used in real-life scenarios. Chapter 4 will present a field study that investigated the usage pattern of small devices in real-life scenarios. The field study consisted of a series of unobtrusive remote observations and face-to-face interviews. Results showed that small device users normally used the device with just one hand, pressed the keys with thumb, made phone calls and sent text messages while walking. They normally corrected typing errors and used abbreviations. On average, small device users switched their attention between the device screen and the surrounding environment 3 times in every 20 seconds. The number of attention switches increased when small device users were walking. Based on the results, a protocol of designing user evaluation with small device users in more realistic settings was proposed.

Chapter 5: Small Device User Evaluations While Walking

Chapter 5 will present a user study that investigated small device users' typing and pointing errors while seated. The aim of the study is to find out whether typing and pointing errors identified in chapter 3 still exist when the users are mobile, and whether the error rates will increase in magnitude under walking conditions. Results of the study showed that small device users had more typing and pointing errors when they were walking, and the magnitude of error rates were close to, in some cases higher than, that of motor-impaired desktop users.

Chapter 6: Solution Migration

Having investigated the common input problems between motor-impaired desktop users and small device users, this chapter aims to answer the last research question, that is can we migrate solutions from one domain to another to address the common problem. We will first review a list of candidate solutions to the input problems identified in previous chapters. Then we will present a typing error correction system for the Mobile Web users. The system was designed based on an existing solution to the typing errors of motor-impaired desktop users, and was aimed to reduce those common typing errors experienced by the Mobile Web users. User evaluation results indicated that the migrated solution helped to reduce typing errors of small device users, and therefore gave an affirmative answer to our third research question.

Chapter 7: Conclusions and Future Wrok

This research has shown that small device users and motor-impaired desktop users experience common accessibility errors on text entry and cursor movement. Although the main error type does not overlap, the research does show that the error rates of small device users in walking condition are close to that of motor impaired desktop users. Furthermore, our solution migration has shown that existing technologies from the Accessible Web domain can be migrated to the Mobile Web domain and help the users to reduce typing errors. We have therefore provided evidence to support the hypothesis that small device users and motor-impaired desktop users share the same typing and pointing problems and solutions can be migrated between the two domains. This chapter concludes the work conducted throughout the PhD project and discusses potential paths for future work.

1.4 Publications

Results derived throughout the research led to the following peer-reviewed publications:

1. Tianyi Chen, Yeliz Yesilada and Simon Harper. *What input errors do you experience? Typing and pointing errors of small device users.* International Journal of Human-Computer Studies (IJMHCI). Volume 68, Issue 3, March 2010, Pages 138-157. http://doi:10.1016/j.ijhcs.2009.10.003

   This paper presents a user study that investigates the input errors of mobile Web users in both typing and pointing. The study identifies six types of typing errors and three types of pointing errors shared between our two user domains. We find that mobile Web users often confuse the different characters located on the same key, press keys that are adjacent to the target key, and miss certain key presses. When using a stylus, they also click in the wrong places, slide the stylus during multiple clicks, and make errors when dragging. Our results confirm that despite using different input devices, mobile Web users share common problems with motor impaired desktop users; and we therefore surmise that it will be beneficial to transfer available solutions between these user domains in order to address their common problems.

2. Yeliz Yesilada, Simon Harper, Tianyi Chen and Shari Trewin. *Small device users situationally impaired by input*. Computers in Human Behavior. Volume 26, Issue 3, May 2010, Pages 427-435. http://doi:10.1016/j.chb.2009.12.001

   This paper describes empirical work which makes the link between the behaviour of motor-impaired desktop users and non-impaired users of small-devices. We find that there is significant overlap in the extent of the problems encountered, but not the magnitude. Eight of the 11 existing errors made by motor-impaired users were also present in our small-device study in which two additional error types, key ambiguity and landing errors, were also observed. In addition, small-device rates for common error types were higher than those of desktop users with no impairment, but lower than those of desktop users with motor impairments. We suggest that this difference is because all users were seated to maintain constancy between studies and assert that this magnitude difference will equalise once the small-device is used in a mobile context.

3. Tianyi Chen. *Input to the mobile Web is situationally-impaired*. In Proceedings of the 10th international ACM SIGACCESS conference on Computers and accessibility. Page 303-304. http://doi:10.1145/1414471.1414550

   This paper presents a study with the Mobile Web users. The study replicated a previous experiment which investigated keyboard and mouse errors of motor impaired desktop users. Results confirm that these two domains share similar problems with regard to typing and pointing. Following the same methodology, we will investigate the problems shared by mobile Web users and disabled desktop users for output.

4. Tianyi Chen, Simon Harper and Yeliz Yesilada. *How do people use their*

mobile phones? A field study of small device users. International Journal of Mobile Human Computer Interaction (IJMHCI). Volume 3, Issue 1, 2011, Pages 37-54. http://doi: 10.4018/jmhci.2011010103

The usability evaluation of small devices (i.e. mobile phones and PDAs) is an emerging area of research. Compared with desktop computers, designing a usability evaluation for small devices is more challenging. Context of use, such as environmental disturbance and a user's physical activities affect the evaluation results. However, these parameters are usually ignored or excluded from simple and unnatural evaluation settings; therefore generate unrealistic results. This paper presents a field study that investigates the behaviour of small device users in naturalistic settings. The study consists of a series of unobtrusive remote observations and interviews. Results show that small device users normally use the device with just one hand, press the keys with thumb and make phone calls and send text messages while walking. They normally correct typing errors and use abbreviations. On average, small device users switch their attention between the device screen and the surrounding environment 3 times every 20 seconds, and this increases when they are walking.

5. Yeliz Yesilada, Tianyi Chen and Simon Harper. *A simple solution: solution migration from disabled to small device context.* In Proceedings of the 2010 International Cross Disciplinary Conference on Web Accessibility. Article Number: 27. http://doi:10.1145/1805986.1806023

   Our studies with small–device users show that they experience common input errors with motor impaired Desktop users. When small–device users are mobile their error rates increase to the same magnitude with, in some cases higher than, that of motor impaired desktop users. To address such common errors, we propose migrating solutions from motor impaired to small– device users domain. To demonstrate the benefits of such solution migration, we propose a prototype system that encodes solutions for long key press error, bounce error, additional key error, and key ambiguity error. This paper is different from other challenge papers as it does not demonstrate a prototype for disabled users, but it demonstrates how research and development for disabled users can benefit all.

6. Simon Harper, Tianyi Chen and Yeliz Yesilada. *Controlled Experimentation*

in Naturalistic Mobile Settings. Applied Ergonomics, Human Factors in Technology and Society. In submission.

Performing controlled user experiments on small devices in naturalistic mobile settings has always proved to be a difficult undertaking for many Human Factors researchers. Difficulties exist, not least, because mimicking natural small device usage suers from a lack of unobtrusive data to guide experimental design. Here we use observational data to derive a set of protocols and a simple checklist of validations which can be built into the design of any controlled experiment focused on the user interface of a small device. These, have been used within a series of experimental designs to measure the utility and application of experimental software. The key-point is the design of the experimental route which the user follows and the check validations– based on observed user behaviour– which they are required to perform at different stages within the journey.

A number of technical reports written throughout the project are listed in Appendix H

Chapter 2

Background and Related Works

This chapter presents the background research that we have conducted. We start by introducing the concept of Web Accessibility and guidelines on producing accessible websites. We then move on to the Mobile Web and discuss the special features of accessing the Web from small devices. We then review and compare existing work from Web Accessibility domain and the Mobile Web domain and draw similarities between accessibility problems experienced by users from these two domains. This comparison drives our further empirical studies that investigate the cross-domain common problems and solution migrations.

2.1 Web Accessibility

Web Accessibility means that people with disabilities can perceive, understand, navigate, and interact with the Web, and that they can contribute to the Web [Henry, 2005]. A website that is sufficiently flexible to be used by people with disabilities is called an accessible website. An accessible website is like an accessible building, which provides curb cuts, ramps and lifts to allow people with disabilities to enter and navigate with ease [Slatin and Rush, 2003].

An important term in this definition is 'people with disabilities'. Disability Discrimination Act (DDA) 1995 [UK, 1995] states that a person has a disability if "*he has a physical or mental impairment which has a substantial and long-term adverse effect on his ability to carry out normal day-to-day activities*". DDA has been superseded by the Equality Act 2010 from October 2010. However, the Disability Equality Duty in the DDA continues to apply [Government, 2010]. World Wide Web Consortium (W3C) specifies this definition as Web users who have visual disabilities, hearing disabilities, physical disabilities, speech disabilities or cognitive and neurological disabilities which affect their experiences of accessing the Web [Brewer, 2005]. The definition also covers people who have multiple disabilities and senior people whose functional ability decrease due to aging.

Disabilities and impairments affect a person accessing the Web in many scenarios. For example, a user with colour blindness who cannot distinguish red from green may have difficulty in ordering new clothes online if the colour of clothes is not specified in text, because the user cannot distinguish red clothes from green ones based on the images shown on a website. In addition, a person with hearing impairments may not be able to perceive audio information, thus has difficulty in receiving online education or entertainment. A user with dexterity problem may have difficulties in controlling a mouse to pin-point an on-screen item. A user with dyslexia may find too much text on a Web page hard to comprehend. On the other hand, able-bodied people who access the Web using small devices such as mobile phones and PDAs also face accessibility problems. For instance, the screen of a small device is normally quite small compared with a desktop screen. Therefore, a small device screen either renders less content or displays content in smaller scale. In addition, small device users also suffer from low input bandwidth. Typing with a small device keyboard is slower and more error-prone comparing with typing with a full size keyboard. This is due to the small size of the mobile keypad and its compact layout. Furthermore, small device users often access the Mobile Web in off-desk environments where they usually get distracted by surroundings and thus cannot devote full attention to using the Web.

Producing accessible website to disabled people is required by law in many countries. In the UK, there are three legislations regarding Web Accessibility: The Disability Discrimination Act 1995, Part III Access to Goods and Services; Special Educational Needs and Disability Act 2001; and The Disability Discrimination Act 1995, Part IV Education [Henry, 2003]. However, due to the great variety of audience, accessible Web is not easily achievable and requires a great amount of effort from all stakeholders, including Web developers, authoring tools and evaluation tools creators, user agents and assistive technologies developers, and end users. W3C Web Accessibility Initiative (WAI)[1] has defined 7 key components to achieve Web Accessibility. These components include Web content, Web browser and media player, assistive technology, users, developers, authoring

[1] See `http://www.w3.org/WAI/`

tools and evaluation tools [Henry, 2006]. Web content refers to the information presented in a Web page, such as text and images, and code or markup that define the structure and presentation of these information. Assistive technologies are *"products used by people with disabilities to help accomplish tasks that they cannot accomplish otherwise or could not do easily otherwise"* [Brewer, 2005]. Assistive technologies usually refer to adaptive software and hardware such as screen readers, alternative keyboards, switches and screen magnifiers. Authoring tools are tools used by Web developers to create Web pages. Evaluation tools are used to evaluate a website against HTML, CSS standards or Web Accessibility guidelines.

As illustrated by Figure 2.1, these components are inter-dependent. On the left hand side, Web developers use authoring tools and evaluation tools to create accessible Web content. For example, a Web developer would provide alternative text to an image used on a Web page so that a blind Web user can use screen reader to read the text and thus get a description of the image. The authoring tools should be able to facilitate and promoting such requirement, and the evaluation tools should be able to detect images that do not have alternative texts and alert the developer. In addition, developers who create content for small device users need to be aware of the capacity of target devices and network. For example, high definition video tends to perform badly on low bandwidth network and cannot be played on most low-end devices. On the right hand side, a user uses browser, media players to retrieve and render content created by Web developers. Disabled Web users rely on assistive technologies to access Web content. For example, a screen reader reads out the alternative text associated with an image for a visual impaired user.

2.2 Guidelines & Best Practices

In order to ensure accessibility features in each component of Web creation and interaction, several organisations (e.g., IBM, DRC, WAI, etc.) have published recommendations that aim to guide both Web developers and users in achieving Web Accessibility. The WAI guidelines are more complete and cover the key points of all the others. WAI has published guidelines corresponding to three Web Accessibility components: Authoring Tools Accessibility Guidelines (ATAG), Web

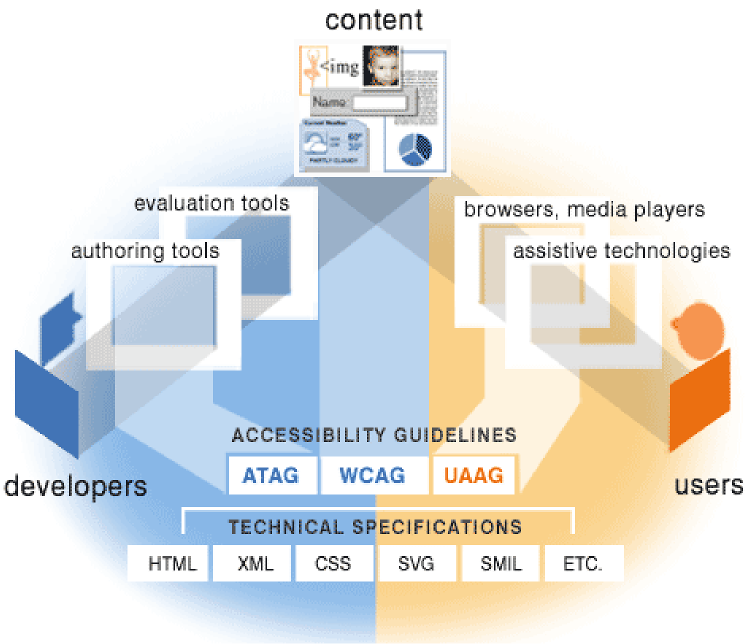

Figure 2.1: How Web Accessibility components relate to each other and corresponding WAI guidelines Henry [2006]

Content Accessibility Guidelines (WCAG) and User Agent Accessibility Guidelines (UAAG). ATAG aims to provide guidance on how to make authoring tools accessible to Web developers with disabilities, and how to use the authoring tools to produce accessible Web pages. WCAG cover the issues that need to be addressed in order to make Web content accessible to users with disabilities. UAAG intends to explain how to design and choose user agents, such as browsers and media players, that are accessible to Web users. The W3C Mobile Web Initiative (MWI) has been working on delivering accessible and usable Web content to small devices. It addresses the interoperability and usability problems through a concerted effort of Web content developers, authoring tools vendors, browser vendors, handset manufacturers and mobile operators [MWI, 2007]. The rest of this section briefly summarizes the WAI guidelines and the MWI best practices.

2.2.1 Web Content Accessibility Guidelines

Web Content Accessibility Guidelines (WCAG) is the center of the WAI guidelines. WCAG 1.0 [Chisholm and Vanderheiden, 1999] became a W3C Recommendation in 1999. It covers issues such as providing equivalent alternatives to auditory and visual content, providing clear navigation mechanisms and providing context and orientation information to help users understand complex pages and elements. WCAG 1.0 consists of 14 general guidelines and 65 specific checkpoints which can be evaluated against by automated tools or manually. Each checkpoint has a priority level based on its impact on accessibility.

Although WCAG 1.0 has been accepted and used by many countries and organisations around the world, it is by no means perfect. Web developers complain it is not easy to follow, as some checkpoints are subjective, ambitious and open to different interpretations [Centeno et al., 2006]. Some indicate that some checkpoints are arbitrary [Kane et al., 2007].

In fact, WCAG 1.0 has received extensive feedbacks since it was published. These feedbacks mainly indicate the need to update WCAG 1.0 to reflect broader and more advanced Web technologies; to be easier to understand by different audiences; to be easier to implement and precisely testable. Based on these feedbacks, WAI published WCAG 2.0 in December 2008 [Caldwell et al., 2008]. WCAG 2.0 include 12 main guidelines which are organized around four fundamental principals. These principals state that accessible Web content must be perceivable, operable, understandable and robust, meaning that users must be able to perceive the information being presented, operate the interface, understand the information, and maintain access to the content as technologies advance. In addition, WCAG 2.0 removes the regulation on using W3C technologies, and gives Web developers certain level of freedom in choosing Web technologies. Another goal of WCAG 2.0 is to be backwards compatible with WCAG 1.0, so that conformance to WCAG 2.0 will only require minor changes in websites that already conform to WCAG 1.0. In addition, this backwards compatibility also addresses the problem of guidelines fragmentation and allows different versions of Web Accessibility guidelines developed by different countries or different regions to update and 'roll forward' to a harmonised standard [Brewer, 2004].

2.2.2 User Agent Accessibility Guidelines & Authoring Tools Accessibility Guidelines

User Agent Accessibility Guidelines (UAAG) is also part of the WAI guidelines. A user agent is a HTML browser or a software that retrive and render Web content. UAAG 1.0 became a W3C Recommendation in 2002 [Jacobs et al., 2002]. Its target audience are user agent developers and format (e.g., HTML, XHTML, XML and SVG) designers. UAAG provides guidelines for designing user agents that are accessilbe for disabled users. A user agent that confirms to UAAG will improve accessibility for disabled users through its internal facilities and communications with external assistive technologies, such as screen readers and multimedia players. UAAG 1.0 adopts the same format and structure as used in WCAG: a set of general guidelines and principles, each of which is followed by several specific checkpoints.

UAAG 1.0 is interlinked with WCAG 1.0. WCAG 1.0 is considered within the UAAG 1.0 and requirements from UAAG 1.0 need to be satisfied in order to make Web content accessible. Some UAAG 1.0 guidelines also interact with WCAG 1.0. For example, Checkpoint 12.1 suggests *"Enusre that at least one version of the user agent documentation conforms to at least level Double-A of the Web Content Accessibility Guidelines 1.0"* [Jacobs et al., 2002].

UAAG 1.0 has several limitations. For example, it includes some checkpoints to ensure that the user is able to control the size and color of visually rendered text content. But it does not address control of non-text content, such as images. In addition, UAAG 1.0 does not include requirements for braille rendering [Jacobs et al., 2002]. To address the limitations of UAAG 1.0, WAI has been working on UAAG 2.0 [Allan et al., 2010]. UAAG 2.0 is currently a working draft. The key message of UAAG 2.0 is to ensure that users have control over their environment for accessing the Web. Also, another important feature of UAAG 2.0 is to ensure that a functionality designed to improve accessibility for one user does not interfere with accessibility for another.

The term *"authoring tool"* refers to editing tools designed to produce Web content, and also tools that produce, save or transfer documents into Web formats. It also refers to tools for site management or site publication. The Authoring Tools Accessibility Guidelines (ATAG) has two purposes: to meet the need of Web content authors by ensuring that the authoring tool user interface is accessible and to assist Web content authors in creating authoring tools that are accessible to disabled Web developers. ATAG 1.0 became a W3C Recommendation in 2000 [Treviranus et al., 2000]. It is organized in the same way as in WCAG and UAAG. In order to be compatible with WCAG 2.0, WAI has developed ATAG 2.0 [Richards et al., 2010]. It is currently a working draft. ATAG 2.0 is divided into two parts to reflect the two purposes mentioned earlier. Part A include guidelines that ensure accessibility of authoring tool user interfaces; and part B provides guidelines that support creating accessible Web content using authoring tools.

2.2.3 Mobile Web Best Practices

Mobile Web Best Practices (MWBP) is a set of best practices for delivering Web content to small devices. The aim of MWBP is to improve user experience of small device users on the Web. MWBP is derived from WCAG and also combines existing guidelines and design tips in industry [Opera, OpenWave, 2006]. Both MWBP and WCAG aim to improve the Web interaction. The difference is that WCAG focuses on disabled Web users whereas MWBP concentrates on small device users. The content of MWBP and WCAG significantly overlap in many areas. However, there are also gaps between the two: WCAG has some requirements that are specific for needs of disabled Web users and not for small device users. On the other hand, some requirement of MWBP, such as to minimize battery consumption and CPU power, is not required by WCAG. MWBP 1.0 [Rabin et al., 2008] is organised in a similar way as WCAG, it contains 5 main headings, each of which is further explained by several related statements. The conformance of MWBP 1.0 can be examined using the 'mobileOK' scheme [Owen et al., 2006] and the online automated checker[2].

2.3 Mobile Web

The term Mobile Web refers to the World Wide Web as accessed from mobile devices, such as smart phones or PDAs. Compared with traditional Web surfing from desktops and laptops, the Mobile Web *"represents a fundamentally different information medium... in terms of access devices used, content availability, bandwidth, and cost to the end user."* [Halvey et al., 2006]. As the term suggested, mobility is a significant advantage of the Mobile Web. As the Web is no longer bound to desktops and laptops, accessing the Web from mobile devices provide instant access to information anytime and almost anywhere. In this section, we will go through the main characteristics of the Mobile Web and highlight the issues that come along.

[2]See `http://validator.w3.org/mobile/`

Compared to the Web as accessed from desktops and laptops, the Mobile Web has following characteristics:

Presentation Variety: the Mobile Web content is authorised in different markup languages from desktop or laptop Web content. Timmins et al. [2006] conducted a survey that examined the content of over one-million mobile Web pages from around the world. They found that the three most popular mobile Web content formats were WML 1.0, WML 2.0/XHTML Mobile Profile (XHTML-MP) and Compact HTML (C-HTML).

Wireless Markup Language (WML) is a XML-based markup language for mobile devices. WML 1.0 was published in 1998. It is lightweight but not compatible with other languages. WML 2.0, on the other hand, is compatible with XHTML and WML 1.0 and can be used together with XHTML without confusions [WAP, 2001]. XHTML is a new markup language that combines the power of XML for structuring information with the strength of HTML for representing information. XHTML-MP is a language that extends XHTML basic by adding features to enhance the Web experience on resource constrained mobile devices [Pemberton et al., 2002]. The Compact HTML (C-HTML) is a markup language that is created by NTT DoCoMo, a Japanese company, and used in its own wireless service: iMode. It is mainly used on mobile devices in Japan [Kamada, 1998].

Constrained input: due to the device size limitation, the input facilities of a mobile device is usually constrained and inefficient compared to a desktop or laptop computer. This can be further quantified from two aspects: speed and accuracy. Take mobile keypad (12-key keypad) for example, the keys are too small to type with full hand, and a keypad is only suitable for thumb or index finger typing. Thus the typing speed suffers and it is extremely difficult to enter URLs. Silfverberg et al. [2000] predicts that the text entry rate using thumb(s) or index finger(s) ranges from 21 to 27 words per minute (wpm). On the other hand, the confirmed typing speed on standard size QWERTY keyboard is 40 to 60 wpm [MacKenzie and Soukoreff, 2002]. In addition, a mobile keypad usually has three or four letters on each key, thus ambiguity arises. A user has to adopt certain approach to distinguish the target letter from the other letters on that key, such as using the multi-tap method where a user sequentially tap a key several times to select one letter [Silfverberg et al., 2000]. This feature also affects the input speed and accuracy.

Mobility: due to its mobility, accessing the Mobile Web raises unique issues that are not likely to be experienced by desktop Web users. First, mobile users who usually participate in multiple activities while accessing the Web have to distribute cognitive resources between multiple tasks. Oulasvirta et al. [2005] investigate the effect of mobile contexts on a user's cognitive resources. They observe that in mobile contexts, a user's attention to a mobile device is often distracted by the surrounding environments, and a user's continuous span of attention is much shorter. A user often divides his attention into small shares and distributes them between other activities besides browsing. Based on this observation, Oulasvirta points out that when accessing the Web in mobile contexts, a user's cognitive resource is competed for and shared by other activities he partly participates in, and the user's attention to the Web declines. Second, the environment factors are also likely to affect a user accessing the Mobile Web. For example, poor lighting conditions, such as sunlight reflection on screen, may affect a mobile user's colour perception and contrast sensitivity, thus increase reading difficulty. In addition, noisy environment will also affect a mobile user's perception of audio information. Also, Accessing the Mobile Web in a bumpy environment, such as entering URL on a bus, will also be likely to affect speed and accuracy, thus resulting inaccessible experience.

Restrained resources: because of the restrained resource of mobile devices, such as small screen, low memory and CPU power, a mobile device usually cannot render the same Web document as used for desktop or laptop computers. From the aspect of a Web developer, he either needs to create a separate version of a Web page specific for mobile devices, or adopts different CSS files for desktop computers and various mobile devices. Adapting the Web from desktop computers to mobile devices faces many problems, navigation is one of them. As the screen size becomes smaller, each Mobile Web page contains less content, thus the amount of scrolling within a page and navigation between pages will increase. [Chae and Kim, 2004]'s study shows that as scrolling and navigation become more often, it is harder for a user to refocus, and the user is more likely to get lost.

Capability differences: due to the capability differences of different mobile devices, device independence issues arise. There are variations in page rendering and layout in different devices. Different devices have different processing power and presentation support. High-end devices support high definition video materials whereas some of the low-end devices only support texts. Therefore, it is difficult for the Web developer to cover all of the requirements from different mobile devices.

Network traffic: Mobile Web relies on wireless connection which usually has high communication cost and sometimes poor connectivity. This in turn will affect the Mobile Web's accessibility and even users' browsing behaviour. Take mobile based Web service for example, due to the usage of XML, requests and replies are larger compared to traditional web interactions and the need for parsing the XML code in the requests adds additional server overhead. According to Tian's experiment [2004], this overhead can be more than five times larger than the original content. Transferring such a large information chunk on wireless connection is time consuming and costly. One solution is to compress a package before sending it out and decompress it on receiving. However, the compression/decompression process will still take time and increase the device workload [Tian et al., 2004].

In summary, the Mobile Web users face accessibility problems caused by low input bandwidth, restrained computing power, diverse device capability and network connectivity. These problems affect different small device users at different occasions. As Sears and Yong pointed out, able–bodied individuals can be affected by both the environment in which they are working and the activities in which they are engaged, resulting in situationally–induced impairments [Sears and Young, 2003b]. For example, an individual's typing performance may decrease in a cold environment in which one's finger does not bend easily due to extended exposure at low temperature. Anecdotally, Trewin suggests that there are strong similarities between physical usability issues in both small–device and accessible desktop Web browsing scenarios. Both small–devices and accessible Web Browsers share the need to support various input techniques; they both benefit from flexibly authored and accessible Web pages; and text entry and navigation in both scenarios are slow and error-prone [Trewin, 2006].

2.4 Overlapping experiences between the Accessible and the Mobile Webs

This section looks at accessibility and usability problems faced by both disabled Web users and the Mobile Web users from the perspective of four basic sensory abilities: visual ability, hearing ability, motoring ability and cognitive ability.

The section explains how defects in each sensory ability would affect user experiences of a computer user, and also draws similarity between problems caused by disabilities of individuals and that caused by device used and environment.

2.4.1 Visual Impariment

Low vision refers to low visual acuity (i.e., person's ability to resolve fine spatial detail), low contrast sensitivity (i.e., person's ability to detect pattern stimuli at low to moderate contrast levels), low visual field (i.e., the useful field of view is the total area over which effective sight is maintained), low colour perception and also sensitivity to glare and rapid shifts in brightness [Jacko et al., 1999, Asakawa, 2005, Hawthorn, 2000]. These problems seriously effect the input efficiency and effectiveness and are usually experienced by visually impaired and ageing users [Jacko et al., 2000].

On closer inspection, small device users also experience similar problems related to vision loss. Compared to desktop displays, the screen size of small devices is much smaller which means that the visual field of a mobile user is also restricted. A number of studies show that screen size does have an effect on performance. Other studies demonstrate that users of small screen devices are less effective in completing tasks than the large screen users [Jones et al., 1999, Reisel and Shneiderman, 1987, Duchnicky and Kolers, 1983] . Some studies also show that due to small screen size, users browse Web pages differently. For instance, Dillon [1990] shows that small screens result in many more page forwards and backwards interactions when subjects were asked to read and summarise text presented in small window.

Likewise Chae et al. [2004] have demonstrated that as each page visible on a small screen contains less content, smaller screen size increases the scrolling within a Web page and navigation between Web pages. Furthermore, as scrolling and navigation tasks are performed more often, it gets harder for users to refocus their attention. These studies also show that smaller screen size increases users' perceived depth, which was introduced to measure the user's understanding of the information structure, and thus they can easily get lost [Jacko et al., 1999]. Additionally, in order to fit large Web pages on a small screen, the size of an on-screen object, such as text, a link, or an icon is usually reduced to smaller sizes than those on a desktop display. This increases the difficulty in reading, especially for ageing small device users, and are similar to visually impaired users' low visual acuity. Furthermore, as small devices are usually used in 'off-desk' environment, poor lighting conditions, such as sunlight reflection on screen, may affect a mobile user's colour perception and contrast sensitivity, increasing reading difficulty [Carter et al., 2006].

To address problems related to vision loss, there are two main approaches. The first is to magnify or highlight the screen especially the input area (e.g., pointing area) to improve the visibility, for example, a screen magnifier can be used to overcome the difficulties related to low vision [Fraser and Gutwin, 2000]. Second is to explore the usage of senses other than vision such as using voice recognition, auditory feedback [Brewster, 2002] and haptic feedback[3] to reduce dependence on visual interaction [Brewster, 2002, Brewster et al., 2007, Wall and Brewster, 2006b, Paek and Chickering, 2007, Oviatt, 2000]. There are also solutions that combine a number of modalities to increase the input efficiency which is called multi–modal input. Although multi–modal, speech, visual and haptic feedback proved to be useful for visually impaired users, we cannot find any work showing they are also useful for ageing users. Therefore, further studies can be conducted to transfer these solutions to ageing users.

2.4.2 Hearing Impairment

Hearing loss refers to the problem experienced by hearing impaired or ageing users whose hearing are reduced and have difficulty in accessing audio content on the Web [Hanson, 2007]. In particular, hearing loss is associated with the deterioration of the ability to detect tones over all frequencies, especially high pitched sounds, and also with the reduced ability to localise sound [Hawthorn, 2000]. In a noisy environment, small device users may also experience a similar problem. For example, services on mobile phones such as voice mail require a user to input with keypad according to voice prompts, such as 'press one to hear new messages'. When accessing such services in noisy environments, a user may have difficulty in hearing the voice prompt, which may cause input error. Visually impaired, motor impaired and cognitive impaired users are unlikely to be affected by this problem.

Enlarging the cursor and gaining-diminished targets are used for addressing the hearing difficulty for hearing impaired, ageing and small device users [Brown,

[3]Throughout this thesis, haptic feedback is used as a generic term that refers to both tactile and force feedback [Oakley et al., 2000].

1992]. Visual feedback should include a highly visible prompt (screen flash, icon, or other symbol) to notify the hearing impaired user about an event. For making audio content accessible on the Web, subtitles are also required [Chisholm and Vanderheiden, 1999]. Similarly, with visual feedback the small device users can also monitor their input from on screen display.

Another solution for this problem is the usage of haptic feedback. It is mainly introduced to improve input performance of small device users show that compared to standard buttons, with haptic feedback via vibrotactile users enter significantly more text and made fewer errors [Brewster et al., 2007]. Although such studies show the advantages of using haptic feedback, we could not find any study in the literature to show the efficiency and effectiveness of haptic feedback for hearing and ageing users.

2.4.3 Physical Impairment

A physical impairment affects a person's ability to move, and dexterity impairments are those that affect the use of hands and arms [Sears and Young, 2003b]. In summary, there are two kinds of impairments that affect dexterity: (a) musculoskeletal disorders that arise from loss, injury or disease in the muscle or skeletal system such as loosing all or part of a hand or arm; and (b) movement disorders that arise from a damage to the nervous system or neuromuscular system such as Parkinson's disease which cause slowness of movement [Trewin, 2006]. People with dexterity impairments use a variety of creative solutions for controlling technology these include solutions such as alternative keyboards and pointing devices, voice input, keyboard-based pointing methods and pointing based typing methods, for example eye-tracking [Majaranta and Raiha, 2002].

Depending on the physical impairment, there are a number of challenges that affect users' interaction such as pointing to a target or clicking on a target [Keates and Trewin, 2005]. Our literature survey shows that similar challenges are also experienced by small device users [Brewster, 2002, MacKenzie and Soukoreff, 2002, James and Reischel, 2001] (see Tables 2.1 and 2.2). However, for small device users, the challenge is not because of the severe physical disability, but because of the environment in which users are working in and the current context. We can say that compared to motor impaired users, small device users experience situationally-induced impairments which occur temporarily [Sears and Young, 2003b].

2.4.4 Cognitive Impairment

Cognitive problems are difficulties in processing information, including such mental tasks as attention, thinking, and memory. They usually occur when there is a difficulty in managing cognitive resources and handling parallel tasks. Specific work indicates that cognitive ability consists of processing speed, attention, visio-spatial skills, abstraction, language processes, working memory and long term storage [Czaja et al., 1998]. Therefore, problems related with any of these abilities can easily affect how users deliver information to the Web. Particularly, cognitive impaired users, who have declines in divided attention, and ageing people, who have declines in processing capabilities, may have cognitive problems [Newell et al., 2003, Czaja et al., 1998, Dawe, 2007]. Motor impaired, visually impaired and hearing impaired users are also very likely to be affected by cognitive problems. On the other hand, small device users who usually participate in multiple activities (e.g., talking, walking, way finding, sidestepping, etc.) while accessing the Web also have to distribute cognitive resources between multiple tasks [Oulasvirta et al., 2005, Lin et al., 2007]. Oulasvirta et al. [2005] investigated the effect of mobile contexts on a user's cognitive resources. They observed that in mobile contexts, a user's attention to mobile device is often distracted by the surrounding environments and a user's continuous span of attention is much shorter. Based on this observation, they pointed out that when accessing the Web in mobile contexts, a user's cognitive resource is competed for and shared by other activities he partly participates in, and his attention to the Web declines. However, there is a gap in the literature on understanding how this cognitive problem affects a mobile user's input performance, such as task completion time or error rate.

2.4.5 Older Users

The world's older[4] population is expected to exceed one billion by 2020. Research shows that approximately 50% of the older population suffers from disabilities such as hearing loss that hinders social interaction [Fisk et al., 2004]. One in five people over the age of 65 are disabled. Population demographics indicate that our populations are ageing across the board. As the population ages the financial requirement to work more years is increased, but age-related disability

[4] This term has been defined in numerous ways; [Nichols et al., 2001] defines as "over 58".

becomes a bar to employment [Mitchell et al., 2006]. At present, only 15% of the 65+ age-group use the internet[5], but as the population ages this number will significantly increase. An aging, but Web literate, population indicates a large market for online services especially when mobility is a problem for the user. In many developed countries, the growth of the knowledge economy and a move away from manual work should improve the prospects of older Web users being able to find employment, providing technology, and specifically the Web, is accessible to them [Fisk et al., 2004].

The aspects of impairment that define ageing is those of a combinatorial nature [Schieber, 1975]. In effect, ageing users have problems found in one or more of the groups listed in this section, but often, these impairments are less sever but more widespread than across impairments.

The four key factors that we have discussed show that small device users can easily have problems with input because of the environment that they are working in and the current context. As summarised below, these factors also confirm the commonalities among disabled and small device users, and show that small device users can experience situationally-induced impairment [Sears and Young, 2003b].

- Because of the limited screen size and lighting conditions, small device users can experience low vision problem similar to visually impaired and ageing users;

- small device users can experience hearing problems because of a noisy environment, as hearing impaired and ageing users do;

- small device users can experience physical limitations as motor impaired and ageing users do (such as not being able to use two hands to type text messages) because of using small devices while walking through an obstacle;

- Because of allocating cognitive resources between multiple tasks, small device users can easily experience cognitive problems as cognitively disabled and ageing users do.

[5]In the UK: `http://www.statistics.gov.uk/`

2.5 Input Problems Affecting Disabled Desktop Users and Mobile Web Users

To support the discussions in previous section, this section presents a systematic literature survey on accessibility problems affecting both disabled computer users and small device users. Our survey identifies twelve key input specific issues experienced by both disabled computer users and small device users. We have grouped these issues into two regarding the basic tasks that people perform: text input; and target acquisition (also referred as "pointing"). These two broad categories, along with the twelve problems and corresponding solutions, are discussed below and summarised, respectively, in Table 2.1 and 2.2.

As shown in Table 2.1 and Table 2.2, we created a matrix that presents the identified input problems along with their corresponding solutions. References are included in the matrix to support the existence of each problem. Cells marked with "×" imply that the user groups are not likely to be affected by an output problem. On the other hand, cells marked with "?" indicate open areas in existing research, which motivate further investigations. The matrix also present existing solutions employed by different user domains to the same problem, which suggest possibilities of solution migrations across user domains.

Table 2.1: Text Input Accessibility Issues and Corresponding Solutions. *Situationally–Induced Impairments

	Motor		**Visual**		**Hearing**		**Cognitive**		**Small Device***		**Ageing**	
	Prob.	Soln.	Prob.	Soln.	Prob.	Soln.	Prob.	Soln.	Prob.	Soln.	Prob.	Soln.
P1: Long key press	Trewin and Pain [1999], Brown [1992]	S1, S14	×		×		?		?		?	S1, S14
P2: Simultaneous keys	Trewin and Pain [1999], Brown [1992]	S2	?		×		?		?	S2	?	S2
P3: Additional keys	Trewin and Pain [1999]	S3, S4	?		×		×		?		?	S3, S4
P4: Bounce error	Trewin and Pain [1999]	S5, S14	×		×		×		James and Reischel [2001]		Brown [1992]	S5
P5: Missing keys	Trewin and Pain [1999]		×		×		×		MacKenzie and Soukoreff [2002], James and Reischel [2001]		?	
P6: Transposition	Trewin and Pain [1999]		?		?		?		MacKenzie and Soukoreff [2002]		?	
P7: Key size	?		?		×		?		Silfverberg et al. [2000]	S15, S17	?	
P8: Key ambiguity	Arnott and Javed [1992]		×		×		×		Silfverberg et al. [2000], Butts and Cockburn [2002]	S18, S19, S20, S13, S32	×	
P9: Inability to use keyboard	Sears and Young [2003b]	S6, S7, S8, S9, S10, S11, S12, S23, S24, S25, S29, S30	?	S11, S13, S15, S17, S29	×		Newell et al. [2003], Dawe [2007]	S30	Newell and Gregor [1997]	S7, S9, S11, S12, S13, S15, S17, S21, S23, S24, S29	×	

Note: *'Im.'* – impairment '×' – no problem *'?'* – further investigations needed *empty cell* – no solutions exist

Solution indices and names:

S1: Repeat key [Trewin and Pain, 1999]	S2: Sticky key [Trewin and Pain, 1999, Wigdor and Balakrishnan, 2003]	S3: Key-guard [Trewin and Pain, 1999]	S4: Slow key [Trewin and Pain, 1999]	S5: Bounce key [Trewin and Pain, 1999]
S6: One-hand keyboard [Matias et al., 1996]	S7: Soft keyboard [Myers et al., 2002, Felzer and Nordmann, 2006, Majaranta and Raiha, 2002, Masui, 1998]	S8: Trackball [Wobbrock and Myers, 2006]	S9: Joystick [Wobbrock et al., 2004, 2007]	S10: Eye tracking [Majaranta and Raiha, 2002]
S11: Voice [Manaris and Harkreader, 1998, Sawhney and Schmandt, 2000, Hawthorn, 2000, Neto et al., 2009]	S12: Prediction [Mankoff et al., 2002, Felzer and Nordmann, 2006, Masui, 1998, Dunlop and Crossan, 2000]	S13: Chording [Blenkhorn and Evans, 2004, Wigdor and Balakrishnan, 2004]	S14: Dynamic keyboard [Trewin, 2004]	S15: Auditory feedback [Brewster, 2002, Sawhney and Schmandt, 2000, Brewster et al., 2003, Friedlander et al., 1998, Pirhonen et al., 2002]
S17: Haptic feedback [Brewster et al., 2007, Pascoe et al., 2000, Pirhonen et al., 2002, Harrison et al., 1998, Poupyrev et al., 2002]	S18: Multi-tap [Silfverberg et al., 2000, Butts and Cockburn, 2002, James and Reischel, 2001]	S19: Two-key [Silfverberg et al., 2000, Butts and Cockburn, 2002]	S20: T9 method [Silfverberg et al., 2000, James and Reischel, 2001]	S21: Handwriting [MacKenzie and Soukoreff, 2002]
S23: Tablet [Wobbrock et al., 2004]	S24: Touchscreen [Wobbrock et al., 2004, Pascoe et al., 2000, Matsushita et al., 2000]	S25: Switch [Felzer and Nordmann, 2006]	S29: Multimodal [Malkewitz, 1998, Pirhonen et al., 2002, Brewster et al., 2003, Serrano et al., 2006]	S30: Predefined text [Majaranta and Raiha, 2002, Newell et al., 2003, Dawe, 2007]
S32: Tilt text [Wigdor and Balakrishnan, 2003]				

Table 2.2: Pointing Related Accessibility Issues and Corresponding Solutions. *Situationally–Induced Impairments

	Motor		**Visual**		**Hearing**		**Cognitive**		**Small Device***		**Ageing**	
	Prob.	Soln.	Prob.	Soln.	Prob.	Soln.	Prob.	Soln.	Prob.	Soln.	Prob.	Soln.
P10: Pointing and dragging	Trewin and Pain [1999], Riviere and Thakor [1996], Hwang et al. [2004]	S17, S33, S35	Jacko et al. [2003]	S15, S16, S17, S31	×		?		Brewster [2002], Smith et al. [1999]	S15, S17, S33	Riviere and Thakor [1996], Chaparro et al. [1999], Moffatt and McGrenere [2007], Walker et al. [1997]	S16, S31
P11: Clicking	Trewin and Pain [1999], Trewin et al. [2006]	S15, S34	Jacko et al. [2003]		×		?		Brewster [2002]	S15	Trewin and Pain [1999], Smith et al. [1999], Chaparro et al. [1999], Moffatt and McGrenere [2007]	
P12: Inability to use mouse	Sears and Young [2003b]	S8, S9, S10, S11, S22, S23, S24, S25, S26, S27, S28	Jacko et al. [2003]	S11, S17, S26, S29	×		×		Greenstein [1997], Brewster et al. [2003]	S8, S9, S11, S17, S23, S24, S26, S29	×	

Note: *'Im.'* – impairment '×' – no problem *'?'* – further investigations needed *empty cell* – no solutions exist

Solution indices and names:

S8: Trackball [Wobbrock and Myers, 2006, Wobbrock and Gajos, 2007]	S9: Joystick [Wobbrock et al., 2004]	S10: Eye tracking [Majaranta and Raiha, 2002]	S11: Voice [Sawhney and Schmandt, 2000, Hawthorn, 2000]
S12: Prediction [Mankoff et al., 2002, Felzer and Nordmann, 2006]	S15: Auditory feedback [Brewster, 2002, Fraser and Gutwin, 2000, Sawhney and Schmandt, 2000, Brewster et al., 2003, Friedlander et al., 1998]	S16: Target size and distance [Fraser and Gutwin, 2000, Worden et al., 1997, Grossman and Balakrishnan, 2005]	S17: Haptic feedback [Brewster et al., 2007, Fraser and Gutwin, 2000, Hwang et al., 2005, 2003, Pascoe et al., 2000, Pirhonen et al., 2002, Poupyrev et al., 2002]
S22: Head-tracking [Kjeldsen, 2006]	S23: Tablet [Wobbrock et al., 2004]	S24: Touchscreen [Wobbrock et al., 2004, Pascoe et al., 2000, Matsushita et al., 2000]	S25: Switch [Felzer and Nordmann, 2006]
S26: Shortcut [Mankoff et al., 2002]	S27: Scanning [Mankoff et al., 2002]	S28: Wrapping [Mankoff et al., 2002]	S29: Multimodal [Malkewitz, 1998, Pirhonen et al., 2002, Brewster et al., 2003]
S31: Screen magnifier [Fraser and Gutwin, 2000]	S33: Goal crossing [Wobbrock and Gajos, 2007, Apitz and Guimbretiere, 2004]	S34: Steady Clicks [Trewin et al., 2006]	S35: Barrier pointing [Froehlich et al., 2007]

2.5.1 Text Input

Different techniques and devices are available for text input such as keypad, voice recognition system, eye-tracking, head-tracking, etc., however, the keyboard is still the most widely used. Our survey shows that either because of an impairment or a situationally-induced impairment [Sears and Young, 2003b], the task of inputting text can easily become challenging. From reviewing the literature, we have identified nine problems related to text input which we list here and compare them across different user groups (Table 2.1, P1-P9). These range from very well-defined problems, such as pressing a key unintentionally, to very generic problems, such as not being able to use a keyboard.

Long Key Press Error

Long key press error occurs when a key is unintentionally pressed longer than the default key repeat delay (i.e., a delay before a pressed key starts to repeat itself), generating unwanted characters [Trewin and Pain, 1999]. This problem affects disabled people who have limitations in fine motor control and thus have difficulties in releasing a key quickly [Brown, 1992]. According to Trewin and Pain's experiments [1999], long key press error is the most significant source of performance error for motor impaired and ageing users. Two solutions exist for long key press error: A repeat key facility (S1) allows a user to manually adjust default key repeat delay [Trewin and Pain, 1999]; and dynamic keyboards (S14), which automatically self-adjusts to their input mechanisms, such as key repeat delay, to suit a users' typing requirement [Trewin, 2004].

Long key press error is unlikely to affect visually impaired or hearing impaired users. However, it may affect cognitive impaired and small device users. Cognitive impaired users who have declines in attention have difficulties in managing simultaneous tasks [Newell et al., 2003]. While a cognitive impaired user is typing, their attention can be distracted by other activities, resulting in a longer key press. small device users' attention, when typing, is usually distracted by other activities they participate in, such as walking and talking [Lin et al., 2007, Barnard et al., 2005]. In addition, small devices are used in off-desk environments, such as in a moving car or crowded bus. These factors make it highly likely that a long key press error can happen. In addition, as small device users' requirements of a key repeat feature may change in different environments, and therefore, it may be beneficial for small device users to adopt a dynamic keyboard

(S14) which will capture such changes in the environment.

Simultaneous Key Press Error

Simultaneous key press error happens when a user cannot press two keys simultaneously, this results in difficulty when using modifier keys, such as 'Ctrl' and 'Shift' [Trewin and Pain, 1999]. Simultaneous key press error is found in both the motor impaired and ageing user groups [Trewin and Pain, 1999]. The Sticky key facility (S2) can address simultaneous key press error because it facilitates the modifier keys being held and therefore enables key press sequences to be performed as though they had been pressed simultaneously [Trewin and Pain, 1999].

Simultaneous key press error is unlikely to affect hearing impaired users or partially sighted users. However, profoundly blind users, who use a normal keyboard, may be affected by this problem because it is difficult for them to locate the positions of two keys without visual interaction. In addition, cognitively impaired users who have difficulty in synchronising two hands may also find it difficult to perform simultaneous key pressing, although here is no work in the literature to show the existence of such problems. small device users may also be affected by this problem, especially when they only have one hand free for typing.

Additional Key Error

Additional key error occurs when keys that are adjacent to the intended one are accidentally pressed; this is a common error for motor impaired and ageing users [Trewin and Pain, 1999]. There are two solutions for this problem: Keyguard (S3), which is an overlap with holes that separate adjacent keys on a keyboard; and the slow key facility (S4), which introduces a certain period of time for which a key needs to be held down in order to be detected, so that the unintended key press will, likely, not be detected [Trewin and Pain, 1999].

While hearing and cognitive impaired users are not likely to be affected by this error, small device users who use keypads for text entry are likely to be affected. It is possible that a mobile user will press an adjacent key by mistake because of the small key size and the compact layout of the mobile keypad; we believe that the slow key facility (S4) may address such problems. Further, this may also be a potential problem for visually impaired users since they may unintentionally press a key adjacent to the targeted one.

Bounce Error

Bounce error occurs when a user unintentionally presses a key more than once, producing unwanted copies of the intended key. This problem is observed for both motor impaired and ageing users, and is mainly due to a users' finger twitching when releasing a key [Trewin and Pain, 1999]. small device users mainly experience this problem when they use a multi–tap input system where the user presses each key one or more times to specify the desired letter [MacKenzie et al., 2001, James and Reischel, 2001]. A multi-tap method works by cycling through letters on a key with each successive press, however this causes problems when two letters on the same key are entered consecutively [Silfverberg et al., 2000]. There are two approaches to address this problem: a fixed time–out is used to decide when a user has finished cycling through letters on a key [Butts and Cockburn, 2002] or a special key is used to skip the 'time-out' ('timeout kill') [MacKenzie et al., 2001]. However, these two approaches increase the possibility of experiencing a bounce error, for example a key can be pressed more than needed selecting an incorrect letter or the special key can be pressed more than once producing unwanted characters.

One possible solution is the Bounce key facility (S5) which inserts a short delay (debounce time) after a key press during which the key cannot be reactivated and thus reduces bounce error [Trewin and Pain, 1999]. In addition, dynamic keyboards (S14) can also be used to monitor a users' key pressing time and adjust its debounce time accordingly [Trewin, 2004]. Bounce error is not common among visually impaired, hearing impaired and cognitive impaired users, however, for small device users, the bounce key facility (S5) or dynamic keyboard (S14) may be used to eliminate this problem; further studies need to be undertaken to demonstrate the effectiveness of these approaches.

Missing Key Error

Missing key error occurs when a key is pressed without sufficient force to activate it. This problem affects motor impaired and ageing users [Trewin and Pain, 1999]. While the problem is unlikely to affect visually impaired, hearing impaired and cognitive impaired users, MacKenzie and Soukoreff [2002] report 'omitting characters' as one basic error when entering text on mobile phones; this finding supports the existence of missing keys error in the situational domain. However, there are no solutions in the literature which address this problem.

Transposition Error

Transposition error refers to the situation which occurs when two characters are typed in reverse order [Trewin and Pain, 1999]. This problem is observed with motor impaired, ageing and small device users Trewin and Pain [1999], MacKenzie and Soukoreff [2002], and may also affect visually impaired, hearing impaired and cognitive impaired users. Similar to the missing key error (P5), there is no direct solution for dynamically reducing transposition error, although the problem can be addressed by retrospective spell checking.

Small Key Size

Key size (small) is a problem specific mainly to small device users. A mobile keypad is only suitable for thumb or index finger typing because of the constrained size of the device. As a result, text entry is slow and can be tiring. Indeed, work suggests [Silfverberg et al., 2000] that the text entry rate using thumbs or index fingers range from 21 to 27 words per minute (wpm). On the other hand, the confirmed typing speed for a standard size QWERTY keyboard is between 40 to 60 wpm [MacKenzie and Soukoreff, 2002]. Auditory (S15) and haptic feedback (S17) on key pressing can be used to improve text entry rate for small device users [Brewster et al., 2007, Brewster, 2002] with haptic feedback users entering significantly more text, making fewer errors, and correcting more of the errors that were made.

Key size may not affect the typing performance of hearing impaired users, but it is likely to affect motor impaired, visually impaired, cognitive impaired and ageing users. This is because as keys become smaller, locating and pressing them without interfering with adjacent ones will become harder, thereby increasing the rate of additional key press error.

Key Ambiguity

Key ambiguity is another problem mostly with small device users although work in the assistive technology domain does exist [Arnott and Javed, 1992]. As each key on a mobile keypad usually contains three or four letters, ambiguity arises, which means a mobile user needs to distinguish a target letter from the other letters on the key. As key ambiguity is a specific feature for mobile keypads, it is unlikely to affect the other user groups who tend to use standard QWERTY keyboards. In this case specific mobile solutions have been evolved such as chording (S13), the multi-tap method (S18), the two-key method (S19), the T9 method (S20), or tilt text (S32) can be used to remove key ambiguity. In a Multi-tap system (S18), the alphabet is divided into eight separate keys, as typically found on a keypad, and one key is used to enter more than one character [Butts and Cockburn, 2002]. Chording (S13) allows a user to type by pressing different keys together; a method of key combination [Wigdor and Balakrishnan, 2004]. The T9 method (S20), which stands for "text on 9 keys", allows words to be entered by a single keypress for each letter [Silfverberg et al., 2000]. This method mainly uses a dictionary and tries to guess the word the user is trying to enter. Finally, tilt text (S32) is a technique where the orientation of the phone is used to resolve the key ambiguity by tilting the phone in one of four directions to choose which character on a particular key to enter [Wigdor and Balakrishnan, 2003]. Although these alternative techniques address the key ambiguity problem, typing rate is the trade-off [Silfverberg et al., 2000].

Inability to Use the Keyboard

This is a generic problem that affects motor impaired, visually impaired and small device users. For severely motor impaired users who lose control of their arms, hands, or fingers, it is almost impossible to type with standard keyboards [Sears and Young, 2003b]. Similarly, due to the device size limitation, small device users cannot use standard keyboards. In addition, it is also difficult for profoundly blind users to use keyboards, because they need to memorise the position of each key and rely on haptic feedback to confirm key pressing; it is true however, that with extensive touch typing training some of this difficulty can be mitigated. Hearing impaired, cognitive impaired and ageing users may not be affected by this problem.

Summary

In summary, literatures show that there are nine major keyboard–based accessibility problems and some of these problems are shared among our user groups (Table 2.1, P1-P9). Long key press error (P1), simultaneous key press error (P2), additional key error (P3) and bounce key error (P4) are experienced by both motor impaired and ageing users. Bounce error (P4), missing key error (P5) and transposition error (P6) affect motor impaired, mobile and ageing users. The inability to use keyboard problem (P9) is experienced by motor impaired, visually impaired and small device users. Our work also indicates that different user groups that have similar problems share similar solutions. For example, repeat key facilities (S1) and dynamic keyboards (S14), both of which address long key press error (P1), are shared by motor impaired and ageing users. On the other hand, for some problems shared by different user groups, we have observed that solutions are not shared. For example, for inability to use a keyboard (P9) and chording keyboards (S13) only exist for small device users and visually impaired users, but not for motor impaired users. Similarly, bounce key facility (S5) and dynamic keyboard (S14) solutions only exist for motor impaired users to address the bounce error but not for small device users. Therefore, we believe the solutions that are not shared can be transferred across different user groups.

Common Solutions to Text Input Problems

While there are individual solutions to solve certain input problems most solutions aim to solve many problems but for a single user domain. Therefore, we can see that for a generic problem, cross domain solutions may exist for motor impaired, visually impaired and small device users the following section discusses these solutions and the overlaps.

Small–device users share the following solutions with motor impaired users: Soft Keyboard (S7), joystick (S9), voice (S11), prediction facility (S12), tablet (S23), touchscreen (S24) and multi-modal interface (S29). The Soft keyboard (S7) is a program that presents keyboard icons in a graphical user interface and allows a user to input by tapping on-screen icons with fingers or stylus. Soft keyboards are popular on PDAs or smart-phones [Hinckley, 2003]. They are also used by motor impaired users who enter text by tapping the touchscreen with a stylus [Myers et al., 2002]. In addition, joysticks (S9), tablets (S23) and touch-screens (S24) are used for text entry as alternative methods to keyboards (keypads) [Chau et al., 2006, Wobbrock et al., 2004, Mankoff et al., 2002, Felzer and Nordmann, 2006, Silfverberg et al., 2000]. Especially with the iPhone[6], MultiTouch [Hodges et al.] and soft keyboards, technologies are becoming popular alternative methods to conventional keyboards/keypads. Voice control (S11), referring to both speech

[6]iPhone, `http://www.apple.com/iphone/`

recognition and non-speech vocalisations[7] is used over different user groups. For example, applications have been proposed [Harada et al., 2007] that allow users with motor impairments to create artwork by using the non-speech properties of their voice, and similarly in previous work [Harada et al., 2006], a voice-based pointer control technique has been demonstrated. Voice interaction is also used on small devices for speech dialling or editing text messages [Karpov et al., 2006] and used by motor impaired [Neto et al., 2009] and visually impaired users [Manaris and Harkreader, 1998] as a substitute for both the keyboard and mouse. A text entry facility (S12), which 'predicts' the words a user is entering by looking for the most relevant key combination in its internal dictionary [Minneman, 1986] has also been adopted to speed up input. Multi-modal interfaces (S29) which combine a number of modalities such as head movement and speech for motor impaired users [Malkewitz, 1998] and handwriting and speech for small device users [Serrano et al., 2006] have also been suggested as possible input solutions, and are gaining popularity.

Some solutions exist for motor impaired users, but not for small device users: One-handed keyboards (S6), trackballs (S8), eye tracking (S10), and switch interfaces (S25) as well as predefined texts or graphical icons (S30). One-hand keyboards (S6) divide a standard QWERTY keyboard into two parts and allow a user to type with just one hand [Matias et al., 1996]. As a one-hand keyboard is usually half the size of a standard QWERTY keyboard, it is too big for a conventional mobile device. In addition, trackballs (S8) have also been used as an alternative mechanism for text entry [Wobbrock and Myers, 2006]. These devices can be made very small, compared with keypad, touchscreen, or handwriting tablet, they can be very sensitive to control for target acquisition on small devices; only in use on the BlackBerry device to any great extent. Eye tracking technologies (S10) which monitor human gaze and allow a user to type with their eyes [Majaranta and Raiha, 2002] have been suggested. However, as eye tracking technology usually requires a user to wear a sophisticated headset, it is not a practical solution for small device users. Switch interfaces (S25) convert the input requirements of a system into a few simple signals and allow a severely motor impaired user to input text by producing the same signals as though the user were pressing a key or moving a finger [Mankoff et al., 2002]. As switch interfaces are targeted for users who can just perform simple movement, they are

[7] Vocal sounds that do not correspond to any words or phrases in a language.

not suitable for small device users who usually can produce many input signals. Predefined texts or graphical icons (S30) can help users to speed up text editing [Majaranta and Raiha, 2002], and have the additional advantage of helping cognitively impaired users who have learning or language impairments to interact with computers [Newell et al., 2003, Dawe, 2007] more efficiently. From a situational perspective, it may be helpful to use these solutions on small devices and thereby provide predefined messages and patterns to improve data entry speed.

Some solutions exist for small device users but not for motor impaired users, characterised by chording (S13), auditory feedback (S15), haptic feedback (S17) and handwriting (S21) input. As chording (S13) requires much fewer keys than a standard keyboard, a chording keypad can be used with just one hand and thus may be useful to small device users who usually need to type with one hand [Lyons et al., 2004] only. As discussed in simultaneous key press error (P2), some motor impaired users have difficulty in pressing keys simultaneously, so they may not be able to use chording keyboards. However, for motor impaired users who lose one hand but have fine control over the other, chording keyboards may improve their typing performance. Situationally, we think a one-handed chording keyboard solution could be transferred from small device users to the motor impaired domain.

Our survey shows that regarding the inability to use keyboards, all solutions existing for visually impaired users also exist for small device users. For instance, chording (S13) is used by visually impaired users to input Braille from QWERTY keyboards [Blenkhorn and Evans, 2004]. In addition, auditory feedback (S15) and haptic feedback (S17) which are used to improve text entry performance for small device users [Brewster et al., 2007], are also used to represent graphical information for visually impaired users [Wall and Brewster, 2006b,a]. However, there are some solutions for mobile device users that are not suitable for visually impaired users as they require visual interaction such as soft keyboards (S7), joysticks (S9), handwriting (S21), tablets (S23) and touch-screens (S24).

2.5.2 Pointing (Target Acquisition)

The second major task when considering input is target acquisition; pointing and selecting. Our review shows that except for hearing impaired users, all of our user groups have problems in using on–screen target acquisition devices such as the mouse. The two main reasons for these problems are the difficulty of positioning the device cursor within a confined area, and the challenge of accurately executing a click (selection). In this section, we discuss these two major problems as well as some generic issues (Table 2.2, P10-P12).

Pointing

Pointing[8] *and Dragging* with a mouse is difficult for motor impaired and ageing users due to their limited hand movement and control. Trewin [1999] suggests that motor impaired users have problems in pointing at small on-screen objects using a mouse, and that the smaller the object is, the harder it is to pinpoint [Hwang et al., 2004]. We also see that there are two major target acquisition problems for ageing users, these are slipping off the target, and drifting from one option to the other [Moffatt and McGrenere, 2007]. In addition, motor impaired also have difficulty when moving the mouse while holding a mouse button down, this results in poor performance when dragging [Smith et al., 1999, Trewin and Pain, 1999]. Indeed, pointing accuracy and linearity of motor impaired and ageing users is much poorer than that of young people with no impairments [Riviere and Thakor, 1996, Chaparro et al., 1999]. Pointing accuracy also affects small device users who rely on the touch-screen and stylus for input. Brewster's study [2002], illustrates that as the on-screen button becomes smaller, the subjective workload of small device users increases, and the overall performance decreases. Pointing is also a problem for visually impaired users who cannot see clearly [Jacko et al., 2003]. While hearing impaired users generally have no problem in using mouse, cognitive impaired users may find pointing small on-screen items difficult.

Clicking Error

Clicking error refers to the situation that a user slightly moves the mouse while performing a clicking task. This may cause the cursor to move out of scope of the target object[9] and thus generate a clicking error. Studies [Trewin et al., 2006] suggest that clicking error affects motor impaired users as well as ageing users [Smith et al., 1999, Moffatt and McGrenere, 2007, Chaparro et al., 1999]. These studies show that ageing users have more 'slip-off' errors and that the cursor

[8] Pointing is also referred as "target acquisition", "area pointing", "mouse pointing", etc. which is the action of acquiring on-screen targets with the mouse cursor or with a pen/stylus [Wobbrock and Gajos, 2007].

[9] Also referred as accidental clicks [Trewin et al., 2006] or drifting errors [Moffatt and McGrenere, 2007].

leaves the target without completing the click more frequently than younger users. Additional studies [Brewster, 2002], find that 'slip-off' error is also experienced by mobile touchscreen users and similar work [Jacko et al., 2003] shows that clicking error also affects visually impaired users. Although, hearing impaired users may not be affected, it is likely that cognitive impaired users are affected by this problem. We find that auditory feedback (S15) may be employed to address this problem [Fraser and Gutwin, 2000, Brewster, 2002], for instance, by producing a non-speech sound when an item is clicked for confirmation. Finally, the Steady Clicks (S34) method[10], used help people who find it difficult to hold the mouse still while clicking such as motor impaired users, has been suggested as a possible solution.

Inability to Use a Mouse

Inability to use a mouse is a generic problem that affects motor impaired, visually impaired and small device users. Severely motor impaired users find mouse use difficult [Sears and Young, 2003b] as do some visually impaired users with low vision Jacko et al. [2003]. In addition, small device users cannot use the mouse due to device size limitations Greenstein [1997]. However, hearing impaired, cognitive impaired and ageing users typically do not have this problem.

Summary

In summary, our review identifies three issues regarding the usage of pointing devices (Table 2.2, P10-P12): the pointing and dragging problem, the clicking problem and problems when using a mouse. These issues are all shared by motor impaired, visually impaired, mobile and ageing users. We think these problems, especially pointing and dragging (P10) and clicking (P11), could also affect cognitively disabled users, but we could not find any study in the literature to support this[11]. While, some solutions, such as eye tracking (S10) and head-tracking (S22) are specifically targeted for motor impaired users, there are shared solutions for the common problems we have identified. For example, both motor impaired and small device users, who cannot use mouse, adopt joysticks (S9) and voice

[10] Which prevents slipping by freezing the cursor at the mouse down position until either the button is released (resulting in a steadied click) or the mouse is moved beyond a freeze threshold (returning the mouse to normal operation) [Trewin et al., 2006].

[11] See '?' in Table 2.2.

feedback (S11) for item selection and navigation.

Common Solutions to Pointing Problems

Similar to solutions to text input problems, a number of novel techniques and methods exist to improve the problems of target acquisition. Auditory feedback [Brewster, 2002] (S15) can be used to improve pointing performance for small device users. Similarly, haptic feedback [Fraser and Gutwin, 2000] through virtual reality mouse (S17) and screen magnification (S31) can improve pointing performance of visually impaired users. Although further studies are required to confirm this, we believe auditory feedback (S15) can be used to improve the pointing performance of motor impaired and ageing users. Screen magnification (S31) software assists visually impaired users with pointer manipulation in two ways: by improving the pointers visibility and also by tracking and locating the pointer on the fly [Fraser and Gutwin, 2000]. Although screen magnification can potentially improve motor impaired users' experience, we believe, because of the screen size limitation, it would be difficult to use on small devices. Many studies show that small device users benefit from haptic feedback (S17) [Brewster et al., 2007, Pirhonen et al., 2002, Poupyrev et al., 2002] as much as visually impaired users do [Fraser and Gutwin, 2000]. We believe haptic feedback (S17) may also be useful for ageing users but user studies need to be conducted to demonstrate this. Visually impaired users who cannot use the mouse may also share similar solutions with small device users. Indeed, haptic feedback (S17) has been introduced into a standard mouse [Wall and Brewster, 2006a] which then generates different haptic feedback according to different on-screen items it is pointing at. Similarly, haptic feedback is also used on small devices in the form of vibro-tactile display [Williamson et al., 2007]. In addition, multi-modal input (S29), which combines speech and hapticis, has been show to help visually impaired users who need to access complex visual information [Wall and Brewster, 2006b, Oviatt, 2000].

Another solution, shows that enlarging cursor and gaining–diminished targets (S16) improves the performance of ageing and visually impaired users in basic task selection [Worden et al., 1997]. This study particularly proposes two pointing techniques: area cursors (i.e., a cursor that has a larger than normal activation area) and sticky icons (i.e., icons that are designed to have an automatic reduction of the cursor's gain ratio when the cursor is on target). These techniques can also be useful for motor impaired users, however, we think that, because of the screen size of small devices, this would be difficult to adopt.

Further studies [Wobbrock and Gajos, 2007] propose an alternative target acquisition method called goal–crossing (S33). A goal–crossing task involves moving a cursor beyond the boundary of a targeted onscreen object to select it. The work shows that goal crossing is a feasible alternative to area pointing for people with motor impairments. However, because of the technical limitations of this approach such as "the occlusion problem" (one crossing goal obscures another one), it will be hard to migrate to small device users. Similarly, because of the high–demand on visual interaction, it would be hard to adapt to visually disabled users, but on the other hand, ageing users might well find this method useful. Supplementing goal–crossing, the barrier pointing method was introduced (S35) [Froehlich et al., 2007] to improve pointing accuracy. This method uses the screen edges, corners, and the screen surface to support faster and more accurate touch screen target acquisition. However, the evaluation of this method shows that the overall target acquisition times were not statistically significantly different between the normal mode of interaction on most mobile device touch screens with stylus. Although this evaluation also shows that the severely motor impaired users benefited greatly from barrier pointing, a number of issues have to be addressed before it is adapted by able–bodied mainstream small device users [Froehlich et al., 2007].

Inability to actually use the mouse is a major problem. Motor impaired and small device users share the following solutions: Joystick (S9), voice (S11), table (S23), touchscreen (S24) and shortcut (S26). Unlike a mouse, a joystick (S9) does not require much dexterity and a motor impaired user can control it using just one finger [Wobbrock et al., 2004]. In addition, a joystick can be applied to small devices because it can be fabricated to a very small form factor [Greenstein, 1997]. Voice (S11) is widely proposed for on-screen cursor control [Manaris and Harkreader, 1998, Dai et al., 2004, Mihara et al., 2005], and provides both motor impaired and small device users with hands–free solutions. Further, as the memory and processing capacity of current small devices are sufficient to support client-side speech recognition, command and control (C&C) technology has been applied [Paek and Chickering, 2007]. Tablet (S23) and touchscreen (S24) technology can translate finger tapping to cursor control and thereby enable use by both motor impaired users and small device users [Wobbrock et al., 2004, Greenstein, 1997]. The Shortcut system (S26) maps the execution of a program to predefined key combination, such as press 'Ctrl' and 'N' to open a new window. Therefore, shortcuts allow motor impaired users to access a specific program or function directly [Mankoff et al., 2002] and can also be used to improve mobile device accessibility Thimbleby [2000].

In addition to the common solutions discussed above, the following solutions only exist for motor impaired user; not for small device users: Trackball (S8)[12], eye–tracking (S10), head–tracking (S22), the scanning interface (S27), the switch interface (S25), and the wrapping interface (S28). Some studies show that motor impaired users prefer trackballs to mice [Wobbrock and Myers, 2006]. This is especially the case for people with muscle weakness or limited hand movement when rolling a trackball is much easier than moving a mouse back and forth. Eye-tracking technology (S10) is also used to simulate mouse functionality [Majaranta and Raiha, 2002] and enable users with severe motor impairment to draw using their eyes [Hornof and Cavender, 2005], however, the technology is not suitable to small device users due to the size limitations of small devices. Like eye-tracking, head-tracking technology (S22) monitors a user's head movement and uses this to control the on-screen cursor. Head–tracking is useful for motor impaired users who cannot use mice, but have reasonably good head control [Kjeldsen, 2006]. However, technologies like eye–tracking and head–tracking have notable drawbacks including the need for high–end equipment, and extensive configuration and maintenance, indeed, previous work shows that these are significant barriers to the adoption and retention of such assistive devices [Riemer-Reiss and Wacker, 2000, Trewin et al., 2006, Phillips and Zhao, 1993, Dawe, 2006]. In this case, we believe technologies such as these are not practical solutions for small device users as they have not been adopted among those who find them most useful [Riemer-Reiss and Wacker, 2000, Trewin et al., 2006, Phillips and Zhao, 1993, Dawe, 2006]. A scanning interface (S27) automatically and sequentially scans on-screen items, with a standard time period dwelled on each one. While a motor impaired user waits until the intended item is scanned, and selects it using switch interface (S25). Indeed, a wrapping interface (S28) can help the scanning

[12] Mainly used on the BlackBerry and still requires sensitive control for accurate target acquisition.

process by setting scanning directions [Mankoff et al., 2002]. Scanning and wrapping are mainly for severely motor impaired users who can hardly move their hands or fingers whereas small device users may not have similar requirements.

Finally, Steady Clicks (S34) enables users to select targets using significantly fewer attempts, and the overall task performance times are significantly improved for users with the highest slip rates. Steady clicks (S34) could also be usefully adapted for both ageing and small device users. However, the challenges of such adaptations are already discussed [Moffatt and McGrenere, 2007] when modifications are made to support ageing and small device users.

Chapter 3

Small Device User Evaluation While Seated

Chapter 2 presents a survey that reveal the common input problems experienced by disabled desktop users and small device users. The survey also shows gaps in literature: some input problems are likely to affect both disabled users and small device users, but they have not been investigated in details yet. For example, anecdotal evidence suggests that problems caused by limited input bandwidth are similar to problems caused by deficiency or impairments in hand or finger control. This being the case, available research can be leveraged between the two, and existing techniques for motor impaired users can be transferred into the mobile Web in order to address the common problems.

To make an empirical link, this chapter presents a user study that investigated the problems experienced by small device users when typing and pointing with a mobile keypad and touch-screen. The user study adopted an existing methodology which was originally used by Trewin and Pain [1999] to investigate the typing and pointing errors of motor impaired users. Here we reproduced Trewin and Pain's original study with able-bodied small device users. Minor modifications were made to the original methodology in order to account for small devices users. The purpose of this study is to answer the following research questions:

1. Do input errors (see Table 3.1) experienced by motor-impaired desktop users also affect small device users?

   This question defines the scope of common input problems of motor-impaired desktop users and small device users. Investigation allows us to understand

Table 3.1: Typing and pointing errors that affect motor impaired desktop users

Typing errors	
Error Type	*Definition*
Long key press error	A long key press error happens when a key is pressed too long that it repeats itself and generates unwanted copies.
Bounce error	A bounce error happens when a key is unintentionally pressed more than once and thus generates unwanted copies.
Missing key error	A target letter is not typed in, either because the participant's aim is off target, or because the key is not pressed with sufficient force.
Transposition error	This error occurs when two characters adjacent to each other are typed in reverse order.
Additional key error	This error occurs when a key adjacent to the target key is unintentionally pressed, the target key may or may not be pressed.
Key ambiguity error	A key ambiguity error occurs when a participant cannot distinguish different letters on the same key.
Pointing errors	
Error Type	*Definition*
Clicking error	A clicking error occurs when a participant clicks at an unwanted position, or slip-off the target before finishing a clicking.
Multi-clicking error	A multi-clicking error occurs when the cursor or pointer slides between clicks.
Dragging error	A dragging error occurs when the cursor or pointer is lifted up before or after the target ending, or it is landed at one position for too long that triggers the pop-up menu.

the common errors types shared by these two domains. This will drive further investigation on error rates.

2. Does previous experience in text entry and the mobile Web affect a user's error rates?

   Question 2, 3 and 4 aim to understand the error rates and users' experiences, confidence and familiarity with the task. This question looks at the correlation between a user's previous experience and their typing error rates. We assume that the more experienced users are, the fewer typing errors they will make.

3. Does familiarity with text materials or device used in the study affect a user's error rate?

   This question aims to find out whether familiarity with the text materials or the device help to reduce typing errors. We assume that they more familiar users are with the material and the device keyboard, the fewer typing errors they will make.

4. Does a user's awareness in avoiding certain types of error reduces the error rate?

   The last question looks at the correlation between confidence level in avoiding typing errors and the number of errors users make. We assume that the more confident users are, the fewer errors they will make.

Results showed that the Mobile Web users often failed to distinguish different characters located on the same key, which generated key ambiguity errors. The more experiences mobile Web users got in text entry, the fewer key ambiguity errors they made. However, those who felt easier about avoiding key ambiguity errors actually made more errors. Besides, they also pressed keys adjacent to the target key, and missed certain key presses by mistake. In addition, mobile Web users sometimes pressed a key too long and this caused the key to repeat itself. They also accidentally pressed a key more than once, or typed two letters in reverse order. When using a stylus, the Mobile Web users often clicked at wrong places, slid the stylus during multiple clicks, or made errors when dragging the stylus to select text. These error types, apart from the key ambiguity error, were originally observed by Trewin and Pain with motor impaired desktop users.

Therefore, our results have confirmed that despite using different input devices, mobile Web users and motor impaired desktop users share similar input problems.

The remaining sections of this chapter is structured as follows: *Section 5.1* presents the methodology used in our study. *Section 5.2* describes how data collected from the study is analyzed. *Section 3.3* presents the typing results and *Section 3.4* presents the pointing results. *Section 3.5* discusses major findings and limitations of the study. *Section 5.7* summarises the study.

3.1 Methodology

This study adopted Trewin and Pain's methodology [1999] which was used to identify common input errors of motor impaired users. This section summarises the study methodology and particularly provides information about the participants, apparatus, venue, tasks and procedure used, and the data collected.

3.1.1 Participants

A total of 15 participants (5 female and 10 male) aged 19-44 (Mean= 28.27; St. Dev= 5.52) took part in the study. All participants were able-bodied, with no disability. The participants were unpaid volunteers and were recruited through emails and personal contacts. All participants had previous experience in using small devices, and nine of them had experiences in using the mobile Web. Participants were asked to rate their previous experience of text entry from small devices and experiences of using the mobile Web. The results are shown in Table 3.2.

3.1.2 Apparatus and Venue

An HP iPaq PDA was used as the main experiment device. This PDA is equipped with a small-size QWERTY keyboard (see Figure 3.1), a touch screen, a joystick and a stylus. Keys on the keypad repeat in the same way as those on a standard keyboard, with an initial delay of 500 msec before the repeat starts. Modifier keys operate in latch mode. The keyboard itself has three modes: one for letters, one for numbers, and one for punctuation. The mode determines what character is produced for a given key press. Thus, switching between typing letters, numbers and puctuation provides an opportunity for a new form of error: the key ambiguity error, discussed later. Three participants had used this PDA before.

Table 3.2: Subjective ratings of our participants for their previous experience of text entry and the mobile Web (1= none, 5= expert)

Participant	*Text entry experience*	*Mobile Web experience*
N1	3	2
N2	2	2
N3	2	1
N4	4	1
N5	5	4
N6	5	5
N7	4	1
N8	3	1
N9	3	2
N10	5	3
N11	3	2
N12	4	3
N13	3	2
N14	3	1
N15	3	1
MEAN	3.47	2.07
STDEV	2.07	1.22

Figure 3.1: HP iPAQ hw 6900 keyboard.

All participants were asked to access a set of experiment Web pages using the Opera Mobile browser [1] from the given PDA, and to conduct a number of typing and pointing tasks on each Web page. Their keystrokes and cursor movements were logged by the UsaProxy[2] software which is a Web proxy that sits between the Web server and client and records input events.

The study was conducted in a quite lab room. Three digital video (DV) cameras were mounted to tripods surrounding the participant, one in front, the other two on the participant's left and right hand side. These cameras recorded the participant's performance from three angles, so that actions not captured clearly from one angle could be compensated from the other ones.

3.1.3 Tasks

The sequence of tasks and tasks themselves were the same as Trewin and Pain's study [1999]. However, the differences between the desktop and small devices meant that the original study could not be precisely replicated. In adapting the original study to the small device environment, the aim was not to assess the usability of an application, but to identify users' errors and experience when performing typical tasks. Therefore, where a desktop task referred to mouse-specific or keyboard-specific items or actions, this was either adapted to the most reasonable equivalent on the small device, or dropped from the study. Three

[1]See `http://www.opera.com/products/mobile/`

[2]See `http://fnuked.de/usaproxy/`

different tasks were used in the original study[3]:

1. *Typing tasks (T)*: participants were given a text passage to type. The original passage was used, which deliberately included characters on all parts of the keyboard. It required a minimum of 553 key presses on the small device. The text material used for this task is attached in Appendix A

2. *Pointing tasks (P)*: participants were asked to conduct 16 sub-tasks, which included tapping, multi-tapping and dragging with a stylus on the PDA. For instance, to select a piece of text with the stylus, dragging is performed by putting down the stylus onto the screen at the starting point of the text and moving the stylus while holding it down and then lifting up the stylus at the end of the text to complete the selection. Three changes were made to the original pointing sub-tasks: a click on a ClarisWorks application button in the top left of the screen was replaced by a tap on a Wiki button of similar size and position; one mouse-specific sub-task (repositioning the mouse on the mousepad) was omitted; and one multi-clicking sub-task that had no specific target was omitted. Appendix B list all pointing tasks.

3. *Editing tasks (E)*: participants were asked to make a set of edits to a given text passage. The original tasks and passage used in the desktop study were used, with some modifications. The text passage to be edited was reflowed to fit the width of the PDA screen. One of the original tasks required the use of the Apple modifier key on the Macintosh keyboard. This was replaced with a use of the Control modifier key on the PDA keyboard. A full list of editing tasks can be found in Appendix C.

In the typing tasks, participants were only allowed to use the physical keypad. They were not allow to use the on-screen keyboard Similarly, in the pointing tasks, they were only allowed to use the touch screen and the stylus. In the editing tasks, they were allowed to use both. Editing tasks were mainly introduced to see the error rates, when more than one input techniques are used together to perform a task. Each task was assigned a unique code: 'T' represents typing tasks, T1 represents first time they were performed and T2 represents the repetition. 'P' represents pointing tasks, and again P1 represents the first time they were

[3]Details of the tasks used in this study can be found at `http://hcw-eprints.cs.man.ac.uk/81/`.

performed and P2 represents the repetition. Finally, 'E' represents editing tasks. In the pointing tasks, sub-tasks required different actions, in order to differentiate those we also used the following: 'C' represents clicking action, 'M' multi-clicking action and 'D' dragging action. For example, P2.11D refers to the 11th sub-task (dragging task) of the repeated pointing tasks.

3.1.4 Procedure

In this study, a double-blind procedure[4] was followed and an external experimenter was used to conduct the study [Anthony and Graziano, 2006]. The study was divided into three sessions: background session, main task session and feedback session. In the background session, the experimenter collected demographic information from each participant, such as age, previous experiences on typing with a small device, and preferred input techniques. After the background session, the participant was given a PDA and had 5 minutes to practice. This was to ensure that the participant was familiar with the device before conducting the main tasks.

When the participant was ready, the experimenter loaded the first experiment Web page into the PDA and started the main task session. The experimenter did not specify how the participant is supposed to use the device but they were all asked to be seated and were allowed to hold the device in their hand or use it on the table. Five tasks were conducted in the main task session and the original sequence of the tasks is replicated. Participants were asked to conduct typing tasks, pointing tasks and editing tasks in sequence, and then to repeat the pointing tasks and the typing tasks which was the sequence followed in the original study. As it is explained by Trewin and Pain [1999] *"since this study was concerned with physical input errors, it was desirable to minimize other errors such as misunderstanding the task. Ideally, this would have been achieved by allowing participants to practice the tasks prior to recording. However, because the experimental sessions were limited to 2 hours, and many participants became fatigued in less than 2 hours, providing long practice sessions would have greatly reduced the volume of data recorded, and the beneficial effects of practice may have been counterbalanced by detrimental effects of cognitive fatigue. In addition, the*

[4]In a *double-blind procedure*, the researcher and participants are blind to the details of the study, for example they do not know the hypothesis being tested, the nature of the experimental and control conditions, and the condition to which each participant is assigned [Anthony and Graziano, 2006].

goal of the study was to examine as wide a range of typing and pointing operations as possible. For this reason, tasks which repeated the same operation many times were also not appropriate. As a compromise, participants were asked to perform the same set of typing and pointing tasks twice".

Participants were not allowed to correct their errors in first trials of the typing tasks and the pointing tasks. However, in the repetitions, error corrections were allowed. Participants were not allowed to use the joystick or onscreen keyboard (via the touch screen) when performing typing tasks, likewise, they were not allowed to use the keyboard when performing pointing tasks.

Task materials, including text passages and instructions, were printed out on a set of A4 size sheets, and were handed out to the participants before the main task session (please refer to Appendix A for the text message used in typing tasks). The participants were asked to follow the instructions, and to perform the tasks by themselves. When participants finished one set of tasks, they should click a link at the bottom of that Web page, and a Web page for the second task set would load. During the process, the experimenter observed the participants and provided helps on technical problems, such as the browser shutting down by accident. In order to avoid bias, the experimenter was not allowed to provide any guidance on how to conduct the tasks.

In the feedback session, participants were asked to rate their typing and pointing performance in the previous tasks. Example questions include: how easy it is to locate the right key and to avoid key ambiguity; how easy it is to release a key quickly and to avoid long key press; how easy it is to avoid pressing additional key; and how easy it is to perform a click. Answers were made on a seven-point scale, with "1" representing "very difficult" and "7" representing "very easy". These ratings reflected participants' awareness or confidence in avoiding typing and pointing errors.

The length of the whole study varied from 40 minutes to 90 minutes, depending on an individual's performance. The study was video recorded for future analysis. An assistant operated the DV cameras, but was not allowed to talk to either the experimenter or the participant.

3.2 Data Analysis

Following data was collected from this study:

1. An automatically generated log file of input events was produced for each participant by the UsaProxy software. The log file consisted of time-stamped input events, including key-down, key-press, key-up and cursor movement events.

2. Three video clips of the participants performing the tasks were recorded, from three different angles.

3. Observations made by the experimenter during the study were written down on paper.

4. Background information recorded before the main tasks and feedback collected in the feedback session were also noted down.

Three variables are analysed based on the collected data: time spent on each typing and pointing task; errors made by each participant; and their subjective ratings of previous experiences and task performance. The duration of each task was retrieved from the time stamps in each log file. Errors were identified by comparing the logs and video recordings with the original task materials, and were manually annotated in the log files. In order to produce consistent analysis results, only one annotator analysed and annotated all the log files by using the systematic analysis technique. The technique was originally used in the Trewin and Pain's study [1999]. Participants' subjective ratings on previous experience and task performance were collected using a questionnaire.

Remote errors and *dropping errors* were investigated by Trewin and Pain on motor impaired desktop users [1999]. *Dropping errors* occur when one fails to press two keys simultaneously. This error was not examined in current study with small device users. This is because with a small device keyboard, a sequential key press will produce the same result as a simultaneous key press on a standard desktop keyboard. For example, in order to enter a capital "A", instead of press "Shift" and "a" at the same time, one can press "Shift" first and then press "a" on a small device keyboard. *Remote errors* which occur when one accidentally press a different key with a digit or body part other than one being used for the intended key press, was examined as part of the additional key press error in current study. This is because since the device used in our study is very small, it is almost impossible to press a key with other parts of the body.

For typing errors, we counted how many errors of each type a participant experienced. For pointing errors, we calculated the error rate for each participant by dividing their succeeded trials on one task with the total attempts they made. If errors of one category did affect more than half of the participants, statistic analysis was conducted using the SPSS[5] software. This is to ensure that the majority of the users experienced this error and to have more confidence in the statistical analysis. Non-parametric statistics were used, as the variables under examination did not have normal distributions. To assess effect of previous experience on error rates, we analysed the correlation between each participant's subjective rating of previous experience and the number of their performance errors. To address the impact of device and material familiarity on error rates, we contrasted participants' performance of the typing and pointing tasks in the first trial with that in the second trial, and conducted Wilcoxon Signed Ranks Test between the error numbers in two trials. Finally, to investigate the relationship between the perceived performance and the actual performance error, we analysed the correlation between each participant's subjective ratings on task performance and their error rates.

3.3 Typing Task Results

The results of our study showed that mobile Web users experienced all of the six categories of typing errors presented in Table 3.1. Participants were mostly affected by key ambiguity errors, followed by missing key errors and additional key errors. However, compared to these errors, bounce errors, transposition errors and long key press errors occurred less frequently. There was also a significant inverse correlation between participants' previous experience in text entry from small device keyboards and the number of key ambiguity errors they made. In addition, there was also a significant positive correlation between participants' ratings on ease of avoiding key ambiguity errors and the errors they actually made.

3.3.1 Overall Performance

All 15 participants completed both the typing task and its repetition. As described in Section 5.2, we use T1 and T2 to represent the two trials of the typing task. Table 3.3 summarises the total key strokes, total time and correction time

[5]See `http://www.spss.com`

Table 3.3: Total keystrokes, time and correction time for the typing task (T1) and its repetition (T2)

	Keystrokes		*Total Time (sec.)*		*Correction Time*	
Participants	*T1*	*T2*	*T1*	*T2*	*T1*	*T2*
N1	570	564	816	506	0	10
N2	558	555	750	516	0	6
N3	565	608	683	549	0	18
N4	534	570	509	459	0	9
N5	537	576	378	309	0	N/A
N6	554	531	456	348	0	2
N7	556	517	760	471	N/A	N/A
N8	522	545	945	1006	0	51
N9	494	482	756	573	34	0
N10	643	569	450	341	36	32
N11	534	666	648	637	0	32
N12	534	528	565	443	20	5
N13	519	579	505	397	0	34
N14	471	550	832	634	0	11
N15	516	552	959	682	0	13
MEAN	540.47	559.47	667.47	524.73	6.43	17.15
STDEV	38.95	41.89	183.77	174.43	13.22	15.38

for each participant. Note that the duration of correction for N7 and N5 were not available due to errors in their log files. According to Wilcoxson Signed Ranks Test, participants spent significantly less time when they repeated the typing task (Z= -3.238, sig.= 0.001).

There was a significant inverse correlation between the time spent on T1 (Spearman $\rho= -0.602$, p= 0.018, 2-tailed) and participants' experiences in text entry. In T2, the relationship became stronger (Spearman $\rho= -0.712$, p= 0.003, 2-tailed). There was also a significant inverse correlation (Spearman $\rho= -0.723$, p= 0.002, 2-tailed) between the time spent on T1 and the experience level in the mobile Web. The significant inverse correlation also held when particpants repeated the typing task in T2 (Spearman $\rho= -0.695$, p=0.004, 2-tailed)

With regard to the correction time, the average time spent on corrections in T2 was 17.15 seconds, which was about 3% of the total time spent. In addition, although participants were told not to correct their errors in T1, 3 participants

(N9, N10 and N12) still did so. Note that the correction time for participant N9 dropped from 34 seconds in T1 to 0 second in T2. This was not because N9 did not make any mistake in T2. We found that this participant left the errors uncorrected instead.

Table 3.4 gives the number of errors in each category. In order of error rate, the errors recorded were listed as following:

1. *Key ambiguity error*: On average, each participant made 9.33 key ambiguity errors (Std. error= 1.423) in the first typing task and 6.33 errors in the repetition (Std. error= 1.355).

2. *Missing key error*: In the first trial of the typing task, the average error rate was 3.2 per participant (Std. error= 0.745); it decreased to 2.53 in the second trial (Std. error= 0.593).

3. *Additional key error*: The error rates in the first trial (Std. error= 0.388) and the second trial (Std. error= 0.412) were the same, 1.4 errors per participant.

4. *Bounce error*: The error rate of bounce error in the first trial was 0.73 (Std. error= 0.284), and that in the second trial was 0.33 (Std. error= 0.159).

5. *Long key press error*: Only 10 instances were observed in both trials.

6. *Transposition error*: Only 8 instances were observed in both trials.

Table 3.5 shows participants' subjective ratings on performing typing tasks. The values, which were designed on a 1 to 7 scale, represented the difficulties of avoiding certain typing error, with "1" representing "very difficult" and "7" representing "very easy". We can see that the mean of "avoid key ambiguity error" was the lowest among the four, whereas that of "avoid additional key error" was the highest. This table also shows that about two third of the participants rated avoiding long key press error, bounce error and additional key error "easy" (6/7) or "very easy" (7/7), whereas only 6 participants, 40% of all participants, had the same opinion on avoiding key ambiguity error. The other 9 participants' ratings on avoiding key ambiguity errors varied from "moderately difficult" (3/7) to "moderately easy" (5/7). However, no one rated avoiding any typing error "difficult" (2/7) or "very difficult" (1/7).

Table 3.4: Number of typing errors in the typing task (T1) and its repetition (T2)

	Long Key		*Bounce*		*Missing*		*Transposition*		*Ambiguity*		*Additional*	
	T1	*T2*	*T1*	*T2*	*T1*	*T2*	*T1*	*T2*	*T1*	*T2*	*T1*	*T2*
N1	0	0	0	0	8	3	1	0	12	8	2	0
N2	0	0	0	1	3	1	1	0	14	3	1	2
N3	0	0	3	0	0	1	0	0	22	2	1	5
N4	0	0	0	0	4	2	1	1	8	19	1	0
N5	0	0	0	0	9	5	0	0	8	2	2	1
N6	0	0	1	0	0	2	0	0	6	1	2	1
N7	0	0	0	0	0	1	0	0	14	17	0	0
N8	0	3	3	1	5	9	0	1	9	6	1	0
N9	1	2	0	1	2	4	1	0	9	8	1	0
N10	0	0	1	0	2	1	0	1	3	5	6	4
N11	0	0	0	0	7	4	0	0	16	6	2	3
N12	0	0	1	0	2	0	1	0	6	5	0	0
N13	0	4	0	2	1	1	0	0	0	2	0	2
N14	0	0	2	0	3	3	0	0	7	7	2	1
N15	0	0	0	0	2	1	0	0	6	4	0	2
Total	1	9	11	5	48	38	5	3	140	95	21	21

Table 3.5: Participants' subjective ratings on avoiding typing errors (1= very difficult, 7=very easy)

Participants	*key ambiguity*	*long key press*	*bounce error*	*additional key*
N1	5	6	5	7
N2	5	4	4	5
N3	4	7	6	5
N4	7	7	6	7
N5	5	7	4	7
N6	5	7	5	7
N7	6	5	6	6
N8	6	5	6	3
N9	6	3	6	4
N10	4	7	6	7
N11	5	6	6	7
N12	7	6	7	6
N13	3	4	5	6
N14	6	7	6	7
N15	3	7	5	7
MEAN	5.13	5.87	5.53	6.06
STDEV	1.25	1.36	0.83	1.28

3.3.2 Key Ambiguity Error

A key ambiguity error happened when another character on a key was typed in rather than the target character. All participants experienced key ambiguity errors in both T1 and T2, except participant N13 who did not make any key ambiguity error in T1. The number of errors ranged from 0 to 22 in T1, and 1 to 19 in T2. Eight participants had 5 to 10 errors in T1 and 7 fell into that range in T2. Figure 3.2 shows that 10 participants had fewer key ambiguity errors in T2 than in T1; one participant (N14) had same amount of errors in both trials; and the other 4 participants had more errors in T2. However, there was no significant difference between number of key ambiguity errors in T1 and T2 (Wilcoxon Signed Ranks Test, Z= -1.604, sig.$>$ 0.05).

There was a significant inverse correlation between the number of key ambiguity errors in T1 and participants' subjective ratings on previous experience in text entry (Spearman $\rho = -0.519$, p= 0.047, 2-tailed). This suggests that the more experienced small device users rate themselves in text entry, the fewer key ambiguity errors they made. However, this correlation became non-significant in T2

(Spearman $\rho = -0.006$, $p = 0.984$, 2-tailed). With regard to participants' subjective ratings on awareness of avoiding key ambiguity error, there was a significant positive correlation between their ratings and errors made in T2 (Spearman $\rho = 0.645$, $p = 0.009$, 2-tailed), which suggests the more confident participants felt about avoiding key ambiguity error, the more errors they made in that trial.

3.3.3 Additional Key Error

An additional key error occurred when a key close to the target key was pressed, the target key might or might not be pressed. A total of 42 additional key errors were observed in T1 and T2, 21 in each trial. As shown in Figure 3.3, 4 participants did not have any additional key error in T1; the majority, 10 participants out of 15, had 1 or 2 errors, except participant N10 who had 6. In T2, there were 6 participants who did not make any additional key error. Six participants experienced 1 or 2 errors. Participant N3 made 5 errors. However, there was no significant difference between the number of additional key errors in T1 and T2 (Wilcoxon Signed Ranks Test, $Z = -0.180$, sig.> 0.05).

Most participants reported avoiding additional key error "very easy" or "easy", only one participant reported that it was "hard". However, there was a significant positive correlation between participants' subjective ratings on awareness of avoiding additional key errors and the actual errors they made in T1 (Spearman $\rho = 0.517$, $p = 0.048$, 2-tailed). This suggests that the more confident participants felt about avoiding additional key presses, the more errors they actually made. For example, as shown in Table 3.5, participant N10 rated "avoid additional key error" "very easy", however, this participant actually made 10 errors in T1 and T2 together, which was the most in all participants.

3.3.4 Missing Key Error

Figure 3.4 shows the number of missing key errors for each participant. Overall, errors ranged from 0 to 9 in both trials. In T1, 12 participants were affected by missing key errors, 7 of whom had 2 or 3 errors, and 3 of whom had more than 6 errors. In T2, 14 participants experienced missing key errors; and 6 of them had only 1 error. There was no significant difference between the number of missing key errors in T1 and T2 (Wilcoxon Signed Ranks Test, $Z = -1.058$, sig.> 0.05).

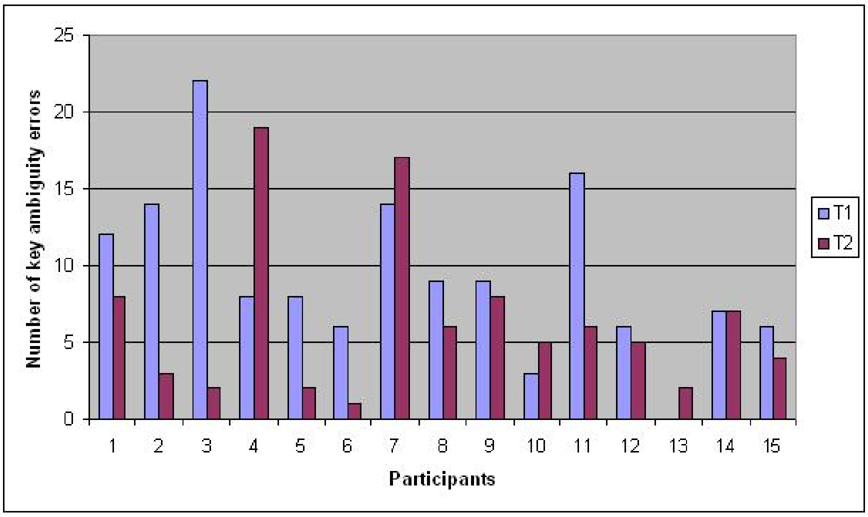

Figure 3.2: Key ambiguity errors across all participants

There was not any significant correlation between missing key errors and participants' subjective ratings on previous experience in text entry or the mobile Web.

We observed that missing key errors happened in two situation. The first situation was that a participant clicked the key but without sufficient force to activate it, which was as expected. However, we also observed instances that participants missed some words when they repeated the typing task. For example, we noticed that one participant missed a whole sentence. However, we cannot tell whether this was deliberately or the participant was just tired and looked at the wrong line of the text passage.

3.3.5 Bounce Error

A bounce error happened when a participant unintentionally pressed a key more than once. Figure 3.5 illustrates the number of bounce errors experienced by each participant. Nine participants out of 15 experienced 16 bounce errors in total. There was no significant difference between the number of errors in T1 and T2 (Wilcoxon Signed Ranks Test, Z= -1.150, sig.> 0.05).

There was no significant correlation between number of bounce errors and participants' ratings on previous experience. With regard to subjective ratings on awareness of avoiding finger bounce, there was a positive correlation between the bounce errors participants made in T1 and their ratings (Spearman ρ= 0.484,

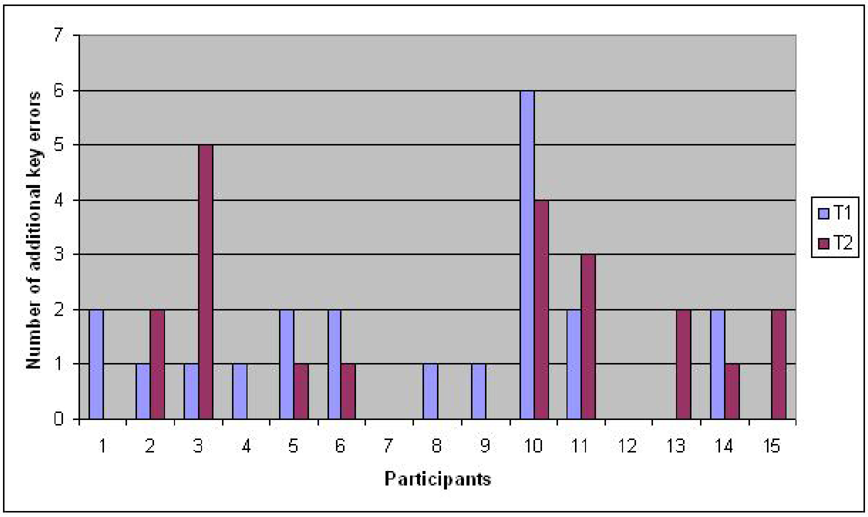

Figure 3.3: Additional key errors across all participants

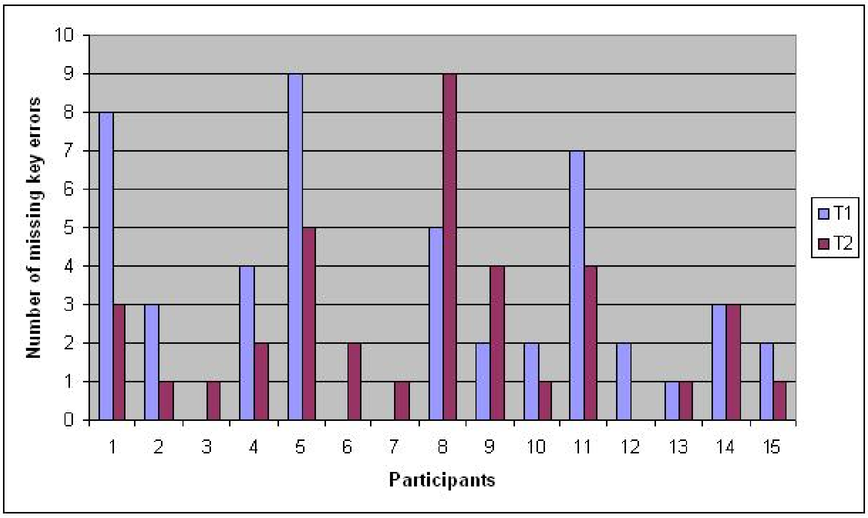

Figure 3.4: Missing key errors across all participants

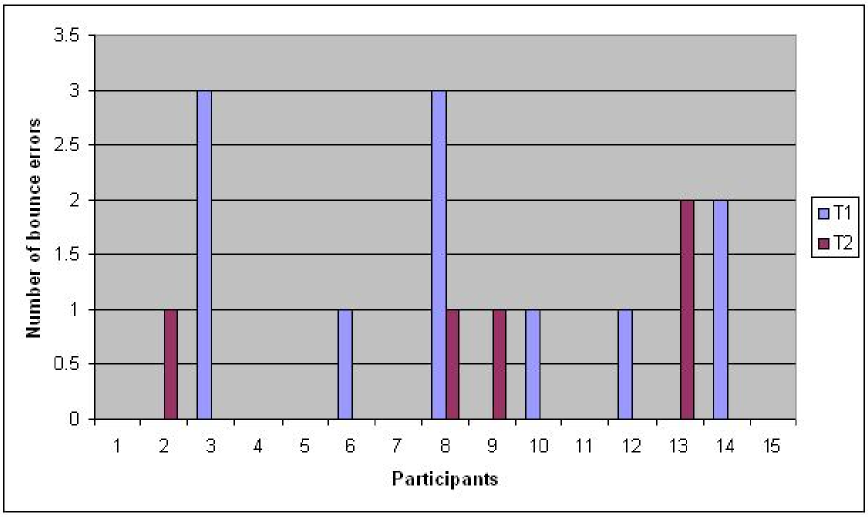

Figure 3.5: Bounce errors across all participants

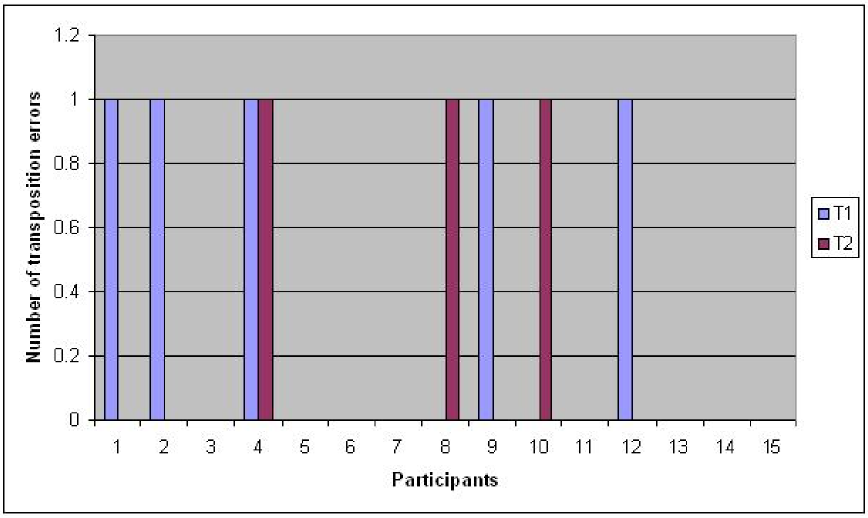

Figure 3.6: Transposition errors across all participants

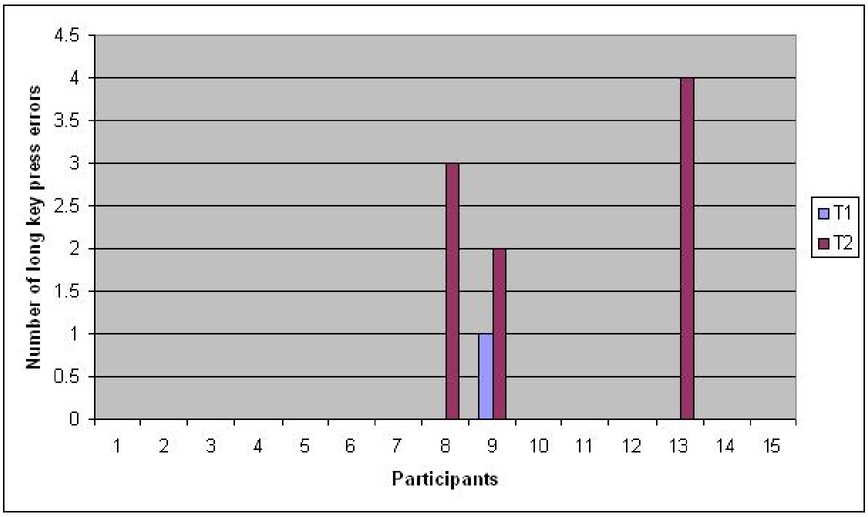

Figure 3.7: Long key press errors across all participants

p= 0.058, 2-tailed). Note that the p value was at the border of significance level. This correlation became inverse when participants repeated the typing task in T2 (Spearman ρ= -0.172, p= 0.524, 2-tailed), but not significant.

3.3.6 Transposition Error

As Figure 3.6 shows, overall 7 participants experienced 8 transposition errors. The mean error rate per participant was 0.33 in T1 (Std. error= 0.126) and 0.20 in T2 (Std. error= 0.107). Unfortunately, too few examples were observed to allow examination of the correlation between these errors and participants' previous experience.

3.3.7 Long Key Press Error

A long key press error occurred when a key was pressed too long that generated unwanted copies. Figure 3.7 shows the spread of this error across all participants. We can see that only 3 participants experienced long key press errors: N8 had 3 in T2, N9 had 1 in T1 and 2 in T2, and N13 had 4 in T2.

Participant N8 made 3 long key press errors in T2. Looking at the log file, we found that when N8 was typing the word "you", the participant pressed "o" too long that generated a unwanted copy. Similarly, N8 pressed "d" and "w" too long when typing "add" and "what" which generated three "d" and two "w" accidentally.

The difficulty in avoiding long key press error was noticed and reported by participants who made these errors. According to the feedback given by participants after conducting the typing tasks, N9 rated 3/7 to "avoid long key press error", which indicated that avoiding this error was "moderately difficult" for this participant. In addition, participant N13 who had the most long key press errors also rated it 4/7 which stands for "neither difficult nor easy". On the other hand, there were also participants who rated avoiding long key press error difficult but did not experience any such error in reality. For example, participant N4 rated it 4/7 but did not have any error at all. This is interesting as it shows the difference between the perceived difficulty and what is actually happening in reality.

3.4 Pointing Task Results

A greater percentage of our participants experienced performance errors in clicking, multi-clicking and dragging than those who did not experience these errors. Dragging error was the most frequent pointing error in terms of error rate. We found that participants had significantly less error rates when they repeated the tasks that required multi-clicking. However, there was no significant correlation between participants' experiences, error awareness and their error rates.

3.4.1 Overall Performance

Table 3.6 shows the time each participant spent on the pointing task (P1), the editing task (E) and the repeat of the pointing task (P2). The table indicates that time spent on P1 varied from 208 seconds to 648 seconds, with a mean of 359.13 seconds (Std. Error= 33.08). In P2, duration ranged from 151 seconds to 409 seconds, with a mean of 238.73 seconds (Std. Error= 21.40). According to the result of Wilcoxon Signed Ranks Test, participants spent significantly less time in P2 than in P1 ($Z = -3.351$, sig.$= 0.001$).

Regarding correction time, although participants were told not to correct their errors in P1, they still spent, on average, 33.67 seconds on error corrections. This was approximately 9.38% of the total time spent on P1. In P2, the mean of correction time dropped to 20.36 seconds, which was about 8.53% of the total time .

Table 3.7 shows participants' subjective ratings on difficulties of performing

Table 3.6: Total time and correction time spent on the pointing task (P1), editing task (E) and repetition of the pointing task (P2)

	Total Time (sec.)			*Correction Time (sec.)*		
Participants	*P1*	*E*	*P2*	*P1*	*E*	*P2*
N1	214	886	151	9	18	9
N2	372	962	198	32	15	6
N3	648	1085	247	110	3	1
N4	525	770	375	7	4	N/A
N5	225	508	176	12	0	7
N6	327	530	363	12	0	29
N7	332	657	180	4	58	2
N8	327	701	201	9	6	14
N9	560	1335	409	199	173	128
N10	306	259	163	17	136	7
N11	349	743	221	6	10	21
N12	208	587	167	7	22	1
N13	298	865	251	1	5	21
N14	406	643	282	19	17	22
N15	290	830	197	61	0	17
MEAN	359.13	757.4	238.73	33.67	31.13	20.36
STDEV	128.12	258.33	82.89	53.91	52.66	32.22

Note:
The correction time for participant N4 in P2 was not available because of the errors in the log file.

clicking, multi-clicking and dragging. The table indicates that dragging was considered the most difficult task among the three, with a mean difficulty of 5.13. The mean of multi-clicking difficulty was the lowest, and that of clicking difficulty was in the middle. The table also illustrates that most participants, 12 out of 15, rated performing multi-clicking “easy” (6/7) or “very easy” (7/7). On the other hand, performing dragging was rated much more difficult than performing clicking and multi-clicking. For example, only 6 participants rated performing dragging “easy” (6/7) or “very easy” (7/7), whereas 8 other participants believed that it was either “moderately easy” (5/7) or “neither difficult nor easy” (4/7), and the last participant rated it “moderately difficult” (3/7). However, none of the participants rated any pointing action “difficult” (2/7) or “very difficult” (1/7).

Table 3.7: Participants' subjective ratings on pointing performance (1= very difficult, 7= very easy)

Participants	*Clicking*	*Multi-clicking*	*Dragging*
N1	7	6	3
N2	6	5	4
N3	4	6	5
N4	5	7	7
N5	4	7	7
N6	5	4	4
N7	7	7	4
N8	7	7	7
N9	5	3	4
N10	3.5	7	6
N11	5	6	4
N12	7	6	7
N13	4	7	5
N14	7	6	6
N15	7	7	4
MEAN	5.57	6.07	5.13
STDEV	1.35	1.22	1.41

3.4.2 Clicking Errors

In this study, a clicking error occurred when a participant clicked at a wrong position. There were 8 participants who experienced clicking errors in the first pointing task (P1), and the error rate of each participant ranged from 12.5% to 46.2%. We observed that participants N15 tried 7 times for sub-task P1.1C which required a single click between the letter "i" and letter "l" in the word "April"; and this participant only succeeded once. When repeating the pointing task (P2), 10 participants made clicking errors; the lowest error rate of these participants was 14.3% and the highest was 50%. There was no significant difference between participants' error rates in these two trials ($Z = -0.864$, sig.>0.05).

Figure 3.8 shows participants' overall trials of clicking sub-tasks in P1 and P2. The figure shows that participants repeated more times when they conducted the same clicking sub-tasks for the second time. This was especially the case for P2.1C and P2.4C. Sub-task P2.1C was the same with sub-task P1.1C. Overall, P2.1C was performed 50 times by all participants, twice of that of P1.1C. We observed that participant N3 conducted P2.1C 13 times continuously, and succeeded each

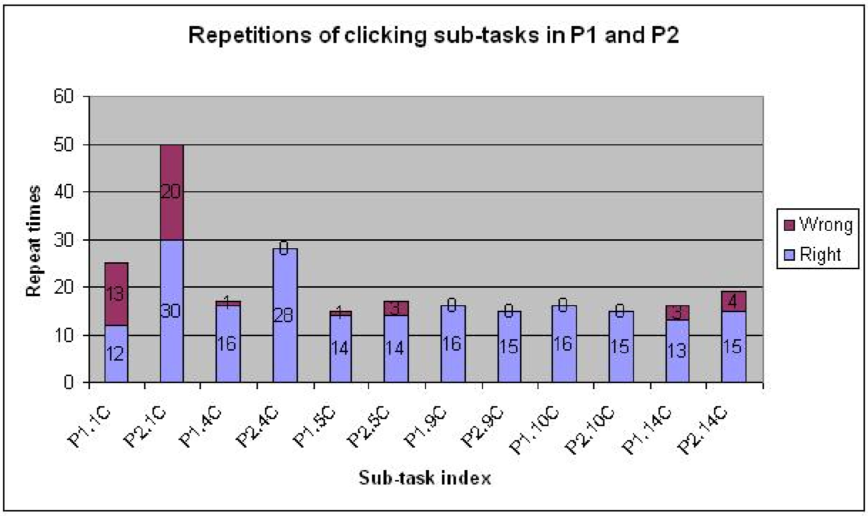

Figure 3.8: Trials of clicking sub-tasks in the pointing task (P1) and its repetition (P2)

time. This participant might be confused and did not realise that every trial actually reached the target, and kept repeating until satisfied. P2.4C required a participant to "click on the Wiki button above the text box". This sub-task was repeated 28 times by all participants whereas it was only tried 17 times in P1.

Eleven participants experienced clicking errors in E, the highest error rate was 55.6%. Figure 3.9 shows the number of trials of clicking sub-tasks in E. Sub-task E.17C and E.24C were most error-prone: almost half of the trials failed. Both sub-tasks asked participants to "use the arrow on the scroll bar to move down the viewport". We observed that those who failed these sub-tasks did not click the arrow at all, they dragged the scroll bar to change the viewport instead. In addition, sub-task E.7C was the same as sub-task E.17C and E.24C. We found four participants failed this sub-task for the same reason.

There was no significant correlation between participants' subjective ratings on performing clicking tasks and their error rates. Neither was there significant correlation between participants' previous experience in the mobile Web and their error rates.

3.4.3 Multi-clicking Errors

A multi-clicking error happened when an obvious cursor movement was made between clicks. Ten multi-clicking sub-tasks were conducted in total: 4 in P1,

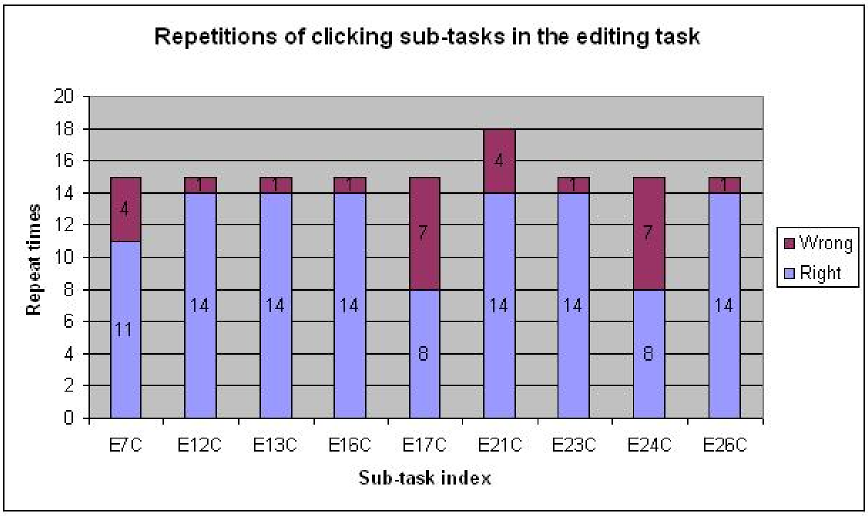

Figure 3.9: Trials of clicking sub-tasks in the editing task (E)

2 in E and the other 4 in P2. Thirteen participants experienced multi-clicking errors in P1, and 12 participants were affected in P2. When we look at the error rates of all participants, their multi-clicking error rates in P2 were significantly less than in P1 (Wilcoxon Signed Ranks Test, Z$= -2.170$, sig.$= 0.030$).

Figure 3.10 shows the number of trials of each multi-clicking sub-task in P1 and P2. As the table shows, participants struggled with sub-task P1.8M and P2.8M: only 6 out of 31 attempts of P1.8M succeeded; the number of successful trials increased to 14 on P2.8M, but there was still 17 failed attempts. Take participant N3 for example, we observed that this participant tried 11 times on P1.8M and failed 10 of them. P1.8M required participants to perform a triple-click on the first line of a text passage. Most of the participants who failed this sub-task moved their cursors between clicks, which broke the triple-click process. Figure 3.10 shows that this sub-task was the most error-prone one among all multi-clicking sub-tasks.

Only two multi-clicking sub-tasks were conducted in E, both of which required participants to perform double clicking to select a word in a text passage. Three participants experienced multi-clicking errors in E. One of them, participant N9 tried 4 times for sub-task E.10M and failed all of them. Instead of double click on the word, N9 tried to drag the cursor to select the word, but did not succeed in the end. In addition, participant N2 made an error on sub-task E.10M; and participant N13 made an error on sub-task E.1M. They both slid the cursor between the clicks which interrupted the double clicking process.

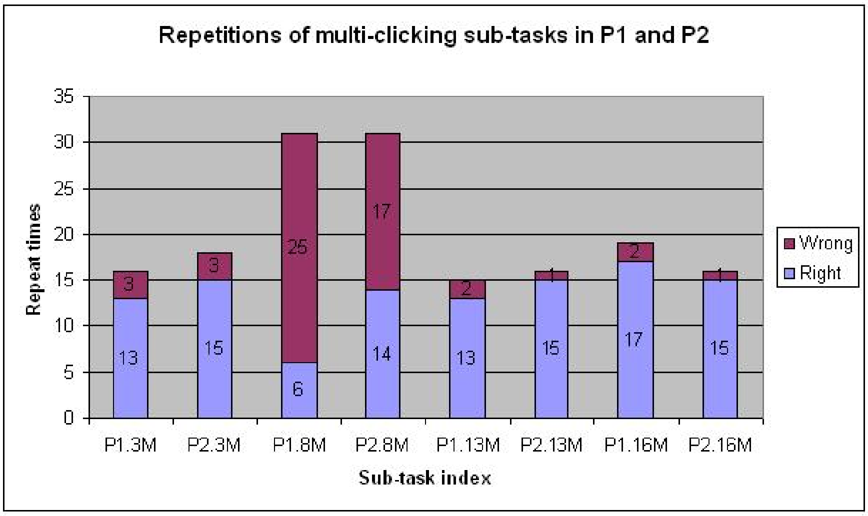

Figure 3.10: Trials of multi-clicking sub-tasks in the pointing task (P1) and its repetition (P2)

Similar to clicking errors, there was no significant correlation between participants' subjective ratings on performing multi-clicking and their error rates. In addition, no significant correlation existed between participants' previous experience in the mobile Web and their error rates either.

3.4.4 Dragging Errors

We found that a dragging error took place in three situations: *fail to start*, where a participant landed the stylus on the screen for too long before starting dragging, and that triggered an on-screen menu; *breaking*, where a participant lifted the stylus before reaching the end and thus only selected part of the wanted material; *exceeding*, where a participant kept dragging the stylus after reaching the end of target and thus selected more materials than wanted.

All participants experienced dragging errors in P1. The error rate of each participant varied from 14.3% to 84%. Figure 3.11 shows the overall performance of dragging sub-tasks in P1 and P2. Compared with the other dragging sub-tasks, sub-task P1.6D and P1.7D both had higher repetitions and higher error rates. Sub-task P1.6D asked participants to drag the cursor to select a sentence. Overall, 13 participants completed this sub-task. Participants N9 and N13 failed it. However, N13 only attempted once whereas N9 tried 10 times. The main difficulty this participant experiencing was the "fail to start" problem. Additionally,

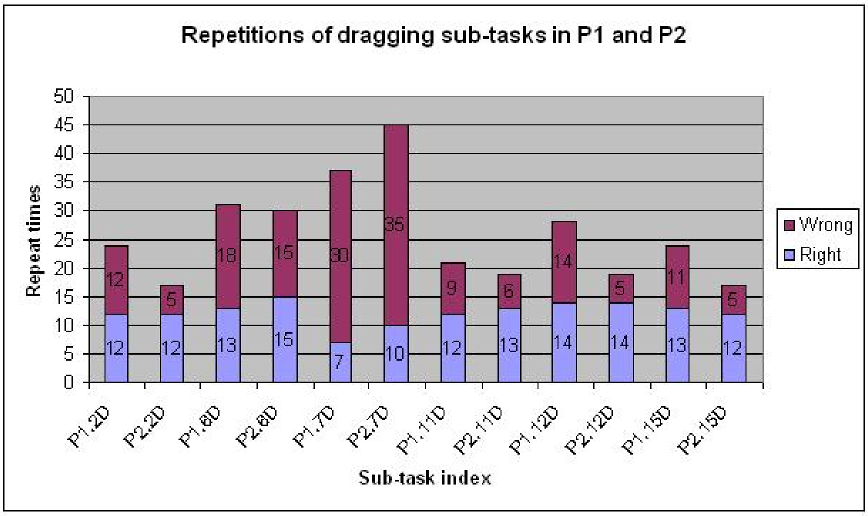

Figure 3.11: Trials of dragging sub-tasks in the pointing task (P1) and its repetition (P2)

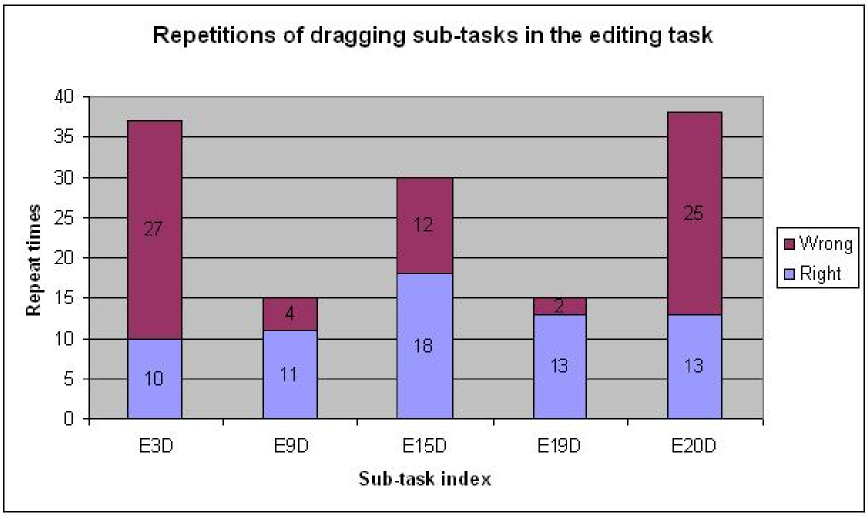

Figure 3.12: Trials of dragging sub-tasks in the editing task (E)

this participant also experienced "exceeding" problems where N9 failed to lift the stylus from the screen at the end of the wanted material.

Compared with P1.6D, sub-task P1.7D, which asked a participant to drag the cursor and select the word "a", was more error-prone. Only 7 participants managed to succeed. Participant N9 still suffered from the same problem as experienced in P1.6D. N9 made 10 attempts on P1.7D and failed all of them. Furthermore, participants who did not have the "fail to start" problem in P1.6D experienced it in P1.7D. Some complained that the PDA touch-screen was not sensitive enough that a very short stylus movement, such as required by P1.7D, was not recognised properly. We also noticed that some participants double-clicked to select the word after a few dragging attempts.

Additionally, sub-task P1.12D, which requested participants to drag the cursor to select a whole paragraph in a text passage, also had relatively high repetitions. Only 6 participants completed this sub-task in one trial. Eight participants tried twice or more times to succeed. Participant N11 made 2 attempts but did not complete the task in the end. As we observed, the difficulty of this sub-task was that the text passage was on two pages, and when a dragging process came to the end of a page and needed to continue on a second page, the viewport did not scroll down automatically. The participants needed to scroll down manually. However, when they scroll the viewports, the materials they already selected would gone, which broke the dragging process. In addition, participants also experienced "breaking" problems where they lifted the stylus before the end of the paragraph.

Participants' dragging performance was improved in P2. As shown in Figure 3.11, both the error rates and the repetitions decreased in P2. However, there was no significant difference between participants' error rates in P2 and that in P1 (Wilcoxon Signed Ranks Test, $Z = -1.783$, sig.> 0.05). The "fail to start problem" still existed in P2 as the amount of repetitions for P2.6D and P2.7D remained at the same level with P1.6D and P1.7D. However, more participants managed to complete P2.6D and P2.7D. The repetitions of P2.12D were much fewer than that of P1.12D as more participants managed to avoid page scrolling by making sure the text materials needed for selection was in one viewport before starting dragging.

There were also 5 dragging sub-tasks in E. Fourteen participants experienced dragging errors in E, and the highest error rate was 85.7%. Figure 3.12 summarises participants' performance. There were two sub-tasks that participants particularly struggled with: E.3D asked participants to drag the cursor and select a word; E.20D asked them to drag to select a sentence. There were 10 successful trials in 37 attempts for E.3D; and 13 out of 38 attempts for E.20D succeeded. Still, the main problem was landing the stylus on the screen for too long. For instance, participants N7 and N12 failed 6 times each for E.3D due to this problem. We also observed some participants experienced difficulties in performing minor cursor movements. For example, E.20D specified that participants need to select the whole sentence, including the full stop. Some participants had difficulties in this sub-task as they could not manipulate the stylus to stop just after the full stop. They either "broke" too early or "exceeded" the target.

3.4.5 Comparison of Pointing Errors

Three categories of pointing errors were observed in this study: clicking errors, multi-clicking errors and dragging errors. Results of the Wilcoxon Signed Ranks Test on error rates of the three categories indicate: in P1, the error rates of clicking sub-tasks were significantly less than that of multi-clicking sub-tasks ($Z = -2.046$, $sig. = 0.041$); the error rates of multi-clicking sub-tasks were significantly less than that of dragging sub-tasks ($Z = -2.102$, $sig. = 0.036$); and of course, the error rates of clicking sub-tasks are significantly less than that of dragging sub-tasks ($Z = -3.408$, $sig. = 0.001$). Therefore, in P1, dragging sub-tasks were the most error-prone ones, followed by multi-clicking sub-tasks and clicking sub-tasks.

However, the results were different in E and P2. In E, the error rates of clicking sub-tasks were significantly less than that of dragging sub-tasks ($Z = -3.015$, $sig. = 0.003$); the error rates of multi-clicking sub-tasks were significantly less than that of dragging sub-tasks ($Z = -2.608$, $sig. = 0.009$); however, the Wilcoxon Signed Ranks Test between error rates of clicking sub-tasks and multi-clicking sub-tasks did not yield a significant result ($Z = -1.426$, $sig. > 0.05$). Therefore, in E, dragging sub-tasks were the most error-prone ones; however, the difference in error rates between clicking sub-tasks and multi-clicking sub-tasks cannot be identified.

The results in P2 were similar to that in E. Participants had significant less error rates in multi-clicking sub-tasks than in dragging sub-tasks ($Z = -2.316$, sig.= 0.021). Additionally, the error rates of clicking sub-tasks were also significantly less than that of dragging sub-tasks (Z= -2.198, sig.= 0.028). However, the difference between error rates of multi-clicking sub-tasks and that of clicking sub-tasks was not significant (Z= -0.440, sig.> 0.05).

According to the results presented above, we can see that in P1, E and P2, dragging sub-tasks were the most error-prone sub-tasks. Although multi-clicking sub-tasks are more error-prone than clicking sub-tasks in P1, no significant difference between these two existed in E and P2.

3.5 Discussion

This section discusses typing and pointing errors identified in the study. In brief, results show that typing and pointing errors are shared between small device users and motor impaired desktop users. Furthermore, this section also illustrates some correlations between small device users' experiences and their typing speed. The section then drills down on a few specific typing and pointing errors. Finally, the limitations of the study are summarised.

3.5.1 Overlaps Between Accessible and Mobile Webs

Six categories of typing errors and three types of pointing errors were observed in this study. In general, participants found typing with the given small device keyboard tiring. Regarding their performance, our participants were mostly affected by key ambiguity errors; and they made more errors in dragging the stylus to select text than performing single or multiple clicking.

As shown in Table 3.1, all these error types, except key ambiguity error, were also reported by Trewin and Pain's study [1999] with motor impaired desktop users. We see that the most significant typing error of motor impaired desktop users was long key press error. This error also affected mobile Web users, but less frequently. Key ambiguity error was not reported in Trewin and Pain's study [1999]. However, Arnott and Javed [1992] reported key ambiguity errors when people with motor impairments used reduced keyboards. Nevertheless, our results confirm that despite using different input devices, mobile Web users and motor impaired desktop users share similar problems. On average, the number of typing errors made my mobile Web users were fewer than that of motor impaired desktop users. However, the error rates of pointing errors were similar between

Table 3.8: A comparison of typing and pointing errors of mobile Web users and motor impaired desktop users

Note: Even though the number of errors cannot be statistically compared because of the differences in both studies, They are provided here to give an idea about the errors experienced by both user groups.

Error Type	*Motor impaired users*	*Mobile Web users*
*T*yping errors	*N*umber of errors	
Long key press error	53.94	0.07
Additional key error	8.89	1.40
Missing key error	5.89	3.20
Bounce error	1.67	0.73
Transposition error	0.06	0.33
Key ambiguity error	N/A	9.33
*P*ointing errors	*E*rror rate	
Pointing/clicking	10%-20%	17.10%
Multi-clicking error	39.50%	39.50%
Dragging error	55.00%	57.00%

the two domains. Mobile Web users even had higher dragging error rate than motor impaired desktop users in Trewin and Pain's study [1999].

3.5.2 Task Completion Time, Correction Time and Experiences

There was a significant inverse correlation between the time spent on the first trial of the typing task and participants' experience level in text entry. This relationship was stronger in the second trial of the typing task. When we asked our participants to rate their experience level in text entry, we specifically asked them about their experiences of text entry from a small device (e.g., PDA). Therefore, the inverse correlation suggests that the more experienced participants got in text entry from small devices, the less time they spent on the typing task. It is also observed that the time taken by participants to perform the pointing task was significantly reduced in the second trial. This suggests that as participants became more familiar with the pointing tasks, they used less time to complete the task.

There was also a significant inverse correlation between the time spent on the first trial of the typing task and participants' experience level in the mobile Web, which also hold when they repeated the typing task. This indicates that the more experience participants obtained in using the mobile Web, the less time they spent on typing with a PDA.

On average, participants spent 17.15 seconds to correct their typing errors in the second trial of the typing task. That was approximately 3% of the duration of the typing task. Although participants were told not to correct their typing and pointing errors in the first trial of those tasks, they still did so. This was especially the case for the pointing task. Three participants corrected their typing errors in the first trial, whereas all 15 participants repeated some pointing tasks in their first trial. Participants might just ignored the instructions. It is also possible that they could not resist correcting their errors. Repeating a pointing task was much easier than correcting a typing error using the small keyboard. They might just try a few more clicks without even noticing that they were actually repeating the tasks.

3.5.3 Key Ambiguity Errors

Key ambiguity errors were the most significant source of typing errors for our participants: 235 instances of this type were observed in two typing tasks, 140 in the first trial and 95 in the second trial.

From the point of view of familiarity to the device, most participants made fewer key ambiguity errors when they repeated the typing task. On average a participant experienced 9.33 key ambiguity errors in the first trial of typing task and 6.33 when they repeated it. In addition, participants (N5 and N6) who had used the experimental PDA before experienced much fewer key ambiguity errors than average.

With regard to experiences, a significant inverse correlation between participants' previous experience in text entry from small devices and the number of their key ambiguity errors was found. This suggests that those who had more previous experience in text entry made fewer errors. In summary, results suggest that key ambiguity errors are highly related to users' familiarity with the small keyboard and also experiences in text entry.

3.5.4 Correlation Between Error Rates and Subjective Ratings

Study results show two significant positive correlations between participants' ratings on avoiding additional key error, key ambiguity error and the actual number of errors they made. These indicate that the more confident participants felt about avoiding the errors, the more errors they made. A possible reason for this is that people over-rated their performance. In other words, they did not realise they had made the errors when they were asked for their personal opinions on task difficulties. For example, participant N4 rated it "very easy" (7 out of 7) to avoid key ambiguity error, however, this participant actually made 19 key ambiguity errors in T2, which was the highest among all participants. Alternatively, it might be the case that participants misunderstood the questions and gave random answers which were not based on their performance.

3.5.5 Clicking Difficulties

In general, participants considered performing clicking and multi-clicking easier than performing dragging. Two difficulties in performing clicking were observed in the study: first, clicking between objects that have very little space between them is difficult; second, participants got confused if no feedback was given after conducting a clicking.

Regarding the first difficulty, it is found that participants made more errors when they were asked to click between two letters in a word. The more similar those two letters look like, such as 'i' and 'l', the more errors participants made. This is because similar letters close to each other have very little space between them, which makes it hard to pin-point in between.

With regard to the second difficulty, it is found that when participants were asked to click on a button, they tended to repeat the task when no feedback was given after the clicking. There were two participants each of whom repeated a pointing task 5 times. Each time they got it right, but they still repeated it. As a stylus user did not get any tactile feedback from clicking an on-screen item, participants can be easily confused if no feedback of other form was given after performing a clicking.

3.5.6 Multi-Clicking Difficulties

The difficulty in performing multi-clicking was holding the stylus at the same position. It is observed participants never clicked at exactly the same position when performing multi-clicking. However, those who made multi-clicking errors slid the stylus between clicks. This was troubling because it broke the process and would not be recognised as a multi-clicking by the system.

3.5.7 Dragging Difficulties

The most noticeable difficulty in performing dragging was "fail to start" where a participant landed the stylus on screen for too long before dragging it. This would cause an on-screen menu to pop up, which broke the dragging process. A second difficulty was dragging for very short distance, such as drag the stylus to select a single letter. Some complained the touch screen was not sensitive enough as their subtle movement was not registered. A third difficulty was that if a dragging process needed to continue from one page to another, the viewport did not scroll down automatically, and using the scroll bar to move down viewport would break the dragging process.

3.5.8 Typing Long Text on Small Devices

Existing research suggest that people do not usually use their small devices to create or edit long documents because of the small screen size and limited input [Cui and Roto, 2008, Luo, 2004, O'Hara et al., 2002, Waycott and Kukulska-Hulme, 2003]. Therefore, the tasks used in this study might not be typical typing and pointing tasks. However, the advantages of PDAs such as flexibility, versatility, show potentials for text editing and creation in education [Waycott and Kukulska-Hulme, 2003], health care [Luo, 2004], business [O'Hara et al., 2002] and mobile Web interaction [Cui and Roto, 2008]. For example, Waycott and Kukulska-Hulme [2003] indicate that the portability of PDAs meant that the students could have access to learning resources at anytime, anywhere, and similarly, Luo [2004] highlights that portability assists convenient document editing in various locations of hospital ward. Although Cui and Roto [2008] show that people typically prefer to read emails on PDAs rather than writing emails, they still show that people use their PDAs to access social networking sites which typically require entering text. Furthermore, in many countries such as India and

Uganda, small device penetration is soaring, and many of these users have limited access to a desktop system [Joshi and Avasthi, 2007]. In this environment, the desktop-oriented tasks studied here are highly relevant.

3.5.9 Limitation of the study

This study has the following limitations:

- Our participants were quite young (average 28.27) years old and this user group might not be a representative for the whole group of small device users.

- This study uses a particular device. There is a possibility that performance errors identified here were tied to the device, however when we chose this device, we checked its features and tried to use one which can represent a *typical* PDA (see the definition of *Default Delivery Context* at `http://www.w3.org/TR/mobile-bp/#ddc`.).

- 15 participants took part in this study. This might be considered as a small number of participants but we aimed to have similar number of participants to the original study [Trewin and Pain, 1999].

- The study examined small device users in sitting condition. However, a major difference between small devices and desktop computers is mobility. The impact of being mobile on users' input performance is not investigated in this study.

3.6 Conclusions

This chapter presents a user study that aimed to demonstrate the common input errors between small device users and motor impaired desktop users. To demonstrate the commonality, we reran a study that was originally conducted with motor impaired users by Trewin and Pain [1999]. The results of this study showed that the scope of errors of small device users were the same to motor-impaired desktop users. Six categories of typing errors were identified with small device users, including long key press error, bounce error, missing key error, transposition error, additional key and key ambiguity errors. In addition, three categories of pointing errors were also observed: clicking error, multi-clicking error and dragging error. However, the magnitude of these errors were less for small device users.

The findings of this study highlight that difficulties able-bodied small device users face when typing with a small device keyboard and pointing with a stylus are the same in scope to those experienced by motor-imparied users, but the error rates are lower. These findings, although limited to a specific device, cover the general gestures and basic use cases of mobile input devices and thus are important to manufacturers of small devices and designers of the mobile Web browsers. Further, the findings support that common typing and pointing errors exist between motor impaired desktop users and small device users.

However, before we attack the input errors experienced by small device users, it is better to fully understand the typing/pointing errors under more realistic scenarios. As discussed in Section 3.5.9, current study only reveal input errors under a 'ideal' condition. Small device users in a real-world scenario may have different use patterns which may have impact on their error rates. Therefore, it would be more beneficial to firstly understand how people use small devices in their daily life and then investigate their input errors in a more natural environment.

Chapter 4

Investigating Use Patterns of Small Device Users

Chapter 3 discusses typing and pointing errors of small device users while seated. Results showed that small device users shared common typing and pointing errors with motor-impaired desktop users, however, the error rates of small device users were smaller in magnitude and the main error types did not overlap.

In addition to the seated condition discussed in Chapter 3, mobile phones and PDAs are often used in other off-desk environments. Many people use their mobile phones to send messages while they are walking on a street or sitting on a bus. Different from using a desktop computer while seated, using a small device in motion means that a user cannot devote all his visual and cognitive attention to interacting with the device. The attention of a small device user is normally switched between a primary task, such as walking and navigating, and a secondary task, for instance the interaction with a small device [Lumsden and Brewster, 2003]. Indeed, small devices, by their nature, are intended to be used in mobile settings. Therefore there is a clear need to understand how small devices are used under mobile conditions and how does mobility affect a user's input errors.

To take the first step, a field study was conducted to investigate the usage patterns of small devices. The output of this study was a protocol for designing a naturalistic device usage experiments; helping anticipate and contextualise changes in error occurrence between seating and standing/walking. The field study consisted of a series of unobtrusive remote observations and face-to-face interviews. In order not to disturb the users or alter their behaviours, the experimenter played a passive and non-intrusive role during the observations. The interviews followed the observations and aimed to confirm the observational results, as well as to obtain details of small device users' long-term habit. As the Mobile Web has becoming increasingly popular, the interview also included questions to reveal how people use the Mobile Web (i.e., Is using-while-walking a valid scenario of using the Mobile Web?). Main research questions of this field study are listed as below:

1. Do small device users use the device while on the move?

   This question addresses the most important usage pattern of small devices. Empirical studies have showed that walking distract small device users' attentions [Oulasvirta et al., 2005]. If using-while-walking is the case, we will take this scenario in to consideration when designing user evaluation for small device users.

2. Do small device users look around while typing or just focus on the device screen with little attention to the surrounding environment?

   This is a question related to small device users' attentions. We want to find out how rapidly a user switch his/her attentions between the device and the surrounding environment. We assert that rapidly attention switch will affect a user's typing performance and increase error rates.

3. How do small device users manipulate their devices? i.e., do they correct their typing errors? Do they use abbreviations? Do they type with one hand or both hands? Do they press the keys with thumb or other fingers? What type of keypad do they prefer?

   This is a general question related to how the device is manipulated. In the previous seated experiment, we observed that most participants correct their typing errors and type every word completely. This question is to find out whether this is a general usage pattern or this is a special behavior in an experimental environment. When designing user evaluations, we will not force users to manipulate the device in a way they are not used to.

4. Do small device users use their mobile phones or PDAs to access the Internet?

> The last question reveals the popularity of the Mobile Web among regular small device users. We would like to find out the reasons why people do not use it. This will help us understand the limitations of the Mobile Web.

Results showed that small device users normally typed on their mobile phones or PDAs while they were walking. They normally typed with one hand and pressed the keys with thumbs, and they also corrected their typing errors. When using the small devices while walking, people had rapid attention switches between the device screen and the surrounding environment. Regarding the use of the Mobile Web, our study indicated that less than one third of small device users accessed the Web from their mobile phones. The main reasons of not using it were bad interface, high cost, and personal preference of laptop or desktop. For those who used the mobile Web, they normally preferred to use it while seated or laying down whereas the "using-while-walking" use case was not reported. Putting the results together, we found general patterns of small device users' behaviours. Small device users normally type on their mobile phones while they are walking alone and not talking. Comparing with typing while walking, small device users have significantly less attention switches when they are typing while standing or sitting still. In addition, small device users prefer a physical keyboard to a soft-keyboard. When using-while-walking, small device users normally use the basic functions of their devices, such as telephoning and text messaging. These general usage patterns are used to build a protocol for designing naturalistic small device user studies.

4.1 Related Work

Different methodologies have been used to investigate how people use their small devices. Widely used methods include field study, on-line survey, and user behaviour analysis with modern technology.

Field studies are characterized by researchers immersing themselves in the environment of their study, gathering data through observations and interviews [Kjeldskov and Graham, 2003]. This method has been widely used to investigate usage of small devices [Petrie et al., 1998, Kristoffersen and Ljungberg, 1999, Weilenmann, 2001]. Kristoffersen and Ljungberg [1999] conducted two field studies with telecommunication service engineers and maritime consulting staff that were heavily involved in field work and used small devices for receiving orders and communicating with colleagues in the field. Their results illustrated the primary problem field workers faced when using small devices was that the interaction required too much visual attention and it required two hands for input. Pascoe et al. [2000] analyzed the fieldwork of a group of ecologists observing giraffe behaviour in Kenya. Weilenmann [2001] conducted a field study with 11 ski instructors during a one-week ski trip. Both studies generated similar results: they found that fieldworkers used a small device in very dynamic context (e.g. while standing, walking, crawling or skiing), with limited attention on the device. They also needed high-speed interaction where the device needed to be able to enter high volumes of data quickly and accurately. In addition, location awareness is also an important feature of the small devices used in outdoor environments. For instance, Sun et al. [2009]'s field studies which were undertaken at large sports events in UK and China showed that spatial context awareness is crucial for enabling the design of personally related mobile services for spectator's at large sports events. Similarly, Greaves et al. [2009] presented a formative field study in which over a period of three days, people were observed in using projector phones and pico projectors. Similar to other field studies, this study also showed the importance of location awareness and context. While field studies can generate rich amount of data in relatively short time, the major disadvantage of this method is the unknown bias and uncertainty of the representative ness of the data. It is possible that behaviours of the participants of the field study are specific to certain population and thus hard to generalize [Kjeldskov and Graham, 2003].

In addition to field studies, surveys are also conducted on how people use the mobile Web. Kim et al. [2002] studied 37 small device users in a period of two weeks, using survey-based method. Results of the study showed that use of mobile Web was highly concentrated in a few key contexts. The most frequently experienced context was when participants felt joyful, in a calm and quiet environment, not moving and used just one hand to manipulate the device. Similar results were also confirmed by Chang [2010] where a survey was conducted with 249 mobile users in Australia. Lee et al. [2005]'s survey extended Kim et al. [2002]'s survey by looking at more context factors such as time of the day, privacy of the content browsed, and crowdedness of the surrounding environment. Similar results also indicated that the mobile Web use was heavily clustered around a few key contexts, rather than dispersed widely over diverse contexts. In addition, Chae and Kim [2004] conducted an on-line questionnaire survey, the results of which suggested that small device users preferred to buy products with low risk when accessing shopping websites using small devices. Kaikkonen [2008] also conduced a global online survey with 390 people. This survey showed that people use the mobile Web in different contexts and for different activities including viewing pictures, videos, etc. Similarly, Schmiedl et al. [2009] conduced a face-to-face survey with 109 participants about the usage and usability of the Web. This survey showed that their participants prefer to use touch screen devices, and they were also faster using the mobile tailored version. The survey-based method requires a participant to report their activities and mental status straight after using the device. However, using this method alone has the risk of being too subjective since the personal characteristics, working habits, and attitude to the study of a participant may mediate the survey and thus affect the results. For example, the participants may choose not to report some details that they think are irrelevant but in fact very important to researchers.

Finally, modern technologies are also used to investigate the behaviours of small device users. Cui and Roto [2008] investigated the use context of small devices using interviews combined with traffic log analysis. They found that the use context of small devices could be characterized with four factors: spatial factor, temporal factor, social factor, and access factor. For example, small device users preferred to access the Web when they were stationary, such as sitting at home or in a restaurant. They also tend to use the mobile Web during short breaks, such as waiting for a bus. A similar study was conducted by Heimonen [2009], which was a four-week diary study with experienced and active mobile Internet users. Participants were asked to use a Web form to keep a diary of their information needs. This study suggested that mobile information services should consider a wider context of use other than location based services, including social interactions and situated activities. A similar diary study was conducted by Amin et al. [2009]. This study showed that people tend to stick closely to regularly used routes and to regularly visited places such as home and office. A more specific application oriented study was conducted by Chin Salomaa [2009] where the context of the study was 2008 Beijing Olympics. The data in this study was collected by a logging application and survey. Even though the target of this study was identifying the most popular application in a suite of applications, this study shows the importance of context which was investigated in other studies such as by Oulasvirta et al. [2005]. Oulasvirta et al. looked at how context affects small device users' attention. In their study, a participant was equipped with three small cameras: two mounted on the mobile phone and one attached to the participant's coat. These cameras were used to record the device screen, the surrounding environment, and the participant's face. In addition, an experimenter carried a fourth camera to record the whole scene. Results of the study showed that when walking in public areas, small device users had much rapid attention switches, and compared with that in a laboratory, the continuous span of attention to the small device was much shorter in public areas. The interview method used by Cui et al. has the drawback that it is limited to those who are accessible and will cooperate, and the responses obtained are produced in part by dimensions of individual differences irrelevant to the topic at hand [Webb, 2000]. Oulasvirta et al.'s [2005] study was conducted in public areas without artificial setting. However the participants had to carry additional equipments with them, which would affect their performance.

4.2 Methodology

The field study was conducted in December 2008. The overall methodology consisted of two phases: phase one included an observational study and phase two included an interview study. The presence of the observer could change the behaviour of the subjects, thus affecting the validity of the results [Webb, 2000]. In this study, remote observation was used to observe subjects from a distance without acknowledging them. Five places in Manchester, the United Kingdom, were chosen for the observational study, including a train station, a shopping centre, a university bus stop, a business area and a market street. These places were chosen for following reasons: first of all, compared to other public areas, the chosen locations, such as train station and market street, have higher volume of passengers. Secondly, it is likely to observe different classes of small device users at different locations. For example, students and younger users are expected at the university bus stop ; and at the business street, more people using high-end business oriented smart-phones should be observed.

At each of these places, the observer first chose an observation spot, for example a seat near the window of a coffee house where the observer could look at people walking on the street. Figure 4.1 is a picture of the coffee shop we used

Figure 4.1: A coffee shop on the Market Street used as one of the observation spots

as an observation spot on the market street. After settling down, the observer then spent about two hours taking notes on the small device users passing by. We deliberately chose different hours of a day to cope with the factor that an individual's behaviour may shift as the time changes [Webb, 2000]. In addition, some environmental factors, such as lighting condition and congestion of the road also changed with time. For example, the market street would have less people than the business area in the morning, whereas it would be the other way around in the afternoon after working hours. The location sampling and time sampling techniques used in this study allow us to obtain a more representative sample of the small device users. Weather condition is another factor that possibly affects small device usage pattern. For example, when it is raining, people will less likely to use mobile phones for text messaging on the street. In this study, two of five observation locations were outside. It was sunny when we did the study. However, the results presented in this thesis might have altered if the weather condition was different.

Appendix D shows a sample of data recording form that the observer used. The observer took notes on time and location of the observation, along with gender and age (judged based on the appearance of the user) of the small device user. The observer took note on whether the user was making phone calls or sending messages, and whether the user used one hand or both hands to keying text. Besides the movement status and hand/finger usage, we also looked at attention switches of a small device user. An attention switch occurred when an obvious change of attention between the device screen and the surrounding environment was observed with a small device user. It is an indicator of the disturbance a small device user received from the environment. The observer counted the number of attention switches of every small device user in a period of 20 seconds. The assumption is that the more attention switches a user had, the less likely the user focuses on small device tasks. For example, a small device user walking on a busy road would have more attention switches than one walking on a quiet road, and would be disturbed more from using the small device. Note that due to the limitation of observation setup, it was difficult to precisely count a small device user's attention switches. In this study, attention switches were counted upon obvious head movements of small device users. Other subtle indicators, such as eye movement and change of walking speed, were not counted .

The observational study gives us a snapshot of small device users' behaviors. The interviews conducted in phase two seek to confirm the observational results and also obtain information on small device users' long-term habit. The interviews were conducted on the street where the interviewer stopped pedestrians randomly and proposed to have a conversation with them about how they used mobile phones or PDAs in their daily lives. Upon agreement, the interviewer asked questions and wrote down the answers on a notebook. On average, an interview lasted 5 to 10 minutes. Again, location sampling and time sampling techniques are used in the interviews to get a more representative sample. Table 4.1 lists questions used in the interview. Questions 1 to 13 were formed based on results of the observational study. These questions seek to confirm the observational study results and also revealed details of small device users' behaviours. Questions 14 to 19 are related to accessing the Internet from small devices. Although this study did not specifically focus on one functionality of small devices, we see use of Internet on a mobile device as a emerging usage pattern and thus devoted some effort to investigate.

Table 4.1: Questions asked in the interviews

Index	*Questions*
1	Do you normally use your mobile phone while you are walking?
2	When you are walking, what do you use your mobile phone for?
3	When using your mobile phone, do you normally type with one hand or both hands?
4	Do you use your thumb to press the keys or other fingers?
5	Do you normally correct your typing errors?
6	Do you normally use predictive text? (e.g. T9)
7	Do you normally use abbreviations?
8	Have you ever used a stylus and a touch-screen on a PDA before?
9	Do you normally type very long text messages?
10	Do you use your mobile phone to do other text editing tasks other than sending text messages?
11	When you are typing while walking, which keypad do you prefer, on-screen keypad or physical keypad, why?
12	Comparing with typing while standing still, do you think you have more attention switches between the mobile phone and the surrounding environments when you are typing while walking?
13	Comparing with typing while walking with friends, do you think you have more attention switches between the mobile phone and the surrounding environments when you are typing while walking alone?
14	Does your mobile phone have the function to access the Internet?
15	Do you use the Internet on your mobile phone?
16	How often do you use it?
17	What do you use it for, news, entertainment, emails, maps or something else?
18	Where do you normally use your mobile phone to access the Internet?
19	If you do not use the Internet on your mobile phone, why not?

4.3 Observational Study Results

431 small device users were observed in total, 100 of whom were typing on their devices, and the other 331 were having phone conversations. The study was conducted at five different locations. It is likely that these small device users are unique. Results presented in this section focus on the 100 small device users making text entry. Of the 100 small device users, 61 are male and the other 39 are female. Judged from their appearance, 63 small device users were in the age range of 15 to 35, and the other 37 were between 35 and 60.

4.3.1 Typing While Walking

Figure 4.2 shows that 83 of the 100 observed small device users were walking while typing on their mobile phones. The other 17 participants were standing or sitting still. In terms of company, 87 were alone while typing, and other people accompanied the other 13. In addition, 90 small device users were not silent while typing, and the other 10 were talking with others.

Based on our observation, the majority of small device users who made text input to the devices were making text entry. Figure 4.3 shows that 79 small device users were entering text using their devices. Due to the distance between the observer and small device users observed, it is hard to find out exactly what text entry task those small device users were doing. They were either sending text messages, or making entries into calendars, or writing emails. However, according to our interview results, 76% of small device users do text messaging as the only text entry task. We have also observed 16 small device users dialling telephone numbers. After hitting the keypad they directly held the phones over their ears, and some started speaking. We also observed 7 individuals reading from the device screen. Again, due to the observational study setting, we could not figure out what exactly were these users reading.

4.3.2 Typing with Just One Hand

With regard to hand usage, Figure 4.4 illustrates that 94 small device users typed with just one hand whereas the other 6 typed with both hands. Those who typed with one hand held the device in palm and press the keys with thumb. The other hand was normally used to carry bags or holding books. Some just put the other

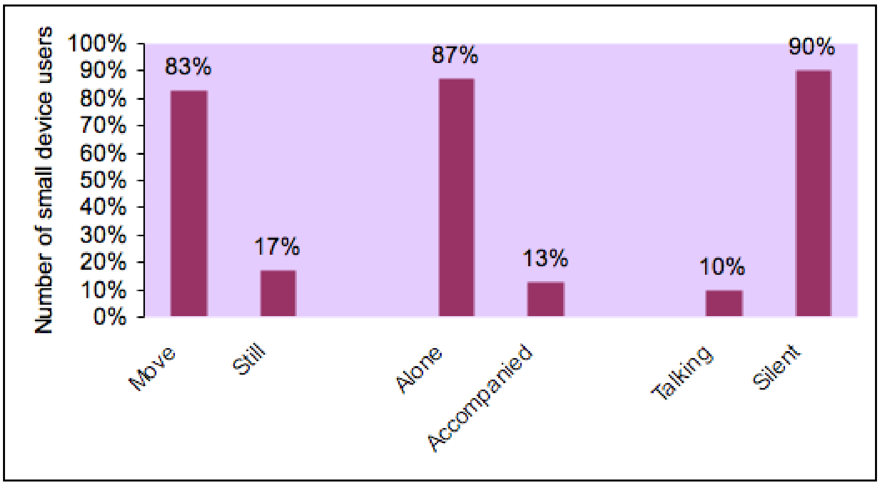

Figure 4.2: Physical status of the observed small device users

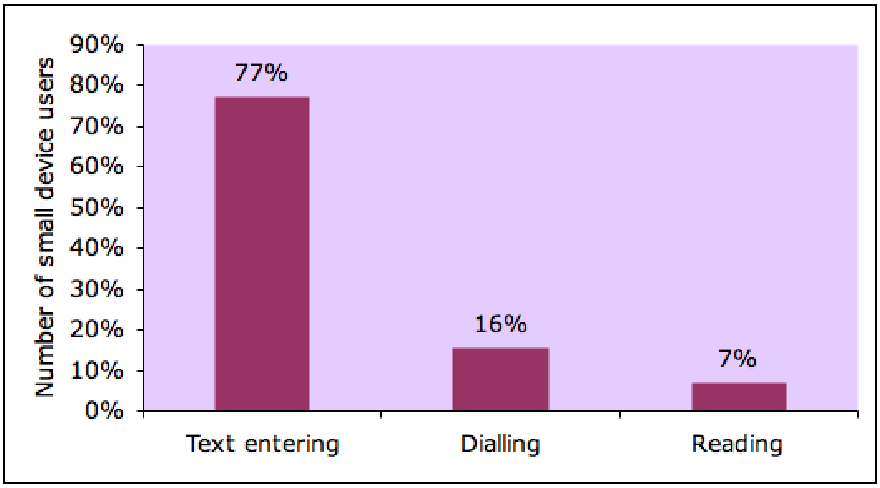

Figure 4.3: Activities of the observed small device users

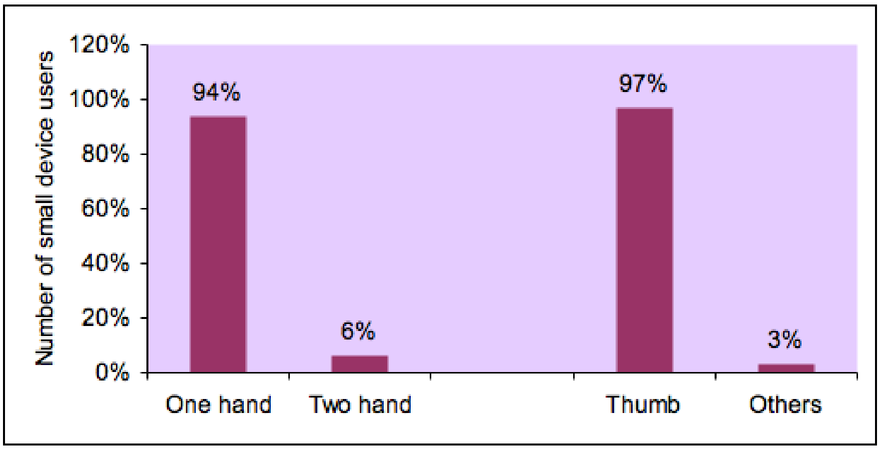

Figure 4.4: Hand usage of the observed small device users

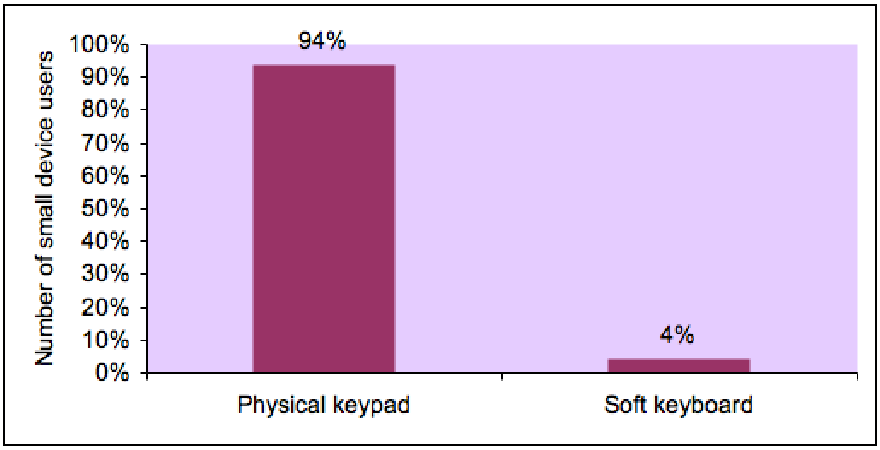

Figure 4.5: Keyboard usage of the observed small device users

hand in pocket. Regarding finger usage, 97 small device users pressed the keys with thumb. There were also 3 individuals who held the device in one hand, and pressed the keys with index finger of the other hand. In addition, Figure 4.5 shows that 94 small device users typed with physical keypads and 4 typed with on-screen soft-keyboard. For the other 2 small device users, we did not know what finger they used due to the lack of observation angle.

4.3.3 Rapid Attention Switches

Notable attention switches were observed on 95 of the 100 small device users. They switched their attentions from the device screen to the path that they walked on. When they typed while walking, they normally quickly checked the

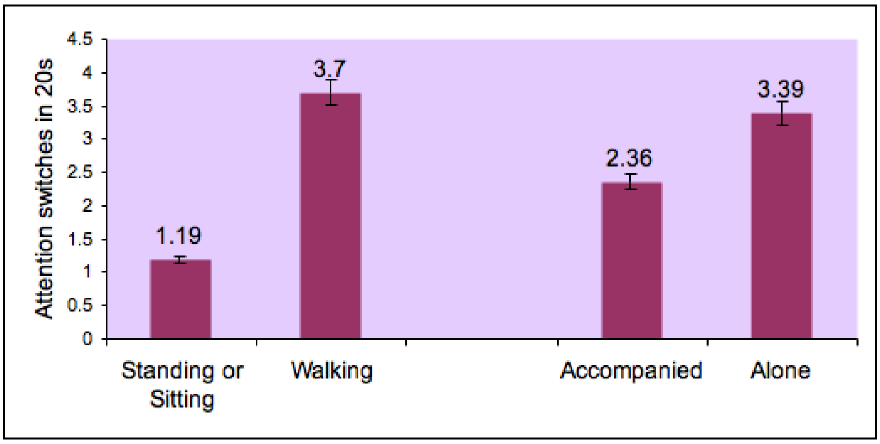

Figure 4.6: Keyboard usage of the observed small device users

path ahead, focused on the typing, and checked the path again after a few seconds. The number of attention switches were counted in a period of 20 seconds. The mean value of attention switches was 3.27 (St. dev = 2.70). Most of the observed small device users (76 out of 95) had less than 5 attention switches in 20 seconds, and there were 10 small device users who had more than 7 attention switches in 20 seconds.

It is found that the average number of attention switches of small device users in standing/sitting still condition was less than that in a walking condition. As shown in Figure 4.6, the 16 static small device users had mean attention switches of 1.19 (St. dev = 2.05), whereas this value was 3.69 (St. dev = 2.55) for the 79 walking ones. Results of the One-way ANOVA test indicate that the mean of attention switches of small device users in a still situation was significantly less than that in a walking situation (One-way ANOVA, $\alpha = 0.05$, p = 0.04). It is also found that the mean attention switches of the small device users who were accompanied or led by other people were less than that of those who were alone. Figure 4.6 shows that the mean value of attention switches of the 11 small device users who were accompanied was 2.36 (St. dev = 1.79); and the value for the other 84 small device users was 3.39 (St. dev = 2.80). However, the result was not statistically significant (One-way ANOVA, $p > 0.05$).

Table 4.2: Genders and age ranges of the interviewees

Genders & Age Range	*Affirmatives*	*Percentage*
Male	29	56.86%
Female	22	43.14%
Age: 15-35	30	58.82%
Age: 35-50	11	21.57%
Age: 50-65	10	19.61%

4.4 Interview Results

A total of 51 small device users were interviewed. Table 4.2 presents the demographic information of the interviewees. The rest of this section presents the interview results in details.

4.4.1 Using Small Devices While Walking

75% of the small device users we interviewed indicated that they used their mobile phones or PDAs while they were walking. The main use, not surprisingly, was making phone calls. 47% of the interviewees also claimed that they had experiences in sending text messages while walking. In addition, 76% of the interviewees claimed that they did not do any text editing tasks other than sending text messages.

4.4.2 Typing with Just One Hand

76% of the interviewees claimed that they typed with just one hand, and 88% claimed that they pressed the keys with thumb. As illustrated in Figure 4.7, interview results also revealed other typing habits of small device users. 61% of the interviewees claimed that they normally used the predictive text function to assist their text entry. 59% indicated that they normally used abbreviations in text messages; and 86% said they would correct the typing errors in their messages if any.

4.4.3 Using a Physical Keypad

Figure 4.8 shows that only 24% of the interviewees used a soft-keyboard for typing; whereas 76% of them used physical keyboards. This is possibly because

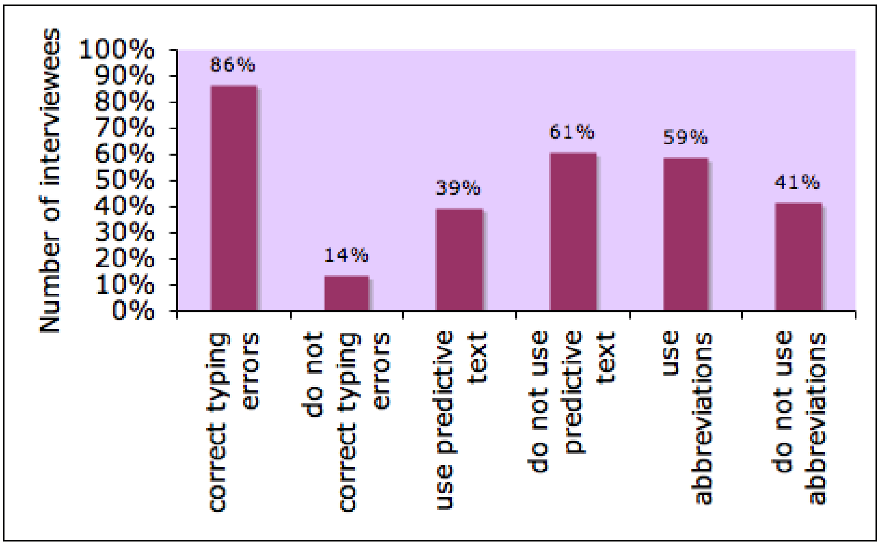

Figure 4.7: Typing habits of small device users

there are more small devices with physical keyboards than those equipped with soft-keyboards in the market. And also small devices with soft-keyboard and touch screen are always high-end product and thus more expensive. However, for those who had experiences in using both soft-keyboard and physical keyboard, still 58% preferred physical keyboard because of the lack of tactile feedbacks on a soft-keyboard. One interviewee commented that as there was no tactile feedback on a touch-screen, he usually makes typing errors by pressing a key that is neighbouring the target key.

4.4.4 More Attention Switches While Walking or Accompanied

In the interview, two questions were asked regarding a small device user's attention switches under different conditions (see Question 12 and 13 in Table 4.2). As shown in Figure 4.9, 43% of the interviewees claimed they had more attention switches when using a small device while walking, and 33% thought they had more attention switches when using the device while standing still. The other 24% responded that they always focused on the device and thus had no attention switch at all. Similarly, 43% claimed they had more attention switches when typing on a small device and walking with a friend; 31% reported they had more attention switches when tying and walking alone. Again, the other 26% of the interviewees claimed they had no attention switch when using a small device.

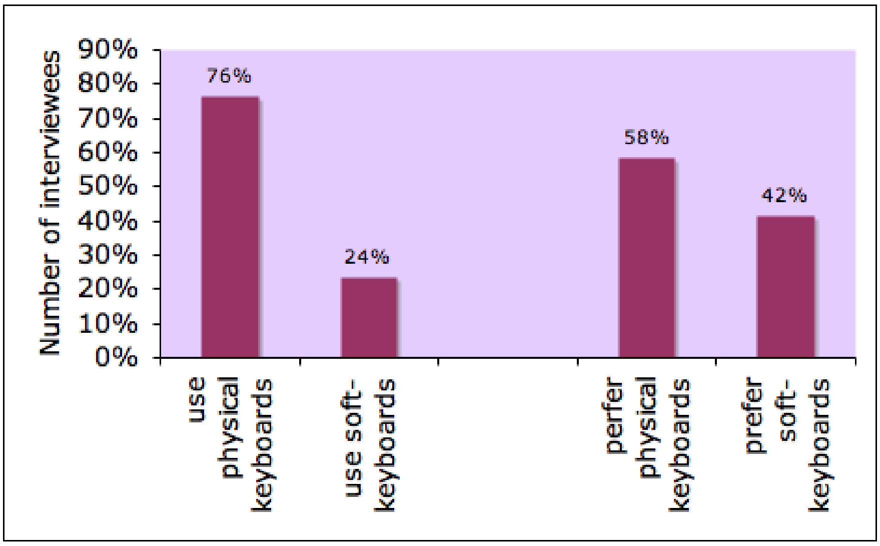

Figure 4.8: Interviews' preferences between physical keypad and soft-keyboard

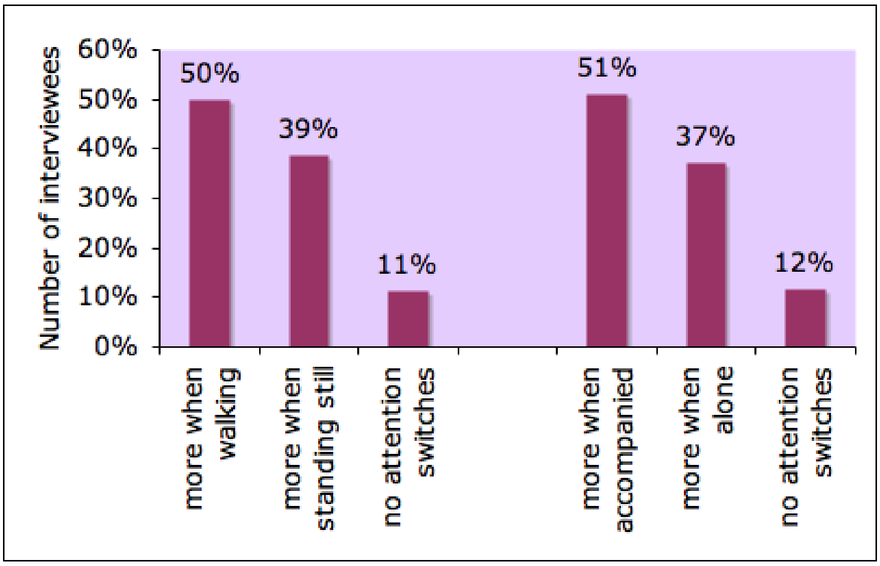

Figure 4.9: Interviews' preferences between physical keypad and soft-keyboard

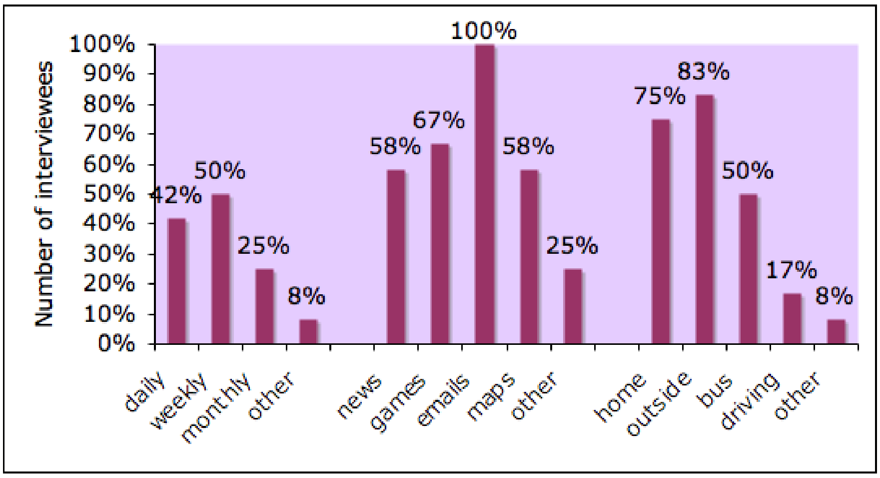

Figure 4.10: Interviewees' responses on how often and where they used the mobile Web

4.4.5 Using the Mobile Web

The interview also include questions about how small device users access the Web (i.e. using the mobile Web). 76% of the interviewees claimed that their small devices had the function to access the Web. However, only 29% of the interviewees reported using the function. Figure 4.10 shows that most of those who claimed using the mobile Web either used it daily or weekly. The main activities on the mobile Web were checking emails, reading news and playing games. With regard to location of using the mobile Web, responses shows that people either used it when they were at home or sitting outside (e.g. in a park or a coffee shop). We did not record any instance that a small device user using the mobile Web while walking.

Figure 4.11 shows the reasons given by interviewees for not using the Web via their small devices. The main reason was that they felt that there was no need to access the Web from their mobile phones or PDAs given that they already had desktop computers or laptops at home or working places. This was followed by criticisms on bad interface of the mobile Web and expensive data traffic cost. In addition, not familiar with the function is another reason mentioned by four interviewees.

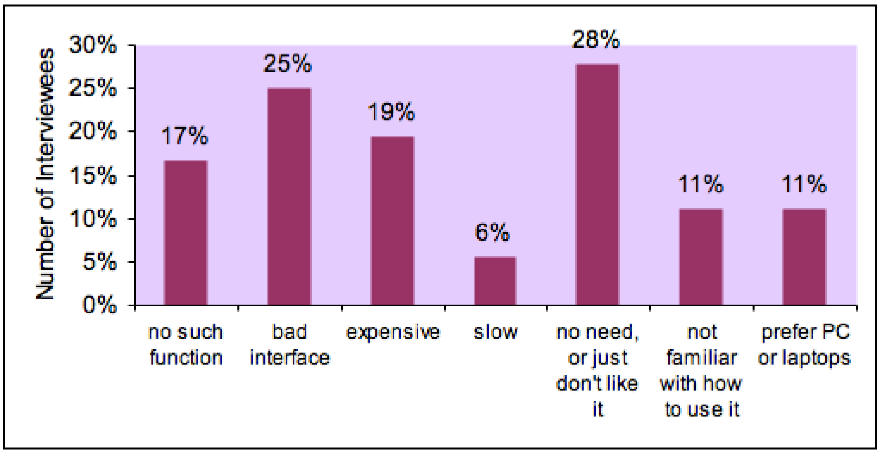

Figure 4.11: Interviewees' responses on why they do not use the mobile Web

4.5 Patterns of Small Device Users

A pattern of use reflects a typical scenario of how a device is used in real life. This section consolidates the results presented above and presents patterns of use of small devices. According to the results of the observational study, patterns of use of small devices can be grouped into three sets: mobility, hand usage, and attention switches. Each of these patterns has several attributes, describing use of a device from different aspects.

- *The mobility pattern* consists of three attributes, each of which has two values: move or still, alone or accompanied, and silent or talking. When all three attributes are used, the mobility pattern has 8 distinct combinations ($2 \times 2 \times 2$). For example, a possible scenario based on one combination of the mobility pattern can be that a small device user is walking with a friend, and he replies a text messages while talking with his friend.

- *The hand usage pattern* has three attributes: one hand or both hands, thumb or other finger, keypad or touch-screen. Since one can only use thumbs when typing with two hands, the hand usage pattern has 6 combinations.

- *The attention switch pattern* has just one attribute: the number of attention switches. It records number of attention switches in any visual cognitive resource demanding environment.

Table 4.3: Possible values of the mobility pattern and hand usage pattern

Pattern Index	*Explanations*
M1	walking alone and not talking
M2	walking while accompanied and talking
M3	walking while accompanied but not talking
M4	not walking and alone and not talking
M5	not walking and accompanied and talking
M6	not walking and accompanied and not talking
M7	walking alone and talking
M8	not walking and alone and talking
C1	one hand typing, using thumb, using physical keypad
C2	one hand typing, using index finger, using physical keypad
C3	both hands, using thumb, using physical keypad
C4	one hand typing, using thumb, using soft-keyboard
C5	both hands, using thumb, using soft-keyboard
C6	writing on a touch-screen with a pen

Table 4.3 lists the possible values of mobility pattern and hand usage pattern. Figure 4.12 and Figure 4.13 reconstruct the observational study results based on these patterns. From Figure 4.12 we can see that 72% of the observed small device users typed while they were walking, alone, and not talking. This observation is supported by the interview result that 75% of the interviewees claimed that they used their small devices while walking and 47% reported that they sent text messages while walking. On the other hand, Figure 4.13 shows that 89% of the observed small device users typed with a physical keypad, using just one hand to manipulate the device, and pressed the keys with thumb. This is also confirmed by the interview results that 76% of the interviewees typed with one hand, and 88% pressed the keys with thumb.

In terms of the attention switch pattern, observational study results show that when typing while walking, small device users had 3.27 attention switches in 20 seconds on average. They also had significantly less attention switches when standing still. Interview results indicate that more participants thought they had less attention switches when standing still, which confirms the observational study results. Interview results also suggest that more participants thought they had more attention switches when being accompanied than being alone. However, the

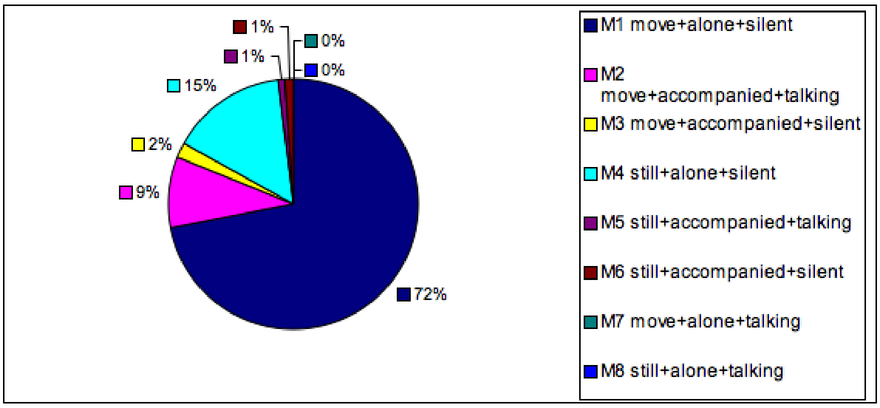

Figure 4.12: A sectorial breakdown of mobility pattern of small device users

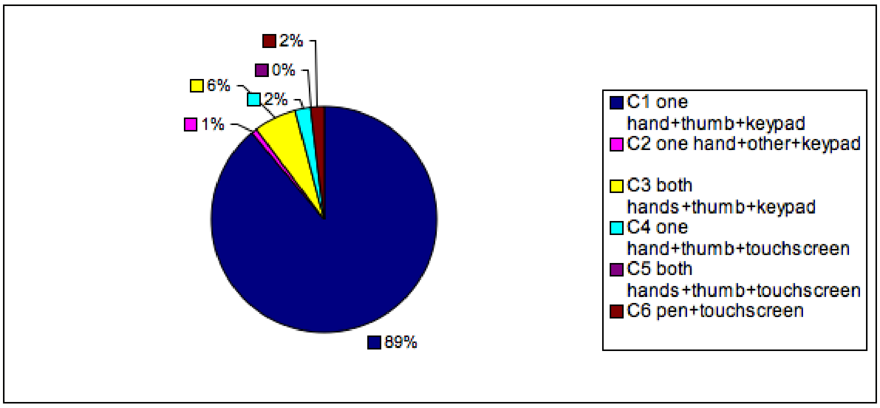

Figure 4.13: A sectorial breakdown of hand usage pattern of small device users

observational study on this comparison yields an opposite but insignificant result. Oulasvirta et al [2005]'s work suggests that a small device user's continuous attention to device fragmented and broke down to spans of 4 to 8 seconds. Our results confirm with Oulasvirta et al [2005]'s results. Since the count of attention switch in our study is based on estimate rather than precise recording, it is difficult to compare two result sets statistically. However, the author would expect the average number of attention switches go up if precise recording techniques was applied.

Although only four touch-screen users were observed during the observation phase, 24% of small device users participating in the interviews claimed that they had used or were using a small device with touch-screen. In addition, we also found that for those who have experiences on both physical keypads and soft-keyboard, more users prefer the former than the later. Some small device users switched back to physical keypad after using soft-keyboard for a while. The reasons of dislike soft-keyboard include: lack of tactical feedback, screen being too sensitive or insensitive, difficult to use with long nails. During the past few years, touch-screen technology and small device operating systems have developed dramatically. Devices such as iPhone and HTC smartphone which run on iOS and Android allow users to accessing vast amount of applications by simply tapping and sliding the screen. As new technologies emerge, behaviours and preferences of small device users may change. For example, it is more convenient to hold a touch-screen device such as iPhone with one hand, and type with the index finger of the other hand. With the improved touch-screen technology, and also larger screen size, a user can press a key on a screen easily. As touch-screen does not provide tactile feedbacks as a physical keyboard does, it would probably requires more visual attention to type with. Therefore, a touch-screen user would devote more attentions to the screen than to the surrounding environment while typing, which means a touch-screen user would either slow down or stop walking when typing with the device. With regard to the use of mobile Web, as entering url and navigating through pages become easier on emerging small devices, the concern about interface will gradually resolve. In addition, as the bandwidth of mobile broadband increases, the cost of accessing rich Internet content will reduce. These factors will allow more and more use of mobile Web.

4.6 Protocol for Designing User Evaluation with Small Device Users

Based on our field study results, here we provide a protocol on designing controlled experimentation in naturalistic mobile settings. In general, the protocol is formed based on the following principles:

- *A study should include different topographical conditions.* In more realistic scenarios, small device users are likely to use the devices while traversing through areas with different conditions, such as on a straight road, on stairs and at corridors. Comparing with using simple path or treadmills, introducing various topographical conditions will increase realism, thus generate more representative data.

- *A study should include different mobility conditions.* Again, people use small devices while they are sitting in a park, standing at a bus stop, walking alone or walking with friends. These mobility differences should be coded in the study so that performance of small device users under different mobility conditions can be compared.

- *An experimenter should take note on each participant.* Results of our field study show that there are general patterns in terms of typing habits and attention switches of small device users. For example, small device users usually type with just one hand and they normally have rapid attention switches when using the device while walking. Such information can be used as indicators of realism of a controlled experimentation. By collecting and analyzing these data, the researcher knows whether the experimentation is naturalistic.

4.6.1 Step-by-Step Design

Based on these principles, here we describe a step-by-step protocol that researchers could follow to design a controlled experimentation with small device users. An example design is presented here to illustrate each step. The example experiment aims to investigate small device users' typing errors under walking conditions.

Step1, identify independent variables. Mobility conditions, topographical conditions, and other factors such as congestion level, lighting condition and noise level are independent variables that will affect participants' performance. These need to be clearly identified before the experiment. More importantly, researchers need to choose which variables to investigate and which to ignore.

Step 2, define values for each variable. If researchers choose mobility condition and topographical condition as two independent variables, they then need to consider possible values for each variable. If mobility condition has 2 values (walking alone and walking while accompanied), and topographical condition has 3 values (open space, straight corridor, stairs), the researchers will have 6 (2×3) combinations.

Step 3, choose a route. Now the researchers need to choose a route that accommodates the possible combinations of the independent variables. The route should be long enough so that same route will not be repeated during the experiment. In addition, open space, corridors and stairs (up and down) need to be included in the route so that the topographical variable can be implemented.

Step 4, split the route into segments. After choosing a path, the researchers now divide the path into 6 segments, each corresponding to one variable combination. The start and end point of each segment should be clearly identified just to keep consistency among participants.

Step 5, choose tasks. Task selection is highly depending on the aim of the experiment. To be realistic, tasks conducted on small devices cannot be too long. People will generally perform better with materials and tasks that they are familiar with. Using day-to-day tasks will recall their daily experiences in using the devices, therefore generates more realistic results as opposed to using tasks that are less likely to undertaken in real life.

Step 6, assign a task to a segment. Now researchers assign one typing task to each segment. To minimize learning effect, materials used for each typing task should not be the same. However, the difficulty of the task should be consistent. This can be achieved by maintaining a same ratio of characters to numbers or characters to punctuation marks.

Step 7, set up user interface. Now that tasks and route are defined, researchers now set up user interface participants use in the experiment. A logging tool needs to be set up so that user input can be recorded in real time. For this example, researchers log each key press with a time stamp. In addition, the logging should be conducted at the background so that the participants will not be interrupted.

Step 8, assign an observer. One principle of our protocol is that researchers keep track of certain indicators of realism. Here the researchers need to assign an observer whose job is to remotely observe a participant during the experiment. The observer take notes on the participant's attention switches, way of typing, or number of pauses during the experiment. The observer can keep a short distance behind or ahead the participant, so that he/she will not disturb the participant but sill has a clear view.

4.6.2 General Guidance

In addition to the step-by-step experimental protocols, there are a number of aspects to the experimental design which should be considered, these are less formal, and may therefore be regarded as general guidance. These general comments are in fact a distillation of the results of our experimental work along with the results of other related work from various researchers within the domain.

Use Realistic Tasks

Tasks used in a user evaluation depends on the variables tested. If text legibility or reading speed is of concern, text comprehension and word searching tasks are often used. For example, Mustonen et al. [2004] examined the affect of walking on mobile phone text legibility. In their study, participants were asked to read a text passage on a mobile phone and answer questions about the content they had just read. Participants were also asked to find a given word from a passage of pseudo-text. Based on the field study, it is suggested that more realistic tasks can be used, such as looking for a telephone number in the contact book, or read and comprehend a piece of news though the mobile Web. In this way, participants of the study are tested with the tasks that they are familiar with, and therefore the study will be more realistic.

On the other hand, if the typing performance of small device users is to be tested, tasks such as composing a text message or an email would be useful. However, one limitation is that since the materials used between participants need to be consistent for the purpose of performance measure, copy typing is normally used for typing tasks where all participants typed in the same text which is given to them before hand. According to the field study, copy typing is not a typical use of small devices. Therefore, a trade-off between the control of variables and the representativeness of real phenomena must be made. Last but not least, pointing performance of small device users is also widely measured. Such tasks always involve participants clicking on-screen items with a pen and touch-screen. For example, in Brewster et al.'s study, participants were asked to click on-screen buttons of different size with a calculator-style on-screen keyboard [Brewster, 2002]. It is suggested that dialling a telephone number by clicking the numeric keypad displayed on the device screen could be a practical task to test a small device user's pointing performance.

Respect a User's Typing Habit and Attention Switch Strategy

In a user evaluation, users should follow their own typing habit as much as possible. For example, the predictive text function should be turned on, and error correction and use of abbreviations should be allowed. Users should have the right to choose between a physical keyboard and a soft-keyboard. Further, they should not carry additional recording equipment or being closely video recorded or continuously instructed by the experimenter, both of which make the setting unnatural and may affect a participant's performance. The interaction between a user and a experimenter should be kept minimal and only allowed if it is crucial for carrying out the evaluation.

Besides typing habits, small device users also develop attention switch strategies to cope with environmental disruptions. Oulasvirta et al's observation results suggest that small device users normally calibrate their attentions early on, where attention to the environment mainly occurs just when they enter a new environment [Oulasvirta et al., 2005]. When small device users are familiar with the current environment, they will focus more on the device screen and briefly scan the environment over long intervals. Similar observations were also made in our study. It is observed that the attention switches of small device users did not spread evenly over the period of observation. They tend to have more attention switches when the environment changed. For example, a small device user had more attention switch when approaching the gate of a shop he wants to enter than when walking from a distance to the shop. In a small device user evaluation, it would be good if multiple environments are used so that the attentional strategies that small device users adopt in real life can apply.

Test Devices under Different Mobility Conditions

Results of the current field study suggest that small devices are not only used in static position, but also used while the users are walking. Further, the use of small devices in walking condition is not only limited to phone calls, but also includes other attention demanding task like typing and reading. Therefore, in a user evaluation, the use of a small device should be tested under different mobility conditions, certainly under walking condition.

In Lin et al.'s study, small device users' pointing performance was examined under three differnet conditions: sitting, walking on a treadmill, and walking through a defined route in a laboratory room [Lin et al., 2007]. Further, Kjeldskov and Stage's study also involved six mobility conditions: sitting, walking on a treadmill with constant speed, walking on a treadmill with varying speed, walking on a court at constant speed, walking on a court at varying speed, and walking in a pedestrian street [Kjeldskov and Graham, 2003]. These settings, although cover most of the mobility conditions, are still unnatural as participants normally conduct different trials, each of which corresponds to a specific mobility condition. It is suggested that different mobility conditions can be all coded in a single trial. For example, participants can go through a route which mixes different topographical conditions. They can also stop at certain points to simulate the sitting or standing condition.

Distinguish Public Space and In-lab Route

According to our results, small device users in real-world scenarios have rapid attention switches between the device screen and the surrounding environment. The cause of attention switches varies from avoiding obstacles to talking with someone else, and it is usually unpredictable. On the other hand, we also observed cases where small device users had fewer attention switches during the process of observation. For example, we observed a lady using a PDA when walking on the pavement very close to the edge of a road. While using the device and walking, this lady had no attention switches in about 20 seconds, which is much less than the average number of attention switches observed with other small device users. This is possibly because the lady knew that no one was going to collide with her from the opposite direction (because there was not enough space between the curb and herself for anyone to go through), and she could just follow the road by scanning the curb with her foresight while looking at the screen of her PDA. Therefore, the user did not need to deliberately shift her attention for path finding. This suggests that when following an edge, small device users will have less attention switches than walking in open area. In a controlled user evaluation, walls on both sides of a corridor, edge of the tape on a treadmill, and the marks on a clearly marked route may have the same effect to a user as the curb of the road did to that lady, which serves as a way edge [Goble et al., 2000, Weilenmann, 2001]. In such settings, users know that they will not be disturbed and by scanning the way edge, a participant may save efforts for path finding and focus more on the device screen.

Based on these principles, it is suggested that small device user evaluation should distinguish the setting of walking along a clearly marked route and the setting of walking in public space where no specific route is acquired. Clearly, using a clearly marked route has the benefit that all participants follow the exactly same route and thus the effect of route variance is fine controlled. However, the trade-off is that disturbance a user receives is low in these settings and thus the performance of that user may be overestimated. On the other hand, using public space means the setting is more naturalistic and that a user may have more attention switches.

4.7 Conclusions

This chapter presents a field study that investigated the usage patterns of small devices.The study consisted of a series of unobtrusive remote observations and face-to-face interviews. Following use patterns of small devices were found based on the field study results.

- Small device users type on their mobile phones or PDAs while they are walking alone and not talking (72% of small device users observed).
- Small device users type with just one hand, and press the keys with thumb (89% of small device users observed).
- Small device users use predictive text function (61%), use abbreviations (59%), and correct typing errors in their text messages (86%).
- Comparing with typing while walking, small device users have significantly less attention switches when they are typing while standing or sitting still.

The patterns derived from this study apply to general small device users. Behaviors of users of advanced touch-screen systems might be different. However, the vast majority of small devices, are still far less sophisticated. Therefore, use of the majority of small devices followed, and will keep on following the patterns presented. Based on results of the study, a protocol of designing user evaluation with small device users in a more realistic way is proposed. This enable the design of our naturalistic small device experiment, created to understand any changes in scope and magnitude of the errors found in our "seated" experiment.

Chapter 5

Small Device User Evaluations While Walking

Chapter 3 presents a user evaluation of small device users under sitting conditions. Chapter 4 looks at how small device users use their mobile phones and PDAs while they are moving. This chapter extends the user study presented in Chapter 3 and presents an experiment with small device users while walking. The aim of the study is to find out whether typing and pointing errors identified in the first user study also exist when small device users are walking in more realistic scenarios and whether the error rates will increase. Specifically, the following two research questions are asked:

1. Do the typing and pointing errors identified on small device users under sitting condition also exist when the users are standing and walking?
2. If so, will the error rates of these errors increase in magnitude under these conditions?

The user study presented in this chapter was designed based on the protocols obtained from the field study. To be explicit, participants were asked to walk along a pre-defined course and to conduct typing and pointing tasks on a PDA at the same time. The walking course consisted of different topographical conditions, such as open outdoor areas, straight indoor corridors, and also involved going up and down on stairs. Three different forms of mobility were employed: walking alone, walking while being led by another person, and standing still. Tasks from our previous study (Chapter 3) were re-used, but were presented in

Table 5.1: The roles of experimenters

Index	*Roles*
Experimenter A	To collect demographic data and feedback before and after the study. To observe the participant during the study and to take notes on the participant's steps and attention switches.
Experimenter B	To release tasks one by one at defined checkpoints on the route. To observe the participant during the study and to take notes on the participant's steps and attention switches.
Experimenter C	To lead the participant in task T7, T8 and T9.

a more realistic format (i.e., composing a short email and editing an existing message). Participants' keystrokes and stylus action were recorded by a logging software. Input errors were then identified by analysing the log files.

Results of the user study showed that apart from transposition error, typing and pointing errors identified with small device users under sitting condition were also observed under standing and walking conditions. When walking, the typing error rates of small device users increased to the same magnitude with, in some cases higher than, that of motor-impaired desktop users. Similarly, the clicking and dragging error rates also increased in walking condition, both were higher than that of motor-impaired desktop users.

5.1 Methodology

This section presents the study methodology, including information about participants, experimenters, tasks, route, procedures, and apparatus.

5.1.1 Participants & Experimenters

A total of 15 participants took part in the user study. All participants were able-bodied, with no disability, and they were not under any influence of alcohol or drug. Participants were unpaid volunteers. They were postgraduate students and research staff recruited via email advertisements. The user study was carried out by three experimenters. The roles of each experimenter are listed in Table 5.1.

5.1.2 Tasks

Three types of tasks were used: pointing task, typing task and editing task. Each of these was performed under three mobility conditions: standing, walking alone, and walking while being led. Therefore, a participant conducted 9 (3×3) tasks in total. Tasks and materials from the user study presented in Chapter 3 were re-used. However, in order to reduce the overall length of the study (previous study lasted for more than 90 minutes, and participants complained that they became very tired toward the end), the number of pointing tasks and the length of the typing tasks were scaled down in this study. For the convenience of analysis, each task was assigned an index. For example, the first task was indexed T1, and the last one was T9.

- *Pointing tasks (T1, T4 and T7)* required a participant to perform pointing, clicking, and dragging actions with a stylus on the touch-screen of the PDA. Five pointing actions were requested in each pointing task, which are listed in Table 5.2. Order of the actions in each repetition was different. This was to overcome the impact of learning effect.

- *Typing tasks (T2, T5 and T8)* required a participant to type a given text passage into an empty text box. Table 5.3 shows the text passages used in each typing task.

- *Editing tasks (T3, T6 and T9)* followed typing tasks. A Web page for the editing task was designed so that it modified the text that a participant had entered in the previous typing task, introduced typing errors at random positions, and reproduced the modified text on the screen. The number of errors introduced were of 20% of the words entered in the typing task, and they were all clearly marked by '$\star$' symbols. The participant was then asked to correct the artificial typing errors using both pointing skills and typing skills.

5.1.3 Route

Each task presented the previous section was designed to be conducted under a certain mobility condition. In the study, a participant went through a pre-defined route while conducting the tasks. The route was carefully chosen so

Table 5.2: Actions required for pointing tasks T1, T4 and T7

Action	*Explanation*	*Example*
Single click	Perform a single tap with the stylus on a specific position of the screen.	Click between letter 'n' and 'o' in word 'abnormal'
Double click	Similar to single click, but perform a double tap.	Double click on word 'BROTHER'.
Triple click	Similar to single click, but perform a triple tap.	Triple click on a sentence shown on the screen.
Short drag select	Drag the stylus to select materials shown on the screen. Short drag required dragging for short distance.	Drag the cursor to select the letter 'a' in word 'watch'.
Long drag select	A long drag select action required a dragging for long distance.	Drag the cursor to select a long sentence.

Table 5.3: Text materials used for typing tasks T2, T5 and T8

Tasks	*T2*	*T5*	*T8*
Texts	J. Quentin said he has lived for 136 years (born in 1875). Are you sure? Maxine added the sum 1875 + 134 = 2009, and knew he is younger. Zinc helps memory!	The jumper smelt of boiled cabbage and old rag mats, size x-large for indoor play, was tacked to a very dirty wall (a cheque of 163 pounds in one pocket).	It depicted simply an enormous face, more than a meter wide: the face of a man of about 45, with a heavy black mustache and ruggedly handsome features.
Total words	28	30	27
Total characters	154	154	152
Punctuation marks	12	6	4
Numbers	18	3	2
Capitalized letters	5	1	1

that specific mobility condition required by each task was fulfilled. As shown in Table 5.4, the route was further divided into 9 sub-routes, each corresponded to a task and a mobility condition. Loading of the Web pages were controlled by an experimenter so that every participant would conduct the same task on the same sub-route. 9 checkpoints were defined on the route, which were the starting points of each sub-route. During the study, experimenter B followed the participant and controlled the loading of the Web pages. When the participant reached a checkpoint, the experimenter released the corresponding Web page for that task. If the participant finished the task before reaching the checkpoint of the next task, the participant would receive a note that the Web page for the next task was loading. The participant could only access the Web page for the next task when he/she reached the corresponding checkpoint. The length of each sub-route was carefully designed so that all participants could finish the task before reaching the next checkpoint. In the user study, none of our participants walked on the sub-route for the next task but still conducting the previous task.

Figure 5.1 shows the route used. The building in the middle of the picture is the Kilburn Building. The red lines represents the path. Although the path is illustrated in straight lines in the figure, it was curvy in reality as participants needed to avoid pedestrians and other obstacles (e.g., trees and lamp posts). A participant started by standing at the loading bay and conducted task T1. Then the participant walked on the pavement around the building to the automatic door on the first floor. In the mean time, the participant conducted task T2. Then the participant entered the Kilburn Building and stood by the message board and conducted task T3. After that, the participant walked upstairs and went to room 2.122 while doing task T4. When arriving room 2.122, the participant stood by the door and conducted task T5. Upon finishing task T5, the participant walked along the straight corridor and found experimenter C at the end of the corridor, during which the participant finished task T6. Experimenter C then lead the participant back to the automatic door where the participant entered the building. While being led, the participant finished task T7. Then experimenter C lead the participant to the sign outside of the Kilburn Building, while the participant conducted task T8. After that, experimenter C lead the participant back to the loading bay where the study started, and the participant conducted task T9 at the same time.

Table 5.4: Task conditions and corresponding sub-routes and checkpoints

Task	*Mobility*	*Task Type*	*Sub-route*	*Checkpoint*
T1	standing	pointing	1	loading bay
T2	walking alone	typing	2	loading bay
T3	standing	editing	3	automatic door on the first floor of the Kilburn Building
T4	walking alone	pointing	4	message board
T5	standing	typing	5	door of room 2.122
T6	walking alone	editing	6	door of room 2.122
T7	guided walk	pointing	7	meet the experimenter
T8	guided walk	typing	8	automatic door on the first floor of the Kilburn Building
T9	guided walk	editing	9	sign of Kilburn Building

Sub-route	*Details*
1	Standing at the loading bay area behind the Kilburn Building.
2	Walking from the loading bay area to the automatic door on the first floor of the Kilburn Building, via Oxford Road.
3	Entering Kilburn Building, standing by the message board near the automatic door.
4	Going upstairs to 2nd floor of the Kilburn Building and walking to room 2.122.
5	Standing by the door of room 2.122.
6	Walking along the corridor, and finding an experimenter in black jacket.
7	Following the experimenter to the automatic door of Kilburn Building
8	Following the experimenter to the sign outside of Kilburn Building.
9	Following the experimenter to the loading bay where the study started.

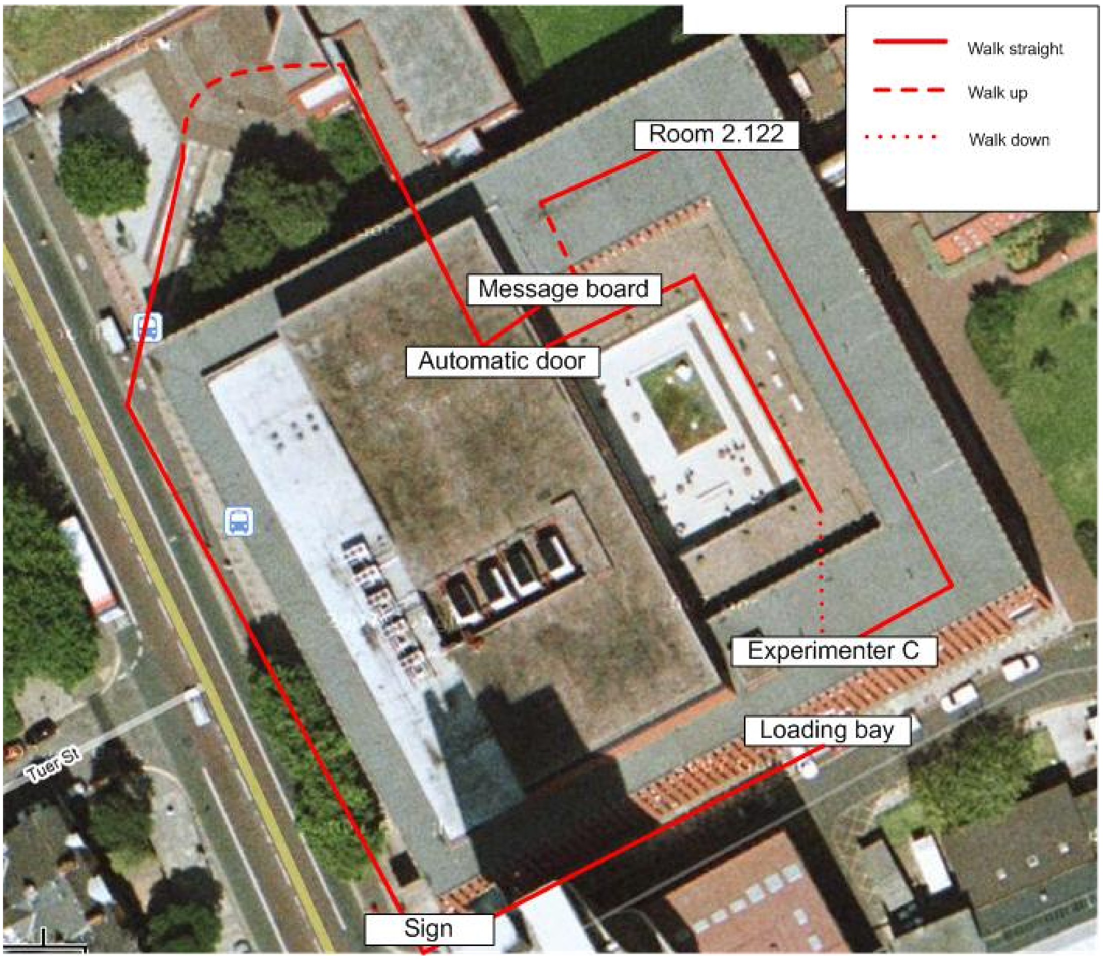

Figure 5.1: A route that participants walked on in the user study

5.1.4 Procedure

The overall study was divided into three sessions: background session, main task session and feedback session. In the background session, experimenter A collected demographic information from the participants. The demographic form used for the background session can be found at Appendix F. After the background session, experimenter A gave the PDA to the participant. The participant could go through a set of practice pages before conducting the main tasks. Although the practice was optional, all our participants went through it before the main task session. Then experimenter A loaded the first Web page to the PDA and started the main task session.

In the main task session, the participant was left alone and conducted tasks according to the instructions shown on the Web pages. Directions were also shown on the Web pages, therefore the participant would not be interrupted by asking directions. The participant walked at his/her own pace. The steps and attention switches that the participant made were carefully counted by experimenter A and experimenter B who followed the participant. On sub-route 7, the participant would meet experimenter C, who would lead the participant to the end of the main task session. When being led by experimenter C, the participant was instructed to keep pace with the experimenter and to stay within 2 meters of the experimenter as he walked. In order to reduce the impact of learning effect, we changed the task order for 5 participants: participant P1 to P10 conducted tasks T1 to T9 in an ascending order, whereas participants P11 to P15 conducted T7, T8 and T9 first, then T1 to T6.

The feedback session followed the main task session. In this session, the participant was asked to rate the typing and pointing performance. Questions include: how easy is it to locate the right key and to avoid a key ambiguity error; how easy is it to release a key quickly and to avoid a long key press error; how easy is it to avoid an additional key error; and how easy is it to avoid a bounce error. Answers were made on a seven-point scale, with “1” representing “very difficult” and “7” representing “very easy”. These ratings reflect participants’ confidence on avoiding typing and pointing errors. A full list of questions asked in the feedback session can be found at Appendix G.

5.1.5 Apparatus

This subsection presents the device, software and Web pages used in the study. We asked participants to access a set of Web pages with a given HP iPaq HW6515 PDA, and to conduct typing or pointing tasks on each Web page. Their input (keystrokes, cursor movements) were logged in real time by a logging software.

Mobile Device

In order to be consistent with previous user study under sitting condition (see Chapter 3), an HP iPaq HW6515 PDA (see Figure 5.2) was used in this user study. This PDA is 118×71×18mm in three dimensions, weighted 165g. The device is equipped with a QWERTY keyboard (see Figure 5.3), a touch-screen, a joystick and a stylus. The screen size is 45×60 mm, with a resolution of 240×240 pixels. Keys on the keyboard are round in shape with a curve surface. The diameter of each key is 5mm. Keys repeat in the same way as those on a standard desktop keyboard, with an initial delay of 500 msec before the repeat starts. There are two modifier keys: a lock-shift key and a blue key. Modifier keys operate in latch mode. To enter a capitalized letter, one needs to press the lock-shift key once, and press the target key. Similarly, to enter an number or a punctuation mark that is printed in blue on top left corner of each key, one needs to press the blue key once, and then press the target key. Modifier key only activates once. To lock the capitalized mode, one needs to press blue key and lock-shift key in sequence; press the same sequence again will switch the input back to lower case mode.

Web Pages

Two sets of Web pages were created for this user study. The first set was three training pages. The purpose of the training pages was to let a participant get used to both the device and the tasks before starting the main task session. Screenshots of the training Web pages can be found in Figure E.6, E.7, E.8 in Appendix E.

The second set of Web pages consisted of nine pages where participants conducted the main tasks. Figure E.1, E.2 and E.3 in Appendix E are screenshots of Web pages used for pointing tasks T1, T4 and T7. Text on those pages were displayed in font size 11, and the button at the bottom was displayed in size 42×5mm. Six sub-tasks were listed on each of these Web pages. In order to

Figure 5.2: HP iPAQ HW6515

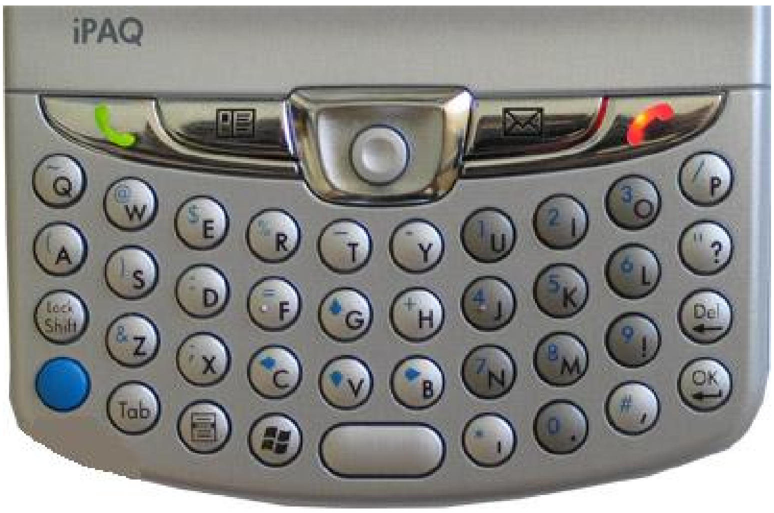

Figure 5.3: HP iPAQ HW6515 keyboard

reduce the impact of learning effect, the sequence of the sub-tasks was different on each page.

Figure E.4 is a screenshot for typing task T8. Again, the text was displayed in size 11. Web pages for typing task T5 and T8 have exactly the same layout, and the only difference is the text displayed in the text box (see Table 5.3).

Figure E.5 in Appendix E is a screenshot of a Web page for an editing task T9. The text box on the top displays the text message a participant enters in the previous typing task (task T8). The text presented in the text box at the bottom is a modified version of the message in the text box on the top. We randomly select 20% of the words that a participant enters. For each word selected, we reversed the letters of that word to generate a typing error. For example, the word “happy” is changed to “yppah”. Participants were asked to correct those artificial typing errors. The way we produced “typing errors” was not the way they were made normally. However, the point here was not to about how closely we could reproduce typing errors, but to examine a small device user's input error.

Before conducting a task, a participant would see an instruction page which told the participant what to do for the next task and where to go while doing the task. Figure E.9 in Appendix E is an example of the instruction page for task T2. When a participant finished a task, the participant would click on the button at the bottom of the page and the instruction page for the next task would load.

In addition to the Web pages for conducting tasks, we also created a page for experimenter B to control the loading of the Web pages. We called this Web page the “control panel”. As shown by Figure E.10 in Appendix E, the control panel has eight check boxes on the top, each of which is responsible for a task. By ticking the boxes and clicking the “Set to 1” button, experimenter B can release the Web page for the corresponding task. A participant can only access the Web page that is released by experimenter B. Note that task T1 is automatically released at the beginning of the user study, and we only control the loading of the rest eight tasks.

Logging Software

A UsaProxy software was used to capture key presses and cursor movements made by a participant on a Web page. The UsaProxy software acts as a proxy that sits between a Web server and a client and monitors a user's input on a

Web page [Atterer et al., 2006]. It does this by adding a JavaScript program to a requested Web page. The JavaScript program records a user's key presses and cursor movements events with local time stamps. The log file is then sent back to the proxy server and is stored in a text file. By analysing the log file, we identified a participant's typing and pointing errors. The UsaProxy software is open source. Several modifications to the original application were made to tailor to the study's needs:

- In order to identify long key press error, the UsaProxy was modified in such way that it records the keydown event (i.e., when a key is pressed down), keypress event (i.e., when a key is registered) and keyup event (i.e., when a key is released) separately. Therefore, a long key press error will be identified in a log file if more than one key-press events appear between a key-down event and a key-up event (i.e., the keyboard user presses down a key, does not release it in time, which causes unwanted copies to be registered).

- According to results from Chapter 3, small device users can make several key strokes within one second. The original UsaProxy records each event in second, which makes it difficult to distinguish a sequence of key strokes that occur within one second. Therefore, the application was modified so that it records keyboard event in millisecond.

- The original application does not record an event when a mouse key is released. This causes problems in identifying dragging action. The mouse-up event was added in so that a dragging action can be recorded as a sequence of mouse-down, mouse-move, and mouse-up events.

5.2 Data Analysis

The following data was collected from the study:

1. Log files produced by the UsaProxy software. Each log file consisted of time-stamped key-down, key-press, key-up, mouse-down, mouse-move, mouse-up events.

2. Observational data from two different experimenters in the user study.

3. Background information collected before the main tasks and feedbacks collected after the tasks.

We analysed following variables from the collected data:

Errors: Table 6.1 and Table 5.6 show the typing and pointing errors identified from the previous user study of small device users under sitting condition (Chapter 3). The study presented here investigate whether these errors still exist when small device users are under mobile condition, and therefore the same data analysis methodology is used.

Ratings: Participants' subjective rating on their previous experiences in text entry from a mobile phone and rating on previous experiences in using the mobile Web were recorded, both measured on a five-point scale. The study also recorded participants' subjective ratings on their performance in conducting typing and pointing tasks, which were measured on a seven-point scale. The ratings were collected using questionnaires in the background and feedback sessions.

Time: Keystrokes and cursor movements were logged in real time. Therefore the duration of each task is derived as the difference in time between the last recorded event of that task and the first recorded event.

Characters entered: This is the number of characters entered by each participant when conducting the typing tasks, which was derived as the number of "keypress" events in the log files.

Typing error interval: This variable indicates on average how many characters a participant entered between each typing error. It was calculated as the total number of characters entered divided by the number of typing errors. For example, if a participant entered 6 characters and made 2 errors, the error interval would be 3. On the other hand, if the participant entered 6 characters and made 3 errors, the error interval would be 2. Therefore, the lower the error interval was, the more typing errors a participant made in the typing tasks.

Pointing error rate: For each pointing task, the pointing error rate was calculated as the number of failed trials divided by the number of total trials.

Table 5.5: Typing errors identified in the sitting experiment

Index	*Error type*	*Interpretation*
P2	Long key press error	A long key press error happens when a key is pressed too long that it repeats itself and generates unwanted copies.
P3	Bounce error	A bounce error happens when a key is unintentionally pressed more than once and thus generates unwanted copies.
P4	Missing key error	A missing key error happens when a character is omitted by the participant, or the key is pressed without sufficient force to activate it.
P6	Transposition key	This error occurs when two characters adjacent to each other are typed in reverse order.
P12	Key ambiguity	This indicates the error that a participant fails to distinguish different characters on the same key. In this experiment, this error happens when a participant fails to switch the input modes between letters, numbers and punctuations.
P13	Additional key	This error occurs when a key adjacent to the target key is unintentionally pressed, the target key may or may not be pressed.

Table 5.6: Pointing errors identified in the sitting experiment

Error type	*Description*
Clicking error	A clicking error occurs when a participant clicks at a wrong position.
Multi-clicking error	A multi-clicking error happens when a participant pauses too long between clicks required by a double-click or triple-click action that the system recognizes it as separate single clicks.
Dragging error	A dragging error takes place in three conditions: *fail to start*, where a participant lands the stylus on the screen for too long before starting dragging, which triggers an on-screen menu; *breaking*, where a participant lifts the stylus before reaching the end and thus only selects part of the wanted material; *exceeding*, where a participant keeps dragging the stylus after reaching the end of target and thus selects more materials than wanted.

Table 5.7: Time spent on each task

	Time duration in seconds, excluding time spent on reading instructions								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
P1	31	237	105	27	144	96	28	137	47
P2	45	232	83	76	157	91	27	155	62
P3	74	406	96	78	184	84	29	215	51
P4	92	214	67	45	144	247	84	155	89
P5	105	204	69	61	122	92	69	135	66
P6	65	306	89	32	169	99	35	176	57
P7	55	250	166	34	146	189	49	147	92
P8	108	317	135	47	205	142	42	160	54
P9	57	195	64	37	114	84	38	120	61
P10	74	302	160	61	188	99	35	191	88
MEAN	70.60	266.30	103.40	49.80	157.30	122.30	43.60	159.10	66.70
STDEV	25.27	65.78	37.80	18.30	29.19	54.77	18.92	23.30	16.79
	T7	T8	T9	T1	T2	T3	T4	T5	T6
P11	78	293	152	48	287	130	44	201	130
P12	60	271	112	36	332	94	33	N/A	98
P13	152	343	154	64	321	75	62	174	96
P14	65	240	91	66	299	100	35	176	66
P15	103	206	78	35	210	85	44	162	160
MEAN	91.60	270.60	117.40	49.80	289.80	104.40	43.60	178.25	110.00
STDEV	37.65	52.09	34.70	14.81	48.00	27.99	11.46	16.38	35.97

Table 5.7 shows the time that participants spent on each task. Note that participants P11, P12, P13, P14 and P15 conducted the tasks in a different order from the first ten participants (P1 to P10).

Table 5.8 shows the characters entered by all 15 participants (including the comparison group). The required number of characters by T2 and T5 were both 154, and that for T8 was 145. Table 5.8 shows that participants entered more characters than required. The exceeded portion was due to error corrections. Note that the data of task T5 and T8 for participant P12 was not complete due to an error in logging. Wilcoxon Signed Ranks Test showed following results:

- Participants entered significantly more characters in T2 than in T5 (Z= -3.109, Sig.= 0.002, 2-tailed).

- Participants entered significantly more characters in T2 than in T8 (Z= -3.408, Sig.= 0.001, 2-tailed).

Table 5.8: Characters entered by each participant

Participants	*Characters entered*		
	T2	T5	T8
P1	194	162	166
P2	173	161	157
P3	267	198	162
P4	178	173	166
P5	165	161	161
P6	192	164	154
P7	179	189	162
P8	182	169	153
P9	180	158	152
P10	177	163	175
P11	196	176	162
P12	188	N/A	118
P13	208	186	195
P14	211	158	176
P15	178	165	158
MEAN	191.20	170.21	161.13
STDEV	24.48	12.62	16.25

- The difference between number of characters entered in T5 and T8 was not statistically significant (Z= -1.329, Sig.= 0.184, 2-tailed).

5.3 Typing Task Results

Figure 5.4 shows the time each participant spent on three typing tasks (T2, T5 and T8). Note that the time duration of task T5 for participant P12 was not available due to an error in the log file.

For the original group (P1 to P10), results of the Wilcoxon Signed Ranks Test showed that:

- Participants spent significantly more time on T2 than T5 (Z= -2.803, Sig.= 0.005, 2-tailed).

- Participants spent significantly more time on T2 than T8 (Z= -2.803, Sig.= 0.005, 2-tailed).

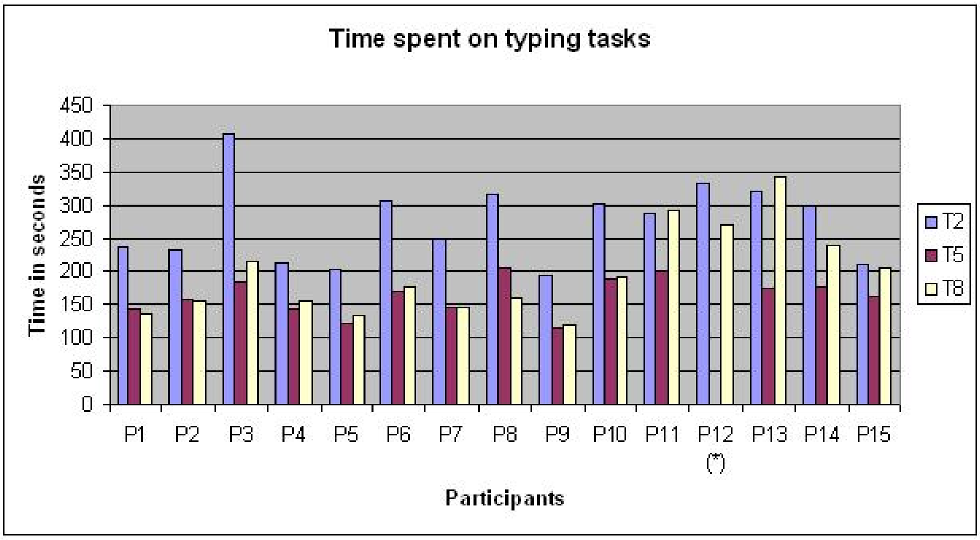

Figure 5.4: Time spent on typing tasks

- The difference between time spent on T5 and T8 was not statistically significant (Z= -1.020, Sig.= 0.308, 2-tailed).

Following results were obtained by comparing the task completion time of the comparison group (P11 to P15) and the original group (P1 to P10).

- The comparison group spent significantly more time on T8 than the original group (Z= -2.023, Sig.= 0.043, 2-tailed).
- For the other two typing tasks (T2 and T5), the difference in task completion time between the comparison group and the original group was not significant.
- There was no significant difference in task completion time of T2, T5 and T8 within the comparison group.

5.3.1 Subjective Ratings

Table 5.9 presents participants' subjective ratings on their typing tasks performance. They rated their performance on a seven-point scale. The higher the rating, the easier they thought avoiding a specific type of typing error. On average, avoiding key ambiguity error was rated the most difficult (Mean.= 4.47, St. dev= 1.25), and avoiding long key press error was rated the easiest (Mean.= 6.67, St. dev= 1.25).

Table 5.9: Participants' subjective ratings on typing tasks performance

	Ambiguity	*Long key*	*Additional*	*Bounce*	*Transposition*	*Missing*
P1	5	7	4	4	7	6
P2	4	7	5	7	5	5
P3	2	6	6	7	7	7
P4	5	7	6	7	7	6
P5	5	7	7	7	7	6
P6	5	7	7	7	7	6
P7	6	7	7	7	7	6
P8	5	4	3	4	7	7
P9	5	6	7	7	7	7
P10	2	7	6	7	7	5
P11	6	7	5	5	6	7
P12	3	7	3	7	4	3
P13	4	7	7	7	7	7
P14	5	7	7	7	7	7
P15	5	7	6	7	6	7
MEAN	4.47	6.67	5.73	6.47	6.53	6.13
ST.DEV	1.25	0.82	1.44	1.13	0.92	1.13

5.3.2 Typing Errors

Table 5.10 and Table 5.11 present a breakdown of typing errors experienced by the first 10 participants (P1 to P10) and the comparison group (P11 to P15). Key ambiguity error was the main source of typing errors. On average, a participant made 7 key ambiguity errors in all three typing tasks. Only one long key press error was observed in the whole user study. It occurred when participant P6 was doing typing task T2. The participant held the 'Z' key down for too long when trying for the word 'Zinc', and thus generated 2 copies of the letter. In addition, no transposition error was identified from the collected data. Therefore these two errors are not listed in Table 5.10 and Table 5.11.

Results of the Wilcoxon Signed Ranks Test indicated significant difference between following data sets of the first 10 participants:

- Participants made significantly fewer missing key errors in T5 than in T2 (Z= -2.032, Sig.= 0.042).
- Participants made significantly fewer missing key errors in T5 than in T8 (Z= -2.000, Sig.= 0.046).

Table 5.10: Typing errors for participant P1 to P10

	Bounce			*Missing*			*Ambiguity*			*Additional*		
	T2	T5	T8	T2	T5	T8	T2	T5	T8	T2	T5	T8
P1	1	0	1	0	0	0	9	3	1	1	0	0
P2	1	1	0	0	0	1	4	0	0	0	0	0
P3	0	0	0	4	1	2	6	3	0	3	3	1
P4	0	0	1	6	1	1	4	0	0	0	0	0
P5	0	1	0	0	0	0	1	1	3	1	0	0
P6	0	0	0	0	0	1	5	1	0	0	0	0
P7	0	0	0	0	0	1	5	2	1	1	5	0
P8	0	1	0	1	0	0	4	5	0	1	0	2
P9	1	1	0	2	0	0	5	0	0	0	0	1
P10	0	0	0	1	0	0	5	1	0	0	0	1
TOTAL	3	4	2	14	2	6	48	16	5	9	8	4
MEAN	0.30	0.40	0.20	1.40	0.20	0.60	4.80	1.60	0.53	0.33	0.33	0.40
STDEV	0.48	0.52	0.42	2.07	0.42	0.70	1.99	1.65	0.97	0.99	1.75	0.70

- Participants made significantly fewer key ambiguity errors in T8 than in T2 (Z= -2.726, Sig.= 0.006).
- Participants made significantly fewer key ambiguity errors in T5 than in T2 (Z= -2.572, Sig.= 0.010).

However, there was no significant difference between the number of typing errors made by the comparison group participants in T2, T5 and T8. In addition, there was no significant difference between the number of typing errors made by the comparison group (P11 to P15) and that from the original group (P1 to P10). This result indicated that task order did not have a significant impact on number of typing errors.

Key Ambiguity Error

Overall, 15 participants made 119 key ambiguity errors in 3 typing tasks and 3 editing tasks. There was no statistically significant correlation between the number of key ambiguity errors and participants' subjective ratings on avoiding this error. Taking a close look on key ambiguity errors, it is found that key ambiguity errors can be further classified into the following three categories.

1. **Failure to distinguish a number and a letter printed on the same key**

Table 5.11: Typing errors for participant P11 to P15

	Bounce			*Missing*			*Ambiguity*			*Additional*		
	T2	T5	T8	T2	T5	T8	T2	T5	T8	T2	T5	T8
P11	1	0	1	3	0	0	5	3	1	3	2	0
P12	1	N/A	0	1	N/A	0	1	N/A	2	2	N/A	1
P13	0	2	0	4	4	4	7	5	8	0	0	1
P14	0	0	0	1	0	5	6	1	2	0	0	0
P15	1	0	0	1	0	0	1	2	1	0	1	0
TOTAL	3	2	1	10	4	9	20	11	14	5	3	2
MEAN	0.60	0.50	0.20	2.00	1.00	1.80	4.00	2.75	2.80	1.00	0.75	0.40
STDEV	0.55	1.00	0.45	1.41	2.00	2.49	2.83	1.71	2.95	1.41	0.96	0.55

As shown by Figure 5.3 in Section 5.1.5, Arabic numbers are printed on the top left corner of ten gray keys. Entering an Arabic number requires a participant to first press the blue modifier key, and then press the key with the target number on it. Fail to do this will end up entering the other character printed on that key, which result in a key ambiguity error. Table 5.12 gives a breakdown of the key ambiguity errors due to failure to distinguish numbers and letters printed on the same key. Overall, participants made 53 such key ambiguity errors in the user study. Since the time of appearance of each character required by the typing task was different, we calculated the error interval for each pair as the time of appearance of two characters on one key divided by the number of errors all participants made when entering those characters. The error interval is to indicate how frequently participants made an error. We can see that participants were most likely to get confused with letter 'j' and number '4'. They were least likely to get confused with '7' and 'n'.

2. **Failure to distinguish a punctuation mark and a letter printed on the same key**
   Table 5.13 lists the key ambiguity errors that participants failed to distinguish a punctuation mark and a letter/number printed on the same key. It is interesting to know that participants particularly struggled with '&' and 'z'. In total, the letter 'z' was entered 15 times, and there were 5 times that participants entered a '&' by mistake. In addition, the '!' and '9' pair and the '∼' and 'Q' pair were also error-prone.

3. **Failure to distinguish similar characters**

Table 5.12: Key ambiguity errors between letters and numbers

Characters on a key	*Required times*	*Number of errors*	*Error interval*
0 and .	105	4	26.25
1 and U	270	8	33.75
2 and I	255	5	51.00
3 and O	405	5	81.00
4 and J	45	8	5.33
5 and K	105	5	21.00
6 and L	210	2	105.00
7 and N	330	2	165.00
8 and M	225	10	22.50
9 and !	30	4	7.50
TOTAL	1980	53	37.36

Table 5.13: Key ambiguity errors between letters and punctuation marks

Error Type	*Required times*	*Number of errors*	*Error interval*
. and 0	105	2	52.50
! and 9	30	4	7.50
- and Y	165	5	33.00
_ and T	255	1	255.00
$ and E	645	1	645.00
% and R	285	2	142.50
(and A	525	13	40.38
) and S	285	1	285.00
@ and W	75	2	37.50
+ and H	210	2	105.00
= and F	150	1	150.00
& and Z	15	5	3.00
˜and Q	15	2	7.50
: and D	300	2	150.00
, and #	75	5	15.00
? and ”	45	2	22.50
TOTAL	3180	50	63.60

Table 5.14: Key ambiguity errors between characters of similar shape

Error Type	*Required times*	*Number of errors*	*Error interval*
, and ’	75	3	25.00
- and _	15	10	1.50
I and L	420	2	210.00
L and !	195	4	48.75
I and !	255	1	255.00
Y and V	195	2	97.50
TOTAL	1155	22	52.50

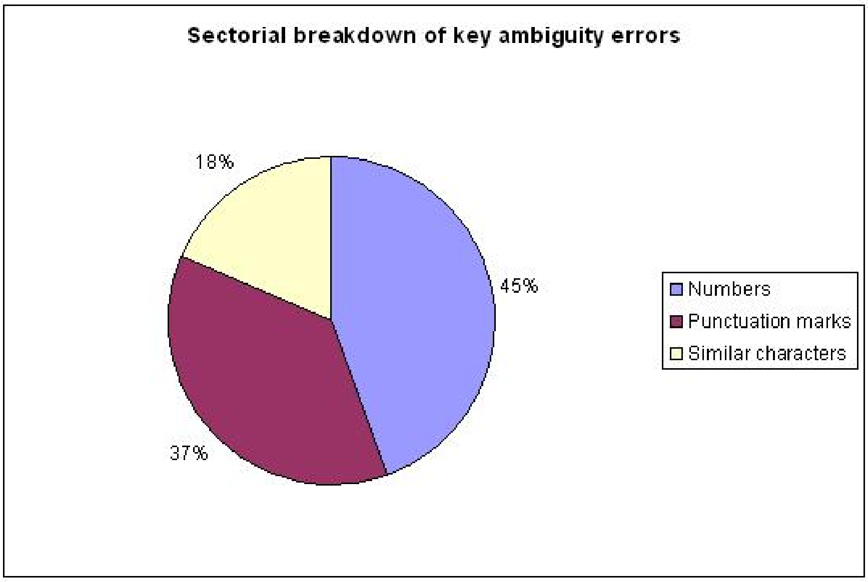

Figure 5.5: Sectorial breakdown of key ambiguity errors

As shown in Table 5.14, there were cases that participants could not distinguish characters of similar shape. These characters were not necessarily printed on the same key. For example, some could not distinguish a comma and a single quote, and the others got confused with ‘i’ and ‘!’. In particular, our participants had problems in distinguishing a minus sign and a underscore. This error type was not observed in the previous user study where participants were under sitting condition.

Figure 5.5 shows a sectorial breakdown of key ambiguity errors of the three categories presented above. Errors in numbers took 45% of all key ambiguity errors, followed by errors in punctuation marks with 37%. Errors in similar characters took 18%.

Types of missing key errors	Detailed cases	Number of errors
miss the shift (fail to capitalize)	miss shift before I in It	5
	miss shift before J in J.Quentin	4
	miss shift before Q in Quentin	2
	miss shift before M in Maxine	2
	miss shift before Z in Zinc	3
	miss shift before T in the	3
	miss shift before A in Are	3
	Total	22
forget to switch back	enter a capitalized A in Maxine	2
	enter a capitalized H in The	3
	enter a capitalized T in It	3
	enter a capitalized E in depicted	2
	enter a capitalized D in depicted	1
	Total	11
miss characters within a word		9
miss a punctuation mark		3
Total		45

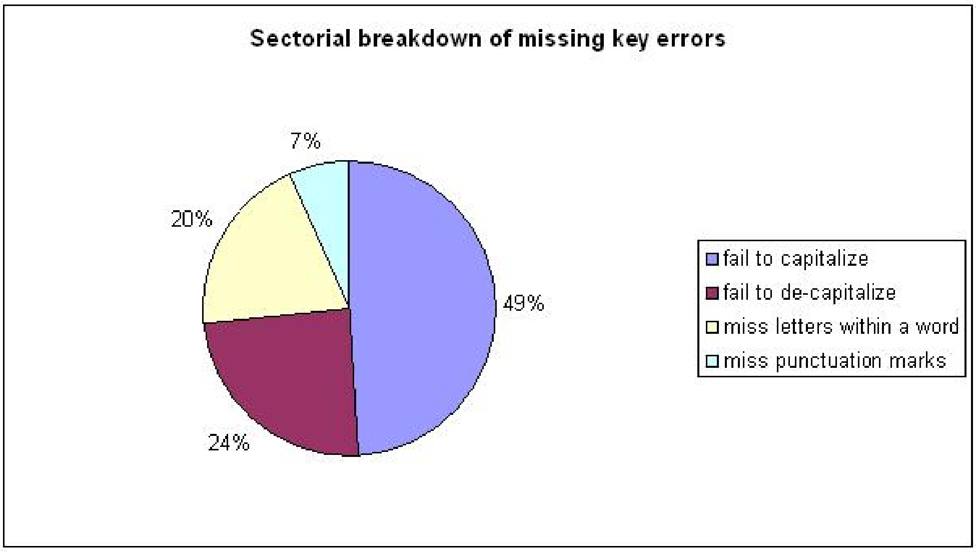

Figure 5.6: Sectorial breakdown of missing key errors

Missing Key Error

Missing key error was the second most frequent typing error observed in this study. Figure 5.6 presents a breakdown of missing key errors. In total, participants made 45 missing key errors in 3 typing tasks and 3 editing tasks. There was no significant correlation between the number of missing key errors and participants' subjective ratings on avoiding this error. Missing key errors observed from this study can be further classified into four categories: missing a shift key before entering a capitalized letter, forgetting to switch back from the capitalized mode to the lower case mode, missing characters within a word, and missing punctuation marks. As can be seen

Table 5.15: A breakdown of additional key errors

Error Type	*Number of errors*
O and I	2
S and A	2
O and P	1
L and K	2
S and E	1
S and D	2
M and N	3
N and B	1
, and .	2
E and R	4
T and R	1
F and D	1
H and G	1
K and J	1
M and !	1
L and ?	1
A and O	1
Del and L	1
Z and S	1
J and H	1
G and F	1

from Figure 5.6, missing the shift key before entering a capitalized letter happened more frequently than the other missing key error types, whereas missing punctuation marks rarely happened.

Additional Key Error

An additional key occurred when a key adjacent to the target key was unintentionally pressed while the target key might or might not be pressed. A total of 31 additional key errors were observed in this study. Table 5.15 shows cases where additional key error occurred in this study. As can be seen, the occurrence of additional key error was quite diverse without limiting to certain keys. This suggests that additional key error was not biased to keys on certain positions of the keyboard, but rather spreading over the whole keyboard.

Table 5.16: A breakdown of bounce errors

Characters	*Required times*	*Number of errors*	*Error interval*
e	645	3	215.00
n	300	3	100.00
k	60	1	60
d	285	1	285.00
l	180	1	180.00
c	150	1	150.00
z	15	1	15
s	255	2	127.50
i	240	1	240.00
m	15	1	15
TOTAL	2145	15	143

Bounce Error

A bounce error happened when a key was unintentionally pressed more than once and thus generated unwanted copies. A total of 15 bounce errors were identified with the 15 participants in this study. Table 5.16 listed the characters that participants made bounce errors with. Although the text materials covered all characters on the keyboard, bounce errors only occured with 10 characters. Apart from capital 'Z' and 'M', participants were likely to make bounce errors when entering letter 'k' and 'n'.

5.4 Pointing Task Results

This section presents the pointing task results. Variables under investigations are time spent on pointing tasks, participants' subjective ratings on their pointing task performance, and pointing errors.

5.4.1 Time

Figure 5.7 shows the time participants spent on three pointing tasks. Results of Wilcoxon Signed Ranks Test showed that:

- Participants from the original group (P1 to P10) spent significantly less time on T4 than on T1 (Z= -2.040, Sig.= 0.041).

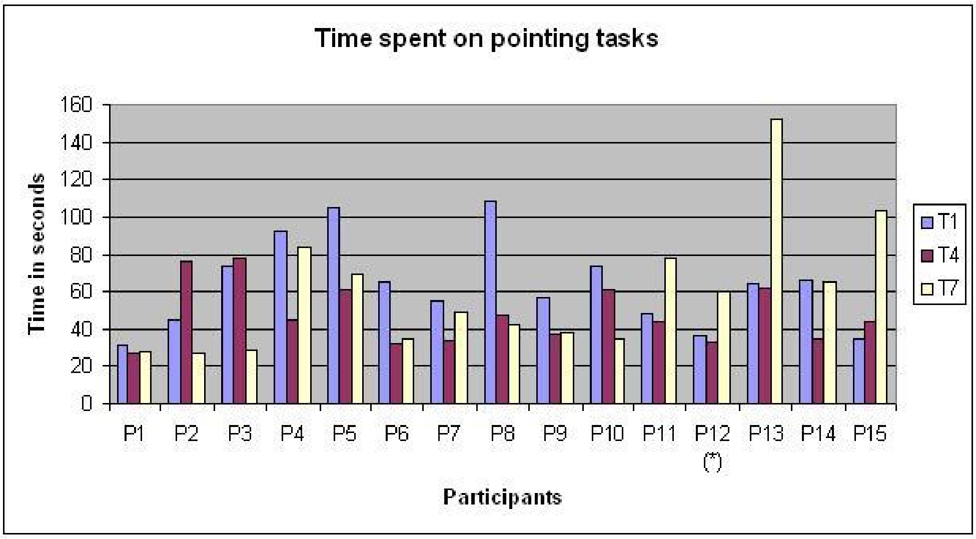

Figure 5.7: Time spent on pointing tasks

- Participants from the original group (P1 to P10) spent significantly less time on T7 than on T1 (Z= -2.803, Sig.= 0.005).
- Participants from the comparison group (P11 to P15) spent significantly more time on T7 than on T4 (Z= -2.023, Sig.= 0.043). Note that the comparison group conducted T7 first.
- There was no significant difference between the time spent on the pointing tasks by the original group and that of the comparison group, which suggests that task order did not have a significant impact on task completion time.

5.4.2 Subjective Ratings

Table 5.17 shows participants' subjective ratings on their pointing tasks performance. Similar to the ratings on typing tasks performance, the ratings on pointing tasks performance were also on a seven-point scale, with higher rating representing better performance. On average, dragging was rated as the most difficult pointing task (Mean= 4.11, St. dev= 1.68), and multi-clicking was rated as the easiest (Mean= 5.72, St. dev= 1.60).

Table 5.17: Participants' subjective ratings on pointing tasks performance

Participants	*Clicking*	*Multi-clicking*	*Dragging*
P1	5	7	4
P2	4	7	5
P3	2	6	6
P4	5	7	6
P5	5	7	7
P6	5	7	7
P7	6	7	7
P8	5	4	3
P9	5	6	7
P10	2	7	6
P11	6	7	5
P12	3	7	3
P13	4	7	7
P14	5	7	7
P15	5	7	6
MEAN	4.72	5.72	4.11
ST.DEV	1.71	1.60	1.68

5.4.3 Pointing Errors

Table 5.18 shows the overall error rates of the pointing tasks. Six sub-tasks were conducted in each of the three pointing tasks (T1, T4 and T7), and the overall error rate of each pointing task was calculated as the number of failed trials divided the total number of trials in completing all six sub-tasks. Since the three pointing tasks were conducted under three mobility conditions (see Section 5.1.3), the overall error rates indicated participants' pointing performance under different mobility conditions regardless specific pointing actions. On average, the overall error rates decreased as participants in the original group repeated the pointing tasks. Unfortunately, the similar trend was not observed in the comparison group. Results of the Wilcoxon Signed Ranks Test indicated significant difference between following data sets:

- For participants in the original group (P1 to P10), their pointing error rates of Task T7 were significantly lower than that of T1 (Z= -1.989, Sig.= 0.047).
- For participants in the comparison group (P11 to P15), their pointing

Table 5.18: Pointing tasks error rates for the original group and the comparison group

Participants	*Error reate*		
	T1	T4	T7
P1	0.17	0.25	0.00
P2	0.43	0.25	0.00
P3	0.64	0.65	0.00
P4	0.56	0.22	0.43
P5	0.62	0.65	0.46
P6	0.38	0.14	0.25
P7	0.17	0.17	0.42
P8	0.78	0.33	0.00
P9	0.14	0.14	0.00
P10	0.38	0.59	0.46
MEAN	0.42	0.34	0.20
STDEV	0.22	0.21	0.22
	T7	T1	T4
P11	0.47	0.20	0.45
P12	0.33	0.25	0.59
P13	0.50	0.50	0.53
P14	0.50	0.17	0.33
P15	0.33	0.00	0.50
MEAN	0.43	0.22	0.48
STDEV	0.09	0.18	0.10

error rates of Task T7 were significantly higher than that of T4 (Z= -2.023, Sig.= 0.043). Note that T7 was conducted before T4 by the comparison group.

- There was not any significant difference between the overall pointing error rates of the original group and that of the comparison group. This suggests that task order did not have a significant impact on participants' overall pointing error rates.

Clicking Error

Table 5.19 shows the error rates of pointing tasks that required a single click. In each of the three pointing tasks (T1, T4 and T7), participants were asked to conduct a sub-task which required a single click between two letters in a word. In T1, they were asked to click between letter "i" and "l" in "April". In T4, they were asked to click between "d" and "a" in "daylight". In T7, they were asked to make a click between "i" and "d" in "wide". From Table 5.19 we can see that the average error rate of the sub-task in T1 was higher than that of the other two, for both the original group (P1 to P10) and the comparison group (P11 to P15).

Wilcoxon Signed Ranks Test showed following results:

- For participants in the original group (P1 to P10), their clicking error rates in T1 were significantly higher than that in T4 (Z= -2.536, Sig.= 0.011).
- For participants in the original group (P1 to P10), their clicking error rates in T1 were significantly higher than that in T7 (Z= -2.546, Sig.= 0.011).
- For the comparison group (P11 to P15), there was no significant difference between the clicking error rates in T1, T4 and T7.
- There was not any significant difference between the clicking error rates of the original group and the comparison group, which suggests that task order does not have a significant impact on clicking error rates.

Multi-clicking Error

Table 5.20 shows the error rates of pointing tasks that required a double-click action and those that required a triple-click action. In each of the three pointing tasks, participants were asked to double click on a word, and then to perform a triple-click on a sentence. Results of Wilcoxon Signed Ranks Test showed that:

- For both the original group (P1 to P10) and the comparison group (P11 to P15), there was no significant difference between participants' error rates of double-click action in T1, T4 and T7. Neither was there any significant difference between the double-click error rates of the original group and the comparison group.
- Similarly, there was no significant difference between participants' triple-click error rates in T1, T4 and T7. And the difference of this error

Table 5.19: Clicking error rates for the original group and the comparison group

Participants	*Error reate*		
	T1	T4	T7
P1	1.00	0.00	0.00
P2	1.00	0.00	0.00
P3	1.00	0.67	0.00
P4	1.00	0.50	0.50
P5	0.50	0.00	0.00
P6	0.40	0.00	0.00
P7	0.00	0.00	0.00
P8	0.78	0.00	0.00
P9	0.00	0.00	0.00
P10	1.00	0.00	0.50
MEAN	0.67	0.12	0.10
STDEV	0.42	0.25	0.21
	T7	T1	T4
P11	0.00	0.75	0.00
P12	0.00	0.00	0.50
P13	0.33	0.67	0.00
P14	0.00	0.64	0.00
P15	0.00	1.00	0.00
MEAN	0.07	0.61	0.10
STDEV	0.15	0.37	0.22

Table 5.20: Multi-clicking error rates of the original group and the comparison group

Participants	*Double clicking*			*Triple clicking*		
	T1	T4	T7	T1	T4	T7
P1	0.00	0.00	0.00	0.00	0.00	0.00
P2	0.00	0.00	0.00	0.00	0.00	0.00
P3	1.00	0.00	0.00	0.00	0.50	0.00
P4	0.00	0.00	0.00	0.00	0.00	0.00
P5	0.67	0.86	0.50	0.00	1.00	0.00
P6	0.00	0.00	0.00	0.00	1.00	0.00
P7	0.00	0.00	0.00	0.00	0.00	0.00
P8	0.00	0.00	0.00	0.75	0.00	0.00
P9	0.00	0.00	0.00	0.00	0.00	0.00
P10	0.00	0.50	0.00	0.00	0.00	0.00
MEAN	0.17	0.14	0.05	0.08	0.23	0.08
STDEV	0.36	0.30	0.16	0.24	0.39	0.25
	T7	T1	T4	T7	T1	T4
P11	0.00	0.00	0.00	N/A	N/A	0.00
P12	0.00	0.00	0.00	0.00	0.00	0.50
P13	0.00	0.00	0.00	N/A	0.67	0.00
P14	0.00	0.00	0.00	0.00	0.00	0.00
P15	1.00	0.00	0.00	1.00	0.00	0.00
MEAN	0.20	0.00	0.00	0.33	0.17	0.10
STDEV	0.45	0.00	0.00	0.58	0.34	0.22

rate between the original group and the comparison group was not significant either.

Dragging Error

Table 5.21 shows the error rates of pointing tasks that require a drag-select action. On each Web page for pointing tasks, participants were instructed to conduct two drag-select tasks using the stylus and touch-screen: the first one was to drag the cursor and select a whole sentence; and the second one was to drag the cursor and to select two letters in a word.

Regarding the drag-select a sentence action, results of Wilcoxon Signed Ranks Test yield three significant results:

- For participants in the comparison group (P11 to P15), their error rates of drag-select a sentence action were significantly higher in T7 than in T1 (Z= -2.023, Sig.= 0.043). Note that participants in the comparison group conducted T7 first.
- For participants in the comparison group, their error rates of drag-select a sentence action were significantly higher in T7 than in T4 (Z= -2.023, Sig.= 0.043).
- In T7, the error rates of participants in the comparison group were significantly higher than that of participants in the original group.

Regarding the drag-select letters from a word action, Wilcoxon Signed Ranks Test only gave one significant result:

- For participants in the original group (P1 to P10), their error rates were significantly higher in T1 than in T7 (Z= -2.243, Sig.= 0.025).

5.5 Comparison with Previous Study

This section compares the results obtained from the current study with those established with previous studies. The comparison shows that the typing error rates of small device users under walking condition increased to a magnitude that close to, in some cases higher than, that of motor impaired desktop users. Similarly, the error rates of clicking, multi-clicking and dragging actions of small device users under walking condition were also higher than that of motor impaired desktop users. The rest of this section presents the comparison results in details.

5.5.1 Comparing Typing Error Rates

Here we compare typing error rates under five conditions: small device users sitting down, small device users standing, small device users walking alone, small device users walking while being led, and motor-impaired desktop users sitting down. Data of small device users in sitting condition is from Chapter 3; data of motor-impaired desktop users is from [Trewin and Pain,

Table 5.21: Dragging error rates of the original group and the comparison group

Participants	*Long drag*			*Short drag*		
	T1	T4	T7	T1	T4	T7
P1	0.00	0.00	0.00	0.00	0.67	0.00
P2	1.00	0.67	0.00	0.00	0.00	0.00
P3	0.00	0.00	0.00	0.83	0.85	0.00
P4	0.00	0.00	0.67	1.00	0.50	0.50
P5	0.75	0.00	0.00	1.00	0.50	0.33
P6	0.00	0.00	0.00	0.75	0.00	0.67
P7	0.00	0.00	0.00	1.00	1.00	0.71
P8	0.50	0.00	0.00	1.00	0.75	0.00
P9	0.00	0.00	0.00	0.50	0.50	0.00
P10	0.00	0.00	0.00	0.50	0.82	0.71
MEAN	0.23	0.07	0.07	0.66	0.56	0.29
STDEV	0.38	0.21	0.21	0.40	0.34	0.33
	T7	T1	T4	T7	T1	T4
P11	0.80	0.38	0.00	0.33	1.00	0.40
P12	0.75	0.00	0.00	0.80	0.75	0.00
P13	0.60	0.00	0.00	0.71	0.50	0.86
P14	1.00	0.00	0.00	1.00	1.00	1.00
P15	0.50	0.00	0.00	N/A	1.00	N/A
MEAN	0.73	0.08	0.00	0.71	0.85	0.56
STDEV	0.19	0.17	0.00	0.28	0.22	0.45

Table 5.22: Typing error interval under three mobile conditions. Note: T2: walking alone; T5: standing still; T8: walking while being led.

	Bounce error			*Missing key*			*Key ambiguity*			*Additional key*		
	T2	T5	T8	T2	T5	T8	T2	T5	T8	T2	T5	T8
P1	194	-	166	-	-	-	21.56	54	166	194	-	-
P2	173	161	-	-	-	157	43.25	-	-	-	-	-
P3	-	-	-	66.75	198	61	44.5	66	-	89	66	162
P4	-	-	166	29.67	173	166	44.5	-	-	-	-	-
P5	-	161	-	-	-	-	165	161	53.67	165	-	-
P6	-	-	-	-	-	154	38.4	164	-	-	-	-
P7	-	-	-	-	-	162	35.8	94.5	162	179	37.8	-
P8	-	169	-	182	-	-	45.5	33.8	-	182	-	76.5
P9	180	158	-	90	-	-	36	-	-	90	-	-
P10	-	-	-	177	-	-	35.4	163	-	-	-	175
P11	196	-	162	65.33	-	-	39.2	58.67	162	65.33	88	-
P12	188	-	-	188	-	-	188	-	59	94	-	118
P13	-	93	-	52	46.5	48.75	29.71	37.2	24.38	-	-	195
P14	-	-	-	211	-	35.2	35.17	158	88	-	-	-
P15	178	-	-	178	-	-	178	82.5	158	-	165	-
MEAN	184.83	148.40	164.67	123.98	139.17	114.85	65.33	97.52	109.13	132.29	89.20	145.30
STDEV	9.26	31.24	2.31	68.89	81.22	57.75	58.28	53.60	59.08	52.29	54.55	47.72

1999]; and data of the other three conditions is from Section 5.3. As discussed in Section 5.2, the typing error rate is represented by the typing error interval, which is calculated as the number of characters entered divided by the number of typing errors. Therefore, the higher the error interval is, the less likely that a participant makes a typing error.

Table 5.22 shows the error interval of all 15 participants under walking (T2 and T8) condition and standing condition (T5). Empty cells indicate that the participant did not make any typing error in that particular typing task. Under standing condition (T5), participants were most likely to have additional key errors, followed by key ambiguity errors, missing key errors and bounce errors. When walking alone (T2), participants were particularly affected by key ambiguity errors, and it was the same when they were walking while being led (T8).

Table 5.23 shows the typing error interval of small device users under sitting condition. In this study, same typing task was repeated twice and the typing error intervals shown in Table 5.23 is calculated as the average of the two trials. Comparing Table 5.22 and Table 5.23, it can be seen that the error frequencies of bounce error, missing key error and additional key error were higher when participants were under sitting condition, which means when participants were standing or walking, they made these errors more frequently. The error interval of key ambiguity error under sitting condition

Table 5.23: Typing error interval under sitting condition

	Bounce	*Missing*	*Ambiguity*	*Additional*	*Long key*	*Transposition*
P1	-	106.13	59.00	285.00	-	570.00
P2	555.00	370.50	112.43	417.75	-	558.00
P3	188.33	608.00	164.84	343.30	-	-
P4	-	209.25	48.38	534.00	-	552.00
P5	-	84.45	67.13	556.50	-	-
P6	554.00	265.50	311.67	357.83	-	-
P7	-	517.00	35.06	-	-	-
P8	359.50	82.48	74.42	522.00	181.67	545.00
P9	482.00	203.83	57.57	494.00	367.50	494.00
P10	643.00	445.25	164.07	124.71	-	569.00
P11	-	204.64	72.19	244.50	-	-
P12	534.00	267.00	110.50	-	-	534.00
P13	193.00	549.00	289.50	289.50	144.75	519.00
P14	235.50	150.54	72.93	392.75	-	-
P15	-	405.00	112.00	276.00	-	-
MEAN	415.94	274.01	112.38	360.85	341.57	548.08
STDEV	175.18	173.93	84.01	129.81	119.38	26.11

was higher than that of walking alone condition, which indicates that when participants were walking alone, they had more key ambiguity errors than under sitting condition. However, when participants were standing or being led, their error interval of key ambiguity errors was between that of the two trials under sitting condition.

Table 5.24 shows the typing error interval of motor impaired desktop users under sitting condition. This data is from Trewin and Pain's study with disabled desktop users who had impairments in hand and finger control [Trewin, 1998]. In Trewin and Pain's study, the same typing task was also conducted twice. The typing error interval shown in Table 5.24 was the average of the two trials. Different from small device users, motor-impaired desktop users were particularly affected by long key press errors. Dropping key error [1] and remote key error [2] were observed in Trewin and Pain's user study [1999], but they were not observed in our study. On the other hand, key ambiguity

[1] The participant failed to press two keys simultaneously (e.g., use of the Shift key) [Trewin and Pain, 1999].

[2] The participant, while trying to press a key, accidentally pressed a different key with a digit or body part other than the one being used for the intended key press. Other accidental key presses, such as leaning on a part of the keyboard, are also remote errors [Trewin and Pain, 1999].

Table 5.24: Typing error interval of motor impaired desktop users under sitting condition, data taken from [Trewin, 1998]

	Long key	*Bounce*	*Missing*	*Trans.*	*Additional*	*Dropping*	*Remote*
P1	-	-	139.06	-	26.99	449.33	-
P2	558.00	-	-	-	-	-	-
P3	18.27	-	133.67	159.25	110.18	637.00	637.00
P4	-	-	420.75	-	141.25	81.90	282.50
P5	28.31	-	139.25	-	116.46	-	-
P6	19.89	59.33	39.56	278.00	286.50	237.33	278.00
P7	20.49	-	134.06	297.00	124.50	140.25	176.55
P8	5.79	-	165.00	-	132.00	-	330.00
P9	25.67	608.00	86.80	-	72.67	304.00	-
P10	2.07	-	-	-	260.67	-	-
P11	647.00	-	647.00	-	243.38	-	-
P12	2.58	426.25	574.50	-	352.13	213.13	556.00
P13	1.50	-	-	-	-	-	-
P14	39.43	-	-	-	-	-	-
P15	28.14	196.67	66.19	-	69.55	171.25	343.57
P16	-	-	364.25	-	388.50	-	-
P17	13.27	-	597.00	-	149.25	-	-
P18	63.44	-	-	-	-	-	-
P19	1.83	191.33	79.75	-	25.01	-	298.50
P20	26.06	166.73	39.68	313.00	34.84	312.50	124.80
MEAN	71.19	270.22	215.92	253.06	161.52	229.62	351.68
STDEV	194.81	202.55	217.32	69.86	114.44	171.23	164.60

errors were not reported in Trewin and Pain's study [1999].

Figure 5.8 compares the average typing error interval under the five different conditions presented above. On average, typing error interval of motor-impaired desktop users was lower than that of small device users under sitting condition, which indicates that motor-impaired desktop users were more likely to make typing errors than small device users in sitting conditions. However, when small device users are standing or walking, their typing error rates increased to an extent that was close to (additional key error), in some cases (missing key error and bounce error) higher than, that of motor impaired desktop users in sitting condition.

In addition, statistical analysis also shows the following significant results:

- Compared with that in a sitting condition, the bounce error interval of

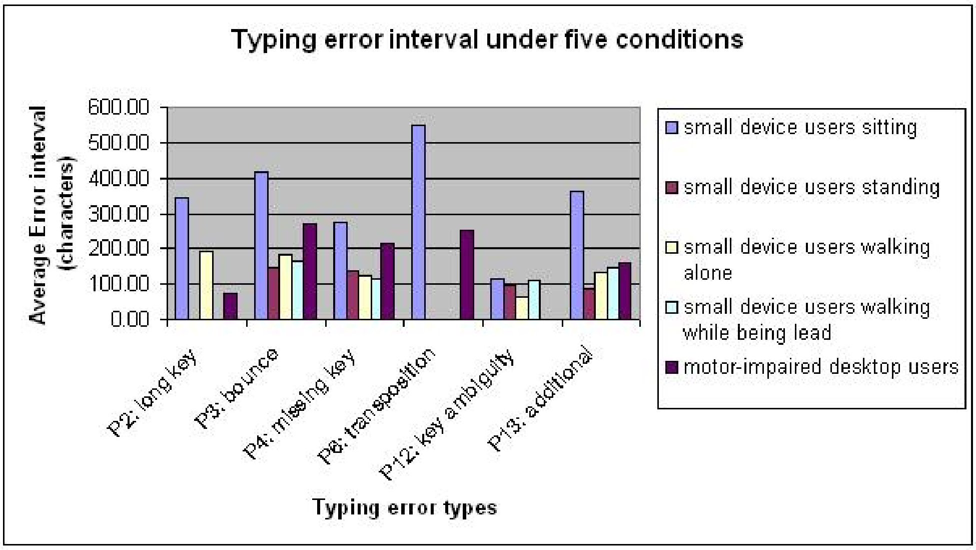

Figure 5.8: Average typing error interval of both small device users and motor-impaired desktop users, note the higher the error interval is, the less likely that a participant makes a typing error

small device users was significantly lower in a standing condition (Z= -2.023, sig.= 0.043). This indicates that the error rates of bounce error increased significantly when small device users changed their typing condition from sitting to standing.

- Similarly, the bounce error interval also reduced significantly when small device users changed their typing condition from sitting to walking alone (Z= -2.201, sig.= 0.028). Therefore, when small device users were walking, they would have more bounce errors than when they were sitting down.
- Compared with that of motor-impaired desktop users, the missing key error interval of small device users under walking alone condition was significantly lower (Z= -1.988, sig.= 0.047). This suggests that the small device users under walking alone condition would likely to have missing key errors more frequently than motor-impaired desktop users.
- In addition, the missing key error interval of small device users walking alone was also significantly lower than that under sitting condition (Z= -2.293, sig.= 0.022).
- Compared with that of motor-impaired desktop users, the additional key error interval of small device users under sitting condition was

significantly higher (Z= -2.551, sig.= 0.011). This suggests that motor-impaired desktop users were likely to have more missing key errors than small device users when seated.

- Compared with that in sitting condition, the additional key error interval of small device users under walking alone condition (Z= -2.521, sig.= 0.012) and walking while being led condition (Z= -2.023, sig.= 0.043) were both significantly lower. This suggests that while small device users were walking, they were likely to make more additional key errors than when they were sitting still.

5.5.2 Comparing Pointing Error Rates

Table 5.25 shows the error rates of pointing tasks under four conditions: sitting, standing, walking alone, walking while being led. Figure 5.9 compares the average error rates of three pointing actions for both small device users and motor-impaired desktop users. Figure 5.9 shows that the clicking error rates of small device users in sitting condition was lower than that of motor-impaired desktop users. However, under walking alone condition, small device users' clicking error rate was much higher than that of motor-impaired desktop users. Regarding multi-clicking action, the error rate of small device users was originally higher than that of motor-impaired desktop users. As small device users stood up and became mobile, their multi-clicking error rates actually decreased to a magnitude that was close to that of motor-impaired desktop users. Similarly, with regard to dragging action, small device users' error rate increased in both standing and walking conditions. It decreased when small device users were being led. However, the dragging error rates of small device users under four conditions were all higher than that of motor-impaired desktop users.

5.6 Confirmatory Study

As presented in Section 5.5.1, comparison results suggest that the typing error rates of small device users under standing and walking conditions were as high as, in some case higher than, that of motor-impaired desktop

Table 5.25: Pointing error rates of small device users under sitting, standing, walking alone and walking while being led conditions

	Clicking				*Multi-clicking*				*Dragging*			
	Sit	Stand	Walk	Lead	Sit	Stand	Walk	Lead	Sit	Stand	Walk	Lead
N1	0.12	0.00	1.00	0.00	0.17	0.00	0.00	0.00	0.46	0.50	0.00	0.00
N2	0.26	0.00	1.00	0.00	0.36	0.00	0.00	0.00	0.55	0.50	0.50	0.00
N3	0.15	0.67	1.00	0.00	0.43	0.40	0.50	0.00	0.56	0.15	0.71	0.00
N4	0.43	0.50	1.00	0.50	0.08	0.00	0.00	0.00	0.64	0.80	0.80	0.56
N5	0.03	0.00	0.50	0.00	0.15	0.83	0.50	0.71	0.38	0.75	0.83	0.25
N6	0.11	0.00	0.40	0.00	0.17	0.50	0.00	0.00	0.33	1.00	0.60	0.50
N7	0.06	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.65	0.75	0.50	0.63
N8	0.18	0.00	0.78	0.00	0.19	0.00	0.60	0.00	0.34	0.50	0.92	0.00
N9	0.24	0.00	0.00	0.00	0.71	0.00	0.00	0.00	0.72	0.67	0.33	0.00
N10	0.10	0.00	1.00	0.50	0.32	0.33	0.00	0.00	0.65	0.25	0.33	0.63
N11	0.26	0.00	0.75	0.00	0.08	0.00	0.00	0.00	0.14	0.60	0.44	0.63
N12	0.08	0.50	0.00	0.00	0.22	0.33	0.00	0.00	0.24	1.00	0.60	0.77
N13	0.20	0.00	0.67	0.33	0.24	0.00	0.50	0.00	0.28	0.40	0.33	0.67
N14	0.11	0.00	0.64	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.50	1.00
N15	0.32	0.00	1.00	0.00	0.15	0.00	0.00	1.00	0.44	1.00	0.50	0.50
MEAN	0.18	0.11	0.65	0.09	0.23	0.16	0.14	0.11	0.45	0.59	0.53	0.41
STDEV	0.11	0.23	0.39	0.19	0.17	0.26	0.24	0.31	0.17	0.31	0.23	0.34

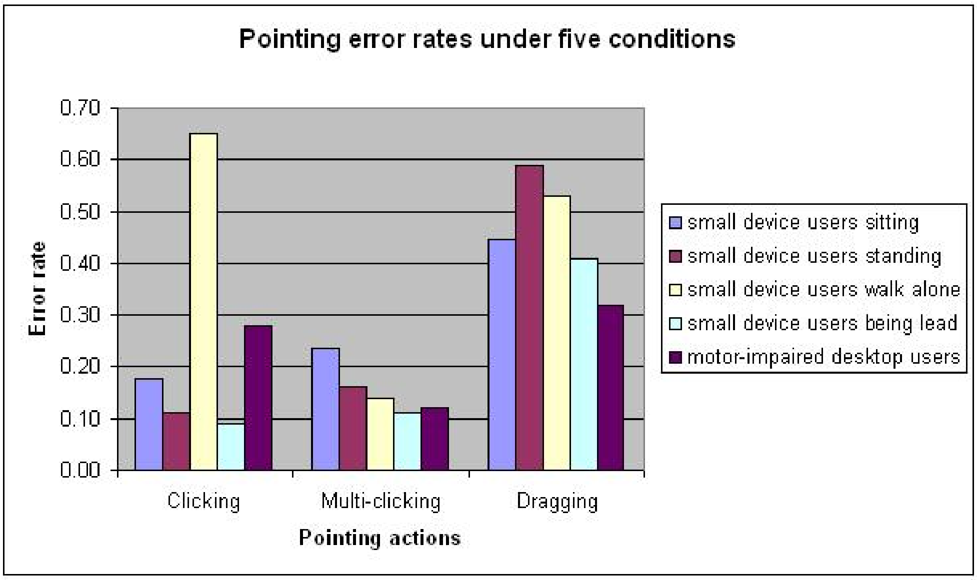

Figure 5.9: Pointing error rates of small device users and motor-impaired desktop users

users. However, the text used for typing tasks in current study was different from that used in Trewin and Pain's study with motor impaired desktop users [Trewin and Pain, 1999]. In order to reduce the effect of typing task materials on typing errors and to confirm our comparison results, we conducted a confirmatory study with five small device users (indexed as CG1, CG2, CG3, CG4 and CG5).

Table 5.26: Eleven sentences used in Trewin and Pain's study and the error interval of each sentence, data taken from [Trewin, 1998]

Index	*Sentence*	*Error Interval*
S1	There was a British grandfather called Quentin who said that he was 101 years old.	3.22
S2	"Are you sure?" asked his friend Maxine.	7.21
S5	But Maxine added in her head the sum 1895 +101 = 1996, and knew that Quentin was actually 100 this year.	13.90
S11	Zinc in the diet is supposed to help the memory, but who knows!	18.46
S10	You may worry about forgetting what the current year is.	26.45
S6	He is younger than he thinks (but not by much).	45.82
S7	Perhaps he has forgotten what year it is.	48.21
S4	"Yes! I was born in 1895" he replied.	52.90
S3	She was 16.	54.81
S8	I do that sometimes too.	103.64
S9	Do you?	302.66

The confirmatory study used the same experimental methodology with the current study. The only difference is the text material used in the typing tasks (T2, T5 and T8). Since the text used in [Trewin and Pain, 1999] contained 530 characters and was considered too long for small device users, a shortened version of that text was generated and used in the confirmatory study. Three sentences were picked from the text material used in Trewin and Pain's study. They were then joined together to form the text material for the confirmatory study. Table 5.26 listed the 11 sentences used in Trewin and Pain's study, along with the error interval of each sentence. It can be seen that sentence S1 was the most error-prone for motor-impaired desktop users, and S9 was the least error-prone. The error interval of sentence S6 was just in the middle. In the confirmatory study, these three sentences (S1, S6 and S9) were used to form a text passage for the typing tasks.

Table 5.27 shows the typing errors made by participants in the confirmatory study. Similar to results presented in Section 5.3.2, no transposition error was observed in the confirmatory study. Only one long key press error was observed with participant CG5 in task T2, which is not listed in Table 5.27. Table 5.28 shows the characters entered by each participant. Based on

Table 5.27: Typing errors made by participants in the confirmatory study

	Bounce			*Missing*			*Ambiguity*			*Additional*		
	T2	T5	T8	T2	T5	T8	T2	T5	T8	T2	T5	T8
CG1	1	0	0	0	0	1	0	1	0	0	1	0
CG2	0	0	0	2	1	0	0	2	1	1	0	0
CG3	0	1	0	1	0	1	4	1	5	0	1	2
CG4	1	0	1	3	0	1	2	1	3	0	0	2
CG5	0	0	0	0	0	3	0	1	0	1	2	1
TOTAL	2	1	1	6	1	6	6	6	9	2	4	5
MEAN	0.40	0.20	0.20	1.20	0.20	1.20	1.20	1.20	1.80	0.40	0.80	1.00
STDEV	0.55	0.45	0.45	1.30	0.45	1.10	1.79	0.45	2.17	0.56	0.84	1.00

Table 5.28: Characters entered by participants in the confirmatory study

Participants	*Characters entered*		
	T2	T5	T8
CG1	148	148	152
CG2	157	142	142
CG3	152	102	156
CG4	214	152	145
CG5	153	154	148
MEAN	164.80	139.60	148.60
STDEV	27.69	21.51	5.55

data shown in Table 5.27 and Table 5.28, we calculated the typing error interval of each typing error type in the confirmatory study, which is shown in Table 5.29. Wilcoxon Signed Ranks Test did not generate any significant difference between the typing error intervals of the comparison group and the original group, which indicates that text materials used in the typing task did not have a significant impact on error intervals.

Figure 5.10 compares the error interval of participants of the confirmatory

Table 5.29: Typing error interval in the confirmatory study

Participants	*Bounce*			*Missing*			*Ambiguity*			*Additional*		
	T2	T5	T8	T2	T5	T8	T2	T5	T8	T2	T5	T8
CG1	148	-	-	-	-	152	-	148	-	-	148	-
CG2	-	-	-	78.50	142	-	-	71	142	157	-	-
CG3	-	102	-	152	-	156	38.00	102	31.20	-	102	78
CG4	214	-	145	71.33	-	145	107	152	48.33	-	-	72.50
CG5	-	-	-	-	-	49.33	-	154	-	153	77	148
MEAN	181	102	145	100.61	142	125.58	72.50	125.40	73.84	155	109	99.50
STDEV	197.50	102	145	100.61	142	118.98	72.50	120.88	73.84	155	96	99.50

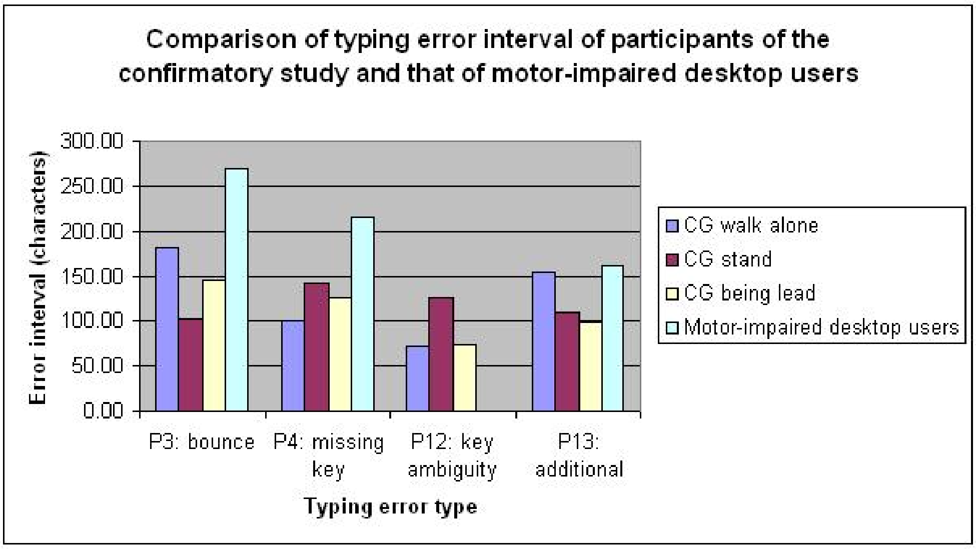

Figure 5.10: Comparison of typing error interval of participants of the confirmatory study and that of motor-impaired desktop users

study and that of motor-impaired desktop users. Note the higher the error interval is, the less likely a participant makes a typing error. Long key press error and transposition error are not presented in this figure because no transposition error and only one long key press error was found in the confirmatory study. On the other hand, key ambiguity error was not reported in [Trewin and Pain, 1999] with motor-impaired desktop users. The figure indicates that the error frequencies of bounce error, missing key error and additional key error of small device users from the confirmatory study (under walking alone, standing, and walking while being led conditions) were all lower than that of motor-impaired desktop users. This result confirms our finding that small device users' error rates under walking and standing conditions were close or higher than that of motor-impaired desktop users.

5.7 Conclusions

This chapter presents a user study that investigated typing and pointing errors of small device users under standing and walking conditions. Previous studies looked at typing and pointing errors of motor-impaired desktop users and that of small device users under sitting conditions, and revealed that small device users shared common typing and pointing errors with motor-impaired desktop users. Therefore the aim of this study was to investigate whether the typing and pointing errors identified previously still exist for small device users under standing and walking conditions, and whether the error rates would increase when small device users were mobile.

Results of the study showed that apart from transposition error and long key press error, all typing and pointing errors observed under sitting condition (Chapter 3) also exist under both standing and walking conditions. No transposition error was identified in the current study and only one long key press error was observed under walking conditions. With regard to error rate, typing error interval decreased under standing and walking conditions, which suggests that small device users will have typing errors more frequently when they are standing and walking. On the other hand, the typing error interval of small device users under standing and walking conditions were close to, in some cases, lower than that of motor-impaired desktop users. This indicates that small device users under standing and walking conditions will have more typing errors than motor-impaired desktop users.

With regard to pointing errors, all pointing errors identified in previous studies were also observed in the current study. Compared with small device users under sitting condition, the error rate of clicking error increased under walking alone condition, but not under standing and walking while being led conditions. On the other hand, the error rate of multi-clicking error decreased under standing and walking conditions. In addition to this, the error rate of dragging error increased under standing and walking alone conditions, but not under walking while being led conditions. Compared with motor-impaired desktop users, the dragging error rates of small device users were higher while sitting, standing, walking alone and walking-while-being-lead.

Based on these results, it is suggested that solutions to the typing errors that already exist in the motor-impaired desktop user domain can be migrated to the small device user domain in order to address the common problems. Next chapter will present the solution migrations in details.

Chapter 6

Solution Migration

Previous chapters have investigated typing and pointing errors of small device users under sitting and walking conditions. Results indicate that small device users experience similar typing and pointing errors as motor-impaired desktop users, and that the error rates increase while walking. We therefore assert that it would be useful to transfer existing solutions from the Accessibility domain to the Mobile Web domain. As the accessibility research for small device users is younger than that for motor-impaired desktop users, more solutions exist in the latter domain. Therefore, we will mainly look at solution migrations from the motor-impaired desktop users domain to the small device users domain.

Chapter 2 presents several technologies that are used in the Accessibility domain. We also discussed the possibility of transferring some of these solutions to the Mobile Web domain. In this chapter, we propose to migrate six existing solutions from motor impaired user domain to small device user domain. These migrated solutions will address the common typing and pointing errors identified in previous chapters. For example, Dynamic Keyboard and TrueKeys system are proposed to address long key press error, additional key error, bounce error and missing key error. Target expansion, steady clicks system, sticky icons, and SUPPLE++ system are proposed to address clicking and dragging errors. After presenting the techniques, we then implement a typing error correction system for the Mobile Web users. The system transfers typing error correction algorithms from the Dynamic Keyboard system to the Mobile Web domain. It helps to reduce typing errors when small device users fill out online forms. We evaluate the typing error correction system by repeating the same walking experiment presented in Chapter 5. Results show that when applying the error correction system, small device users make fewer typing errors then they use to. This supports our assertion that solution migration helps to reduce errors of the Mobile Web users.

6.1 Proposed Migration

Existing research provides solutions to the typing and pointing errors experienced by motor-impaired desktop users. This chapter proposes to migrate some of the techniques from the motor-impaired desktop user domain to the small devices user domain, and thus to address the common input problems. In this section, 6 candidate techniques are discussed: dynamic keyboard and TrueKeys address the common typing errors; target expansion, Steady Clicks, SUPPLE++, and Sticky Icons to solve the common pointing errors.

6.1.1 Dynamic Keyboard

Long key press errors and bounce errors can be reduced by adjusting the configuration of the keyboard [Trewin, 2004]. For example, long key press errors can be reduced by extending the key repeat delay. Bounce errors can be reduced by increasing the debounce time. A debounce time is a time period that starts when a key is released. If the same key is pressed again during debounce time, the key press will not be registered. However, the problem is that motor-impaired desktop users do not know or have difficulty in adjusting the keyboard configuration [Trewin, 2004].

A dynamic keyboard is a keyboard that continuously adjusts its key repeat delay and debounce time to suit the user's typing performance [Trewin, 2004]. It is designed so that a user can type normally while keyboard features, such as key repeat delay and debounce time, are adjusted automatically. So that the user does not need to apply changes to the keyboard manually.

Small device users experienced fewer long key press errors and bounce errors than motor-impaired desktop users (see Chapter 3). However, when one is on the move, a small device user's attention to typing is usually distracted by other activities one participates in, and the error rates increase dramatically (see Chapter 5). In addition, various use contexts may require a small device user to change the keyboard configuration accordingly. This may be difficult and inconvenient for small device users unless a dynamic keyboard is used.

6.1.2 TrueKeys

Additional key error, missing key error and transposition error can be corrected by applying spell checking. Unlike other spell checking systems, the TrueKeys system allows a user to type normally, while automatically correcting error in-place [Kane et al., 2008b]. A word is first checked against a known word list. If unknown, the TrueKeys system creates a ranked list of suggestions, and allows a user to choose one correction from a drop-down list.

User evaluation shows that the TrueKeys system significantly reduced typing errors for both motor-impaired and non-impaired desktop users [Kane et al., 2008b]. However, the typing speed also reduced when the system was turned on. Small device users experience typing errors such as additional key error, missing key error, transposition error and key ambiguity error. In addition, error rates increase when small device users are walking (see Chapter 5). Therefore, the TrueKeys system may be beneficial to small device users.

6.1.3 Target Expansion

Trewin and Pain's study [1999] suggests that motor-impaired mouse users had difficulties in positioning the mouse cursor over small targets, resulting in clicking errors. On the other hand, our study shows that small device users also experienced problems in clicking small targets using a stylus and touch-screen (see Chapter 3), and this is especially the case while a small device user is using stylus while walking (see Chapter 5).

One solution to address the clicking errors is to enlarge the active area of the cursor. The 'bubble cursor' technique uses a notion of cursor area instead of cursor point. It uses a bubble to replace the mouse cursor. Items that are closest to the center of the bubble will be selected [Grossman and Balakrishnan, 2005]. Therefore, when using the bubble cursor, a user does not need to place the cursor exactly over the target; instead, move the bubble close to the target will trigger the selection. The bubble cursor has been demonstrated to be helpful in a 2D selection task with young, non-disabled people [Grossman and Balakrishnan, 2005]. However, whether this technique is beneficial for motor-impaired mouse users is not clear.

Another solution is to expend the target area as the mouse cursor approaches [McGuffin and Balakrishnan, 2002]. Gajos et al.'s study [2008] suggests that motor-impaired users who can perform rapid but inaccurate cursor movement preferred to use interface that has relatively large targets. Therefore this technique may improve the accuracy of motor-impaired mouse users. On the other hand, target expansion may also be useful to small devices that use a trackball as pointing device, such as BlackBerry PDAs. However, on a small device that uses a stylus and touchscreen for clicking, the cursor movement is discrete rather than continuous. A touchscreen user will not slide the stylus along the screen while approaching the target. Instead, the user tend to directly hit the target with the stylus. Therefore, when applying to small devices that use stylus and touchscreen, the target expansion technique needs to be modified such that the target area can be enlarged before a click is made.

6.1.4 Steady Clicks System

Trewin and Pain's study [1999] also indicates that motor-impaired mouse users had difficulties in keeping the cursor over the target while clicking (i.e., they slipped the mouse cursor off the target while clicking). Many clicked the mouse unintentionally while moving the cursor to the target position. Our study also shows that when performing multi-clicking, small device users slid the cursor between clicks, causing a multi-clicking error (see Chapter 5).

The Steady Clicks technique is designed to help in situations where people successfully click down on a target but slip before releasing the mouse button. It does this by freezing the cursor at the button down location until either the button is released or the mouse cursor is moved away to a distance that is beyond a threshold [Trewin et al., 2006]. Evaluation with motor-impaired desktop users shows that the Steady Clicks technique enabled participants to select targets using significantly fewer attempts and less time.

For small device users, the Steady Clicks technique can also be useful because it freezes the cursor and prevents cursor from sliding between clicks, and thus reduces the multi-clicking errors.

6.1.5 Sticky Icons with Adaptive Gain Control

A third problem of motor-impaired mouse users and small device users is that when they performed a dragging action, they either released the mouse button or lifted up the stylus from the touchscreen before the end of the target, which caused a dragging error (see Chapter 5). Sticky Icons is a technique that automatically reduce the mouse cursor's gain ratio (the ratio between mouse movement and cursor movement) when the cursor is on a target icon. By decreasing the gain locally, one can make it easier to stop the cursor on the icon [Worden et al., 1997]. However, if every icon on the screen has the same 'stickiness', a user may end up sticking the mouse cursor to other icons along the way, leading to slower cursor movement. Ideally, only the target icon should be sticky. Adaptive Gain Control is a technique that adjusts the 'stickiness' of a icon based on the velocity of the cursor movement. When the velocity of a mouse cursor drops to 30% of its peak velocity during the movement and the cursor is over an icon, the gain ratio of that icon will reduce and make it easy to point the cursor over it. Worden et al.'s study [1997] shows that when Sticky Icons and Adaptive Gain Control were used together, the target selection time reduced for both younger and older participants; and their accuracy improved as well. During the user studies, it is observed that small device users lifted up the stylus just one or two characters away from the target end of the material. This is considered as a lack of fine control of the stylus (see Chapter 5). The

Sticky Icons technique, along with the Adaptive Gain Control technique, can help in this situation. During a dragging process, when the velocity of the cursor movement reduces to a threshold, the 'stickiness' of the items near the cursor will increase, and thus small cursor movement can be achieved by bigger stylus movement, which makes it easier for small device users.

6.1.6 SUPPLE & SUPPLE++

Most user interfaces are designed for the "average user", and thus motor-impaired users must adapt themselves to the interfaces by using specialized devices. On the other hand, an adaptive interface adjust its output based to the actual abilities of individual users, and allow users access to custom interfaces fine-tuned to their abilities and preferences [Gajos et al., 2008].

The SUPPLE system automatically generates user interfaces based on device constraints (e.g., screen size and input device), usage trace (i.e., sequences of elements manipulated by a user), and a cost function [Gajos and Weld, 2004]. With the ARNAULD preference elicitation engine [Gajos and Weld, 2005] integrated in, the SUPPLE system allows a user to create an interface by going through a set of paired user interface fragments (which are functionally equivalent but differ in presentation) and choosing the preferred one [Gajos et al., 2008]. Instead of based on preference, the SUPPLE++ system models a user's motor abilities directly from a set of one-time motor performance tests, and then generates an interface that best suits the user's requirements [Gajos et al., 2008]. The motor performance tests contain four types of tasks: pointing, dragging, list selection and multiple clicking.

A user evaluation was conducted with motor-impaired desktop users and able-bodied users. The participants were asked to perform pointing tasks using a standard user interface and interfaces generated by SUPPLE and SUPPLE++. Results show that both the SUPPLE system and the SUPPLE++ system reduce total task completion time, navigation time and error rates for motor-impaired desktop users. Participants of the evaluation also found that SUPPLE and SUPPLE++ were easy to use, attractive, efficient and not tiring.

It is proposed to migrate the SUPPLE system and the SUPPLE++ system to small devices. It is possible that these systems will address the pointing errors of small device users by adapting user interfaces to available input devices and users' abilities.

6.2 A Typing Error Correction System

Inspired by solutions presented in Section 6.1 and to demonstrate the direct solution migration is possible, we designed and implemented a typing error correction system for small device users. The system aims to support the Mobile Web users by preventing and correcting their typing errors made when making text input on a Web page.

The prototype system aims to support small device Web users by preventing or correcting four types of typing errors: long key press error, additional key error, bounce error and key ambiguity error. The error correction algorithms mainly come from the research with motor impaired users [Trewin, 2004]. The prototype system is implemented using JQuery [1] and is deployed as a Javascript plugin to an existing Web page. A Web developer simply needs to includes a JavaScript file in the header section of their Web pages. No installation is required on the client side. When a Web page is loaded to a user's small device browser, the system is activated automatically. It parses the DOM of a Web page and identifies objects that require text input (such as text areas and input boxes). The system then adds event handler to these identified objects and listens to keyboard events such as key presses made to these objects. When a user start typing, the system starts tuning itself towards the user's typing habit. It then detects keystroke events that are exception to a user's normal typing behavior, and gives error corrections accordingly. The algorithms for "*tuning*" and error correction is described in the following section.

[1] See `http://jquery.com/`

6.2.1 System Architecture

Figre 6.1 shows the architecture of the proposed error correction system. The system has five components. At the front, the *event listener* listens to user input. It sends recorded key press events to the *typing behavior tuner* which then analyzes the patterns of a user's input and fires error correction events when exceptions to identified pattern occur. Typing errors such as additional key error and key ambiguity error are highly dependent on the layout of the keyboard used. For example, the location of a key and its neighboring keys is different from device to device. In order to detect and correct such typing errors accurately, the system needs to know the keyboard layout of the device before making any error correction attempt. Our system achieves this by parsing the HTTP request sent by a device, and getting the type and model of the device from the request. It then queries the *profile access layer* for the key-map of the used device. A key-map is a data structure we create to describe the layout of a small device keyboard. It stores information such as characters that are located on the same key, and characters that are located on keys close to each other. Different keyboards have different key-maps, this is especially the case for small device keypads. Locations of letters and other characters vary between different brands and models. At the back end of the system, we use a device description database, specifically a Tera-WURFL database to store key-maps of different mobile phones and PDAs [2]. When a query comes in, the *profile access layer* searches the Tera-WURFL database, gets the key-map, and returns it back to *typing behavior tuner*. The component then makes decisions based on the key-map. In addition, the system also includes the Google spell checker in the *error correction component* so that any typing error missed before it is notified and corrected after the user finishes the word.

6.2.2 Error Correction Algorithms

As described before, the proposed error correction system aims to correct four types of typing errors identified with both motor impaired desktop

[2] Tera-WURFL, see `http://www.tera-wurfl.com`

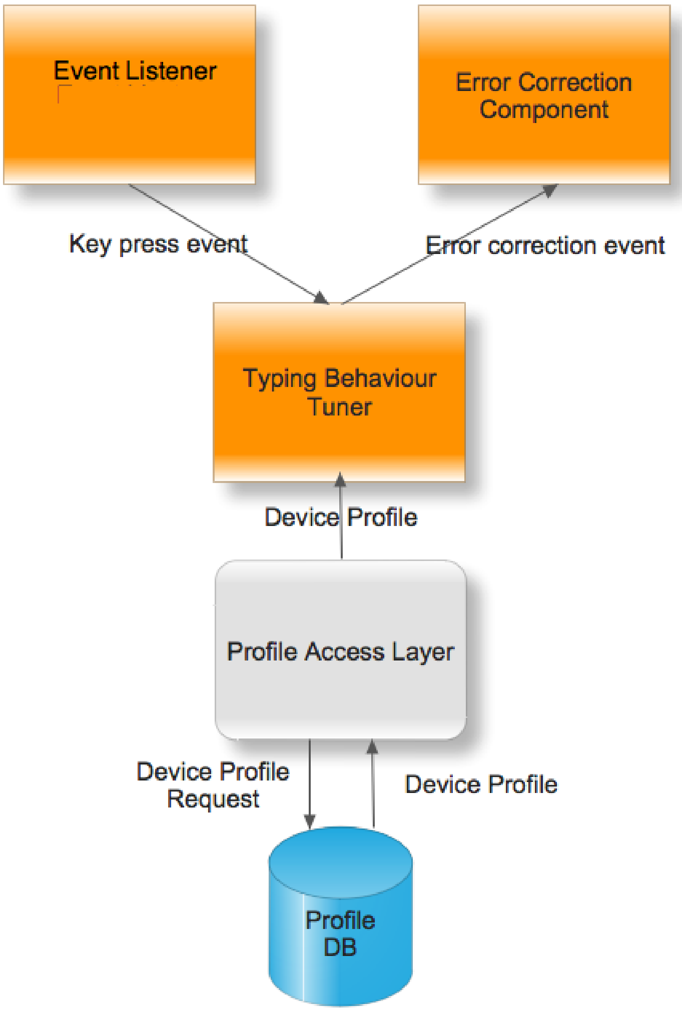

Figure 6.1: System Architecture of the proposed error correction system

users and small device users. This section looks at how each of these error types are detected and corrected.

- *Long key press error*: as presented many times in previous chapters, a long key press error occurs when a key is unintentionally pressed too long that it start to generate copies of itself. Our system records the gap between the time a key is pressed down and the time that pressed key starts repeating itself. Next time a key is pressed down for a period that is longer than this gap, they system will automatically prevent the key registration for its copies. Different devices may have different threshold of pressed key repeating itself. Therefore our system does not hold a default value for all devices, instead, it tunes the time gap according to specific device in use. Note that a user may want to delete some thing by holding down the DEL key. In order to allow this use case, the system does not apply long key press error correction feature to DEL key.
- *Bounce error*: this error occurs when a user's finger bounce while releasing a key so that the user accidentally presses the same key twice, resulting an unwanted copy. Our system logs the gap between each key press a user makes, and calculates the average gap between two continuous key presses on the same key. Once a key is pressed twice, the system first check whether the gap between key presses is significantly less than the average value. If so, it is likely that a user is making a bounce error, and system will prevent the second key press. Typing speed may vary between different individuals, and also varies as the environment changes, especially with small devices. Our system adapts to such variety by dynamically adjusting the threshold according to a user's typing performance. As the user types faster, the threshold decreases. When the user types slower, the threshold increases.
- *Additional key error:* this error occurs when a key near a target key is accidently pressed. Similar to bounce error, our system logs and calculates the average gap between the two key presses. If a key press occurs very close to the previous one, it is likely to be an additional key error. Therefore the system prevents the second key press.
- *Key ambiguity error*: letters, numerical characters and punctuation

marks are packed on small keyboards of mobile devices. Key ambiguity error happens when a user fails to distinguish different characters on the same key. Our previous study shows that key ambiguity error is the primary error source on a small device keypad. In particular, small device users have problems entering numbers and punctuation marks. They are likely to press the correct key, but enter the letter on that key instead. Currently, most smart phone or PDAs relies on an additional function key to switch typing mode between letters, numerical characters and punctuation marks. For example, as shown in Figure 6.2, on a HP iPAQ hw6515 keyboard, a user presses the blue key at the left bottom corner of the keyboard to switch between letters and numerical characters. On a iPhone 4 soft-keyboard (shown by Figure 6.3), a user also needs to press the function key at the left bottom corner of the screen to flip input mode. Instead of using additional functional key, our system addresses key ambiguity error by providing suggestions as a user types. When a user presses a key, the system get all possible characters available on that key from the key-map obtained from back end database, and list them in a suggestion box. If a user wants to enter a number or punctuation mark, he/she can choose from the suggestion list directly. Otherwise, the user can continue typing, and the suggestion list will change as the user types. For example, as shown in Figure 6.4, a Mobile Web user is typing his birthday into a text box. Instead of switching between numbers and punctuation marks, the user just press the key with target characters on it, and the error correction system will automatically suggest a correct combination.

6.3 User Evaluation

In order to evaluate the typing error correction system, we reproduce the user evaluation presented in Chapter 5 with 15 small device users. The user evaluation was set up in the same way with the one conducted with small device users under walking condition (see Section 5.1). A user is asked to finish 9 typing and pointing tasks on a series of Web pages accessed via a

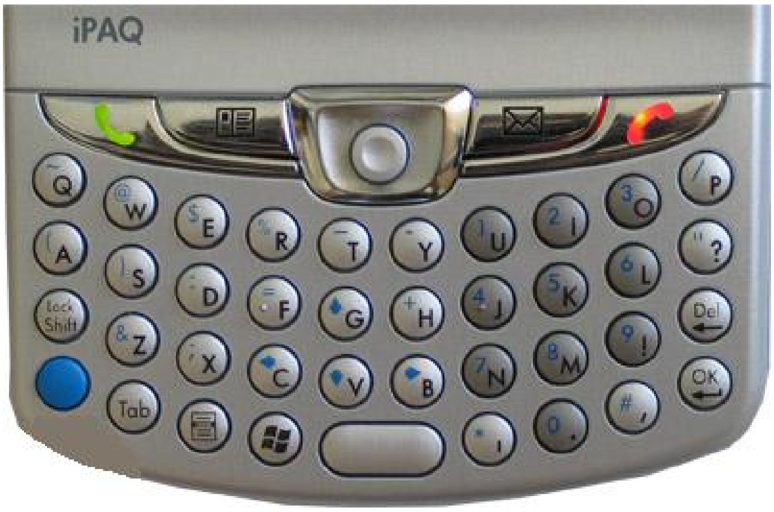

Figure 6.2: HP iPAQ hw6515 keyboard

Figure 6.3: Soft-keyboard of iPhone 4 [webpage, 2010]

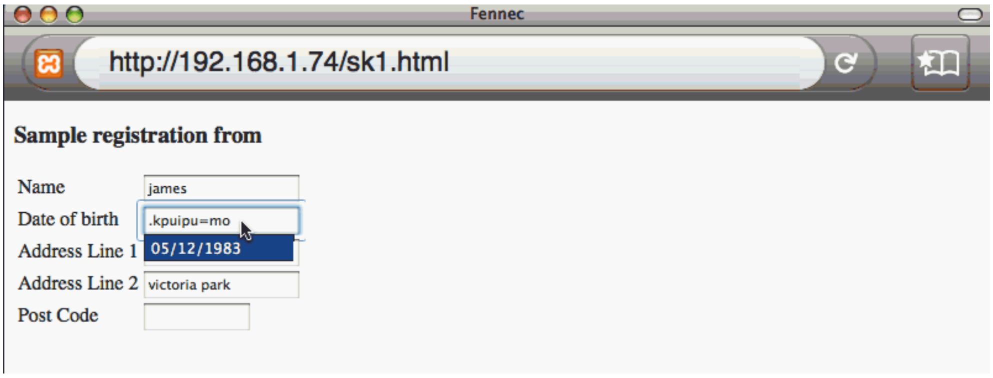

Figure 6.4: The error correction system suggest a number punctuation combination while the user is typing

PDA while walking along a pre-defined path in public space. User input is logged by a UsaProxy and analyzed manually for typing errors. The only difference is that in the current user evaluation, the error correction system was turned on while users conducting typing tasks.

The hypothesis of the user evaluation are listed as follows:

- The typing error correction system reduces long key press error of small device users while walking.
- The typing error correction system reduces bounce error of small device users while walking.
- The typing error correction system reduces additional key error of small device users while walking.
- The typing error correction system reduces key ambiguity error of small device users while walking.

6.3.1 Typing Task Results

Table 6.1 shows the typing errors each participant made in three typing tasks. Note that T2, T5 and T8 stand for the three typing tasks described in Table 5.3. As shown in Table 6.1, key ambiguity error was still the largest error source of the four, followed by additional key error. A relatively smaller number of bounce error and long key press error were identified in the study. Results showed that key ambiguity errors were much larger in magnitude than the other observed typing error types. Even if the error

Table 6.1: Typing errors of participants in three typing tasks

	long key error			*bounce error*			*key ambiguity*			*additional key*		
	T2	T5	T8	T2	T5	T8	T2	T5	T8	T2	T5	T8
P1	1	1	0	0	0	0	5	4	0	0	0	0
P2	0	0	1	0	0	0	2	1	1	0	0	0
P3	0	0	0	0	0	0	3	2	0	2	2	1
P4	0	0	0	1	0	1	2	2	1	0	0	0
P5	0	0	0	0	0	0	1	0	2	1	1	0
P6	0	0	0	0	0	0	0	0	0	0	0	1
P7	1	0	0	0	0	1	4	2	0	0	2	0
P8	0	0	0	0	0	0	4	3	0	1	0	0
P9	0	1	0	0	1	0	3	1	0	0	0	1
P10	0	0	0	1	0	0	6	2	3	0	0	1
P11	0	0	0	0	0	1	4	2	0	0	0	0
P12	0	0	0	0	0	0	2	3	1	0	0	0
P13	0	1	0	1	0	0	3	0	0	1	0	1
P14	1	0	0	0	1	0	3	0	0	0	0	1
P15	0	0	1	1	0	0	3	2	0	0	0	1
TOTAL	3	3	2	4	2	3	45	24	8	5	5	7
MEAN	0.20	0.20	0.13	0.26	0.13	0.20	3	1.60	0.53	0.90	0.80	0.40
STDEV	0.41	0.41	0.35	0.45	0.35	0.41	1.51	1.24	0.92	0.62	0.72	0.52

correction system had been provided to prevent this error type, it still existed and remained the main source of typing errors from small device keypad.

Table 6.2 shows the number of characters each participant entered in the typing tasks. On average, participants entered 190.73 characters in T2, 169.6 characters in T5 and 161.4 characters in T8. Table 6.3 lists the typing error interval of each participant. As discussed in Section 5.2, typing error interval is calculated as the total number of characters entered divided by the number of typing errors. As shown in Table 6.3, the typing error interval of key ambiguity error was the lowest of the four, which indicates that key ambiguity error occured much more frequently than the other types of typing errors.

User feedbacks showed that the system that helped to reduce key ambiguity errors was not always helpful. As the suggestions changed as a user typed, the user's attention was sometimes distracted from the text they were producing. The suggestion feature was very helpful when the users knew they

Table 6.2: Characters entered by each participant in three typing tasks

Participants	*Characters entered*		
	T2	T5	T8
P1	200	156	155
P2	180	162	159
P3	190	176	162
P4	192	170	160
P5	180	162	162
P6	195	160	154
P7	204	180	153
P8	188	164	160
P9	190	155	153
P10	182	162	160
P11	191	180	159
P12	172	162	152
P13	199	187	181
P14	201	187	181
P15	197	181	170
MEAN	190.73	169.60	161.40
STDEV	9.11	11.17	9.20

were going to type a number as they could easily picked up the correct suggestion. However, when typing normal words, the suggestion feature was not very helpful. In addition, most of our participants commented that there was a lag between the key press and the suggestions appearing on the screen. This was especially the case when the user typed very fast. This was due to the design of the system. Since the client of the system talked to the server via the Mobile network, the quality of service is highly subjective to the quality of the network. At certain locations where network signals were very low, the communication between the client and server could be dropped, which caused the suggestion list failed to load. In order to reduce the impact of network quality on performance of our error correction system, we could pre-load the entire server end to a user's device when the user starts Internet browser. This way, the communication between client and server will occur locally. Since the server side, including the library for is tiny, it can be easily downloaded and installed.

Comparing the mean values listed in Table 6.3 and that listed in Table 5.22,

Table 6.3: Typing error intervals in three typing tasks

	Long key			*Bounce*			*Ambiguity*			*Additional*		
	T2	T5	T8	T2	T5	T8	T2	T5	T8	T2	T5	T8
P1	200	156	-	-	-	-	40	39	-	-	-	-
P2	-	-	159	-	-	-	90	162	159	-	-	-
P3	-	-	-	-	-	-	63.33	88	-	95	88	162
P4	-	-	-	192	-	160	96	85	160	-	-	-
P5	-	-	-	-	-	-	180	-	81	180	162	-
P6	-	-	-	-	-	-	-	-	-	-	-	154
P7	204	-	-	-	-	153	51	90	-	-	90	-
P8	-	-	-	-	-	-	47	54.67	-	188	-	-
P9	-	155	-	-	155	-	63.33	155	-	-	-	153
P10	-	-	-	182	-	-	30.33	81	53.33	-	-	160
P11	-	-	-	-	-	159	47.75	90	-	-	-	-
P12	-	-	-	-	-	-	86	54	152	-	-	-
P13	-	187	-	199	-	-	66.33	-	-	199	-	181
P14	201	-	-	-	187	-	67	-	-	-	-	181
P15	-	-	170	197	-	-	65.67	90.50	-	-	-	170
MEAN	201.67	166	164.5	192.5	171	157.33	70.98	89.92	121.07	165.5	113.33	165.86
STDEV	2.08	18.19	7.78	7.59	22.62	3.79	36.59	38.29	50.25	47.64	42.16	11.77

we can see that bounce error, key ambiguity error and additional key error occured less frequently in current user evaluation with the typing error correction system. Figure 6.5 compares the typing error interval of current study and that of previous studies. Note that in the figure, "EC" stands for error correction. We can see that the typing error correction systems effectively reduced bounce error and additional key error of small device users. Long key press error was rarely observed in the study presented in Chapter 5. In the current user evaluations, the error interval of long key press error was at the same level with that of bounce error. With regard to key ambiguity error, the improvement in error interval was not significantly. Comparing results of current study and the one conducted in a laboratory environment (see Chapter 3), we can see that apart from key ambiguity error, the typing error intervals of small device users in realistic environment were still much lower than that of small device users in laboratory environment. This suggests that as small device users become mobile, their typing errors increase.

6.4 Conclusions

This chapter presents solution migrations from the Web Accessibility domain to the Mobile Web domain in order to address common typing and

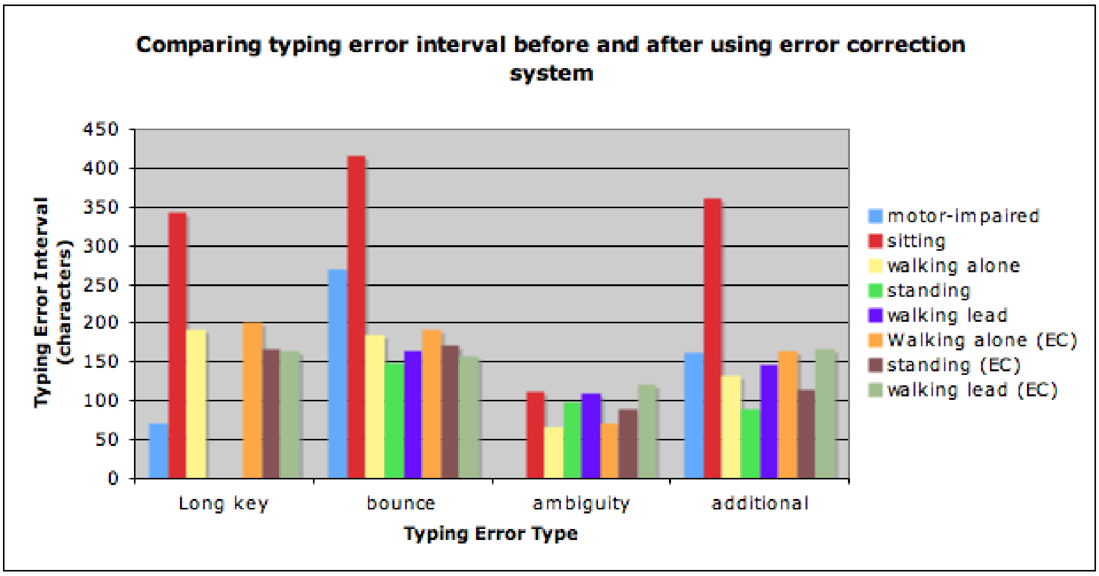

Figure 6.5: Comparing typing error interval before and after using error correction system

pointing errors. Six technologies were discussed and a error correction system was implemented and evaluated with 15 Mobile Web users. The error correction system reused existing error correction algorithms developed for motor-impaired desktop users, and helped to reduce four types of typing errors experienced by the Mobile Web users. User evaluation was conducted in naturalistic settings where participants entering texts into a Web page while walking along a pre-defined path. Results showed that the error correction system successfully reduced the target typing errors. The results support our assertion that existing solutions can be migrated between different domains in order to address common problems. In general, our work has illustrated that similar typing and pointing errors are shared by the Mobile Web users and disabled Web users. More importantly, we have demonstrated that it is practical to directly migrate existing solutions from one user domain to another to address the common problems. Furthermore, our work has indicated that Web Accessibility and the Mobile Web are not two disjoint fields. They are inter-linked and common solutions can benefit both domains. This allows Web designers and device manufacturers to integrate research from both Web Accessibility and Mobile Web fields, and provide accessible content for both disabled users and small device users.

Chapter 7

Conclusions and Future Work

Accessing the Web from small devices such as smar-phones and PDAs has becoming increasingly popular in recent years. Small devices provide flexibility to the users and allow them to access on-line information in many different contexts. However, the Mobile Web users are sometimes hindered by limited input and output bandwidths of the devices. The limited keyboard and pointing devices cause problems in text entry and cursor movement. In addition, various environmental factors, such as sunlight, passengers, noise all distract users from concentrating on using the Mobile Web. These problems affect the usability of the Mobile Web by means of introducing more typing and pointing errors, and also slowing down typing and pointing speed. On the other hand, disabled Web users who use desktop to access the Web also have difficulties in manipulating a standard keyboard and mouse. For example, users with dexterity problems make typing errors by pressing a key too long without releasing it, or unintentionally pressing a key more than once. They also find it difficult to pin-point an on-screen item using a standard mouse. Web Accessibility research has studied the errors affecting disabled Web users and provided many solutions accordingly. However, very little attempt has been made on investigating whether these solutions developed in the Web Accessibility field can also be beneficial to the Mobile Web field. Instead of looking for specific solutions for the problems faced by the Mobile Web users in the Mobile Web domain, the research presented in this thesis aims to integrated research between Web Accessibility and the Mobile Web, and thus migrate existing solutions from the former to the latter, given that they share common problems.

This chapter concludes the thesis by summarizing the research presented, appraising its contributions and significance, describing any outstanding issues and addresses future directions that could follow.

7.1 Thesis Overview

The accessibility problems affecting the Mobile Web users have been described similar to those experienced by disabled Web users. [Trewin, 2006, Sloan et al., 2000, Sears and Young, 2003a]. Therefore, if it is possible to transfer solutions from one domain to another, then time and effort wasted on implementing solutions within one domain can be reduced. This thesis investigates this similarity from the aspect of user input. The project hypothesis was that small device users and motor-impaired desktop users share the same typing and pointing errors, and solutions can be migrated between these domains to address the common problems. In particular, we focus on migrating existing solutions from the motor-impaired desktop users to the small device users.

During the research, we have identified 12 common typing and pointing errors experienced by disabled Web users and the Mobile Web users. Our research covered a wide range of impairments, including visual-impairment, motor-impairment, hearing impairment, and cognitive-impairment. We also included aged users in our spectrum because as people become elder, they are likely to face a combination of different types of impairments to a certain extent. A series of user evaluations were conducted through controlled experiments in laboratory setting, field study and controlled experiment in naturalistic setting. Results indicated that the Mobile Web users and motor-impaired desktop users share common typing and pointing errors. In terms of error rates, the error rates of small device users under sitting conditions were much lower than that of motor-impaired desktop users. However, as the Mobile Web users became mobile in more realistic environments, the error rates increased in magnitude and reached the same level with motor-impaired desktop users. Based on this, we have proposed to migrate a set of existing solutions available in the motor-impaired desktop user domain to help addressing the problems that also identified with the Mobile Web users. In particular, we implemented a typing error correction system that helps to reduce the common typing errors for the Mobile Web users. A user evaluation was conducted that supported our hypothesis as the results indicated that the tool can significantly reduce the target typing errors. Therefore, Web designer can integrate this tool in their Web pages and help the Mobile Web users reducing typing errors. This work is important not only because it has identified a set of typing and pointing error types of the Mobile Web users; more importantly, it has demonstrated that Web Accessibility and the Mobile Web are two inter-linked domain and that it is possible to directly migrate solutions from one domain to another.

7.2 Contributions of the Thesis

The three research questions listed in Section 1.2 have been successfully addressed and have made the following contributions to the field of Web Accessibility and the Mobile Web.

7.2.1 Motor-Impaired Desktop Users and the Mobile Web Users Share Common Input Problems

Throughout the literature it is shown that common input problems are reported on different user domains, including users with physical impairments and users using small devices. Our research has linked these anecdotal evidences up. As discussed in Chapter 2, we have produced a matrix that reveals the common input problems across the board, along with the existing solutions in each specific user domain. Furthermore, we have also identified the gaps in the literature. We have found the “virgin” areas where no work has been done before, which motivated our research. Not only that, as shown in Chapter 3 and Chapter 5, we were the first to investigate the common input errors of small device users and motor-impaired desktop users using empirical studies. By reproducing Trewin and Pain’s original study [1999] with small device users, we have demonstrated that those input errors that hinder motor-impaired desktop users also affect small device users. However, the error rates of small device users are very low in the laboratory setting compared with that of motor impaired desktop users. This is due to the fact that the experiment was conducted in an "ideal" environment where participants sat comfortably in a quiet lab. The lighting condition was ideal for reading and writing, and there was no distraction to those participants so that they could purely concentrate on their tasks. Nevertheless, research presented in Chapter 2 and Chapter 3 has indicated that common input problems do exist between the Mobile Web users and the motor-impaired desktop users.

7.2.2 The Error Rates of Input Errors Increase in Magnitude as Small Device Users Become Mobile

The second research question presented in Section 1.2 is answered in Chapter 4 and Chapter 5. Because of the nature of small devices, the Mobile Web is bound to be used in more challenging environments where its users need to conduct multiple tasks at the same time and are more likely to get distracted by the environment. Therefore only conducting in-lab user evaluation is not enough to fully understand the input problems of the Mobile Web users. More sophisticated and more realistic experiments need to be conducted to reveal users' behaviors in real life. However, without understanding how people use their devices in real life, it is impossible to design an experiment that are truly "realistic" and 'naturalistic". Therefore, there is a clear need to investigate the usage patterns of small devices.

The field study presented in Chapter 4 has fulfilled this need. We use unobtrusive study methodology to study the behaviors of small device users. Throughout the field study, we have identified four key patterns of usage of small devices. For example, we have observed that small device users use their devices while they are walking; and they normally type with one hand, correct their typing errors, do not often use abbreviations. This finding has confirmed an assumption that several existing research [Lin et al., 2007, Mizobuchi et al., 2005, Brewster, 2002] were based on, that is people do use their devices while walking. They walk and type at the same time rather than stop walking for typing. They tend to quickly scan the road ahead between two typing period. They tend to follow a existing landmark for direction, such as curb of the pavement. In addition, we also found that small device users normally have rapid attention switches between the device screen and the surrounding environment. Our data shows that on average small device users have more than 3 attention switches in 20 seconds. As the context becomes more complex, the number of attention switches increases. These patterns all indicate the fact that small devices are inevitably used in more attention demanding contexts and the user behaviors will be very different compared with a in-lab environment. Therefore when designing user evaluations, one need to clearly recognize such differences and design routes or tasks accordingly.

The experiment presented in Chapter 5 is designed based on the findings of Chapter 4. Results indicate that as small device users become mobile, their error rates increase in magnitude. Comparison of error rates show that the typing error rates of small device users are close to that of motor-impaired desktop users, and for some error type, the error rate of small device users exceeds that of motor-impaired desktop users. In addition, comparison also indicates that small device users who use a stylus and touch-screen have higher pointing error rates than motor-imparired desktop users. The contribution of this study is that it reveals the fact that small device users and motor-impaired desktop users, not only do they share a scope of input problems, but also the error rates are align in magnitude. This finding lays the foundation of solution migration between these two domains: since common problems exist and the error rates are similar, it is reasonable to transfer solutions from one to the other.

7.2.3 Existing Solution Migrated from the Motor-Impaired Desktop User Domain Benefits the Mobile Web Users

Chapter 6 shows such migration is practical. In this chapter, six existing solutions are proposed to be migrated from the motor-impaired user domain to the Mobile Web domain. As a pilot study of migraton, we have implemented a typing error correction system for the Mobile Web users. The system re-use the error correction algorithms originally created for motor-impaired desktop users [Trewin, 2004] and address four types of typing errors for small device users. It also support error correction on various made and model of small devices by maintaining their keyboard specifications in a back-end database. Results of the user evaluation have demonstrated the solution migration successfully reduce typing errors of small device users. Therefore, it is supported that existing solutions can be migrated between domains to address common problems.

7.3 Outstanding Issues

Although this work has made significant contributions to the field of Web Accessibility and the Mobile Web, there are a number of outstanding issues that needs be addressed in the future.

(a) The experiments conducted in this research is targeting device with physical QWERTY keyboard and stylus based touch-screen. While most of the device on the market still use physical keyboard, there is a emerging market of touch-screen devices, especially those powered by multi-touch technology, such as iPhone and iPad [1]. Typing on a touch-screen and on a physical keyboard may be different due to the lack of tactile feedback on a touch-screen. Furthermore, pointing and clicking on screen items with a finger may be different comparing to using a stylus. Additional research needs to be done on typing and pointing errors of touch-screen devices. Investigation can be done by reproducing the same experiments presented in Chapter 3 ad Chapter 5 with touch-screen device users. Results then need to be compared with those generated using physical keyboard and also with those generated by motor-impaired desktop users. This would show the difference in both scope and magnitude as the input method has changed. It would be interesting to see whether typing and pointing errors identified here still exist when using touch-screen devices, and also how the error rate will change for each error type. Furthermore, it would be better to find out whether the current solution migration will still be beneficial on a different type of device.

(b) The solution migration presented in this thesis only address common typing errors between motor-imparied desktop users and small device

[1] See `http://www.apple.com/uk/ipad/`

users. For those pointing errors which have even higher error rates on small devices (see Section 5.5), there is not yet an implementation of migrated solution. It would be interesting to see whether solutions such as SUPPLE++ and Steady Clicks will help small device users improve their pointing performance. This will lead to further user evaluations with small device users into examining whether the pointing error rates will decrease using the proposed solutions.

(c) The research aims to investigate retrospective interoperability between the accessible and the Mobile Webs. However, research presented in this thesis only looks at how existing technologies from the Accessible Web can benefit the Mobile Web users, but not vice versa. Further analysis is needed to find out the solutions benefiting in the Mobile Web users and can also potentially benefit the Accessible Web users. The solution then needs to be implemented on a desktop computer to help motor-impaired users. Additional user evaluation needs to be conducted with motor-imparied users to determine whether the migrated solution can reduce their typing errors.

7.4 Future Work

The research provided a set of contributions but also has some outstanding issues that when attempted to resolved can offer new paths for future work.

Touch-screen Keyboard As discussed in previous section, work presented in this thesis looks at typing errors related to small QWERTY keyboard. On the other hand, the introduction of touch-screen based text entry methods has raised usability questions whose answers may influence future design and market trend. The on-screen keyboard minimizes the need for a physical input device and therefore maximizes the display size [Butler et al., 2008]. In addition, because touch-screen keyboards are software based, they can be easily adjusted in terms of key size, characters on the keys and screen orientation [Paek et al., 2010]. On the other hand, a significant disadvantage of touch-screen keyboard is the lack of tactile feedback to key pressing. Rabin [2004] has shown that tactile feedback contributes to consistency of finger movements during typing by providing information about the start location of the finger which helps to perform typing movements accurately. On a touch-screen keyboard, such tactile feedback is missing and users often have to focus on the keyboard area to locate the correct key. In addition, they will have to verify the typing output [Paek et al., 2010]. This will slow the typing rates. Indeed, it is found that the typing rate of users with touch-screen keyboard is generally less than those with physical keyboard [Hoggan et al., 2008]. Furthermore, touch-screen keyboard users are less often to notice typing errors [Brewster et al., 2007]. Paek [2010] found that small device touch-screen keyboard users are often confused on verifying output, verifying whether auto-suggestion has changed their input, and the location of the next key.

Multimodal feedback, which was originally used in the Web Accessibility area, has been migrated to the Mobile Web domain in order to address the problems with touch-screen keyboard. For example, Brewster [2002] has studied the benefit of providing audio feedbacks to key pressing on small device touch-screen keyboards. Results showed that if sound was added to buttons, then the size of buttons can be reduced significantly without much loss in quantitative performance. However, reduction in button size would cause significantly increase in subjective workload. Hoggan et al. [2008] have investigated the effectiveness of tactile feedback for small device touch-screens. Results showed that the addition of tactile feedback to the touch-screen can significantly improve the text entry performance in terms of error rates and typing rates.

Future work can follow this path and look at whether typing errors identified on physical keyboards exist on touch-screen keyboards. Controlled user evaluations can be conducted to investigate the error types of touch-screen users. If the typing errors experienced by small device physical keyboard users also affect touch-screen users, we can then migrate solutions from Web Accessibility area accordingly. There are generally two approaches: (1) adding additional feedbacks to touch-screen keyboard. As discussed above, audio feedback and tactile feedback are all ideal candidates to supplement visual feedback provided by touch-screen keyboard. (2) adding error correction system to touch-screen keyboard. Work conducted in this PhD project has already shown that error correction system can significantly reduce the typing errors on a physical keyboard. We assume that it is likely to do the same on a touch-screen keyboard. However, this needs further investigation to verify.

Visual-impaired Mobile Web Users Work presented in this thesis suggest that existing solutions can be migrated from the Accessible Web field into the Mobile Web field in order to address the common input problem. As the Mobile Web develops, solutions that are originally designed for small device users can also benefit disabled Web users. Currently, the Mobile Web is predominately used by non-impaired users. Visual-impaired people find touch-screen small devices, such as iPhone, very difficult to use because these devices require the user to visually locate objects on the screen. Unfortunately, most touch-screen do not provide audio or tactile feedback. By introducing audio feedback to the touch-screen device, this accessibility barrier will be crossed. Existing research has demonstrated visual-impaired users can rely on audio feedback to control touch-screen devices. Kane et al. [2008a] has developed a system that allow blind mobile users to navigate on a touch-screen device by means of audio feedback. Li [2008] also suggests that small device users can store and access calendar information using voice and without looking at the screen or keyboard. These solutions, which are originally developed for non-impaired small device users, may be beneficial to visual-impaired small device users. However, further investigation is needed to first categorize the problems that visual-impaired small device users facing and then proposing and evaluating solutions accordingly.

Investigation on Common Output Problems This PhD project mainly focuses on the common typing and pointing problems between the Accessible Web and the Mobile Web. On the other hand, there are output problems that are likely to affect both domains. For example, the screen size of small devices may cause similar problems as visual-impaired desktop users experienced. Various attention demanding environments where the Mobile Web users are in may cause them problems that are similar to those experienced by cognitive-impaired desktop users. As part of the literature review, we also identified 15 common output problems faced by users from both domains, along with 24 corresponding solutions. These problems range from "Limited access to visual objects" to "Inaccessible user agent configuration". Solutions range from "Provide speech/non-speech output" to "Provide confirmation after user input". Details about the survey on output problems can be found in our technical report [2]. Further research can follow this path using the same methodology as used to investigate the common input problems.

This thesis provided the basis for understanding the common input problems between the Accessible Web and the Mobile Web. A tool was presented that should assist Mobile Web users to reduce their typing errors and thus improve accessibility and usability of the Mobile Web. This research contribute to both Web Accessibility area and Mobile Web area by integrating research from these two previously known as disjoint domains and also demonstrating that it is possible to migrate solutions between domains in order to address the common problems. This will directly benefit both domains.

The research presented in this thesis also provided encouraging results into understanding the usage patterns of small devices and the basis into understanding the cognitive load of small device users. This project can be further advanced and one should consider this as supporting information into the foundation for enhancing Web Accessibility and the Mobile Web.

[2]See `http://wel-eprints.cs.manchester.ac.uk/119/`

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Appendix A

Typing Task Instruction Form

This is the first task you need to do in this session. You need to enter the text passage below to the textbox presented on your PDA, using the keypad provided with the PDA. Please note that you are not allowed to change the typing errors, so please be careful. When you finish, please click the link below the textbox and go to the next task.

Begin of the passage

There was a British grandfather called Quentin who said that he was 101 years old. "Are you sure?" asked his friend Maxine. She was 16.

"Yes! I was born in 1895" he replied. But Maxine added in her head the sum 1895 + 101 = 1996, and knew that Quentin was actually 100 this year. He is younger than he thinks (but not by much). Perhaps he has forgotten what year it is. I do that sometimes too. Do you?

You may worry about forgetting what the current year is. Zinc in the diet is supposed to help the memory, but who knows!

Appendix B

Pointing Tasks Instruction Form

This is the second task you need to do in this session. The following text passage is presented in the textbox, you need to follow the instructions on next page and conduct pointing tasks with the stylus provided with the PDA. Please note that you are not allowed to change your pointing errors, so please be careful. When you finish, please click the link below the textbox and go to the next task.

<u>1984</u>

******* a ********************* April ****** ************** ********** ****** *********** ************ ********* ****** **** *********** ******** ********* ***** ***************** **** ************ ****** ****** ************ ******** ****** *** and *** ***** ***** *********.

The hallway smelt of boiled cabbage and old rag mats. At one end of it a ******************** ********** ***************** ******* ********* ****** ************ *********** ********* wide: *** ****** ** * *** ** ***** *******, ***** * **** ***** ****** *** *** ****** ** * *** ** ***** **. ****** **** ***. ** *** ** ***** *** *** **** ****** ********* ****** **** * * **** ** ******** ***** ***** **** ***** **** **** ** ****** **** daylight *****. ** *** **** ** ***** ******* ****** ****** ****** ****** ******* ******** ******** *** *** ***** ** ***** *** *** ** *** ******** ********* ******* **** *** *
so ***** ***** **** *** *** *** * **** ***. BIG BROTHER IS WATCHING YOU, *** ***** **** ***.

************ ********** ********** **** **** ***** ********** ****** ***** ********* ****** * ********** ***** **** ******* *****. It was the police patrol, snooping into people's windows. ******* ******* *** **** ************ **** ******* * ********** ***** ****** ****** *** ******, however, ******* *******.

Pointing Tasks

(a) Find the word ‘April’ in first paragraph, and click between the ‘i’ and ‘l’ in ‘April’.

(b) Drag the cursor to select the word ‘WATCHING’, in the second paragraph.

(c) Double click on the word ‘BROTHER’ at the end of the second paragraph.

(d) Click on the Wiki button above the textbox.

(e) Click between the ‘i’ and ‘d’ of ‘wide’, in the second paragraph.

(f) Drag the cursor to select the sentence “The hallway smelt of boiled cabbage and old rag mats”, in the second paragraph. NOTE: Include the final full stop.

(g) Drag the cursor to select the word ‘a’ at the beginning of the passage.

(h) Triple click on the first line of the second paragraph.

(i) Click on the App button above the textbox.

(j) Click the Close button on the popup box.

(k) Drag the cursor to select the phrase: “BIG BROTHER IS WATCHING YOU” at the end of the second paragraph. NOTE: Do not select the comma at the end of the phrase.

(l) Drag the cursor to select the whole of the first paragraph.

(m) Double click on the word ‘wide’ in the second paragraph.

(n) Click between the ’d’ and ‘a’ of ‘daylight’ in the second paragraph.

(o) Drag the cursor to select the word ‘and’ in the first paragraph.

(p) Double click on the word ‘so’ in the second paragraph.

End of pointing Tasks

Appendix C

Editing Tasks Instruction Form

This is the third task you need to do. You need to follow instructions and edit the following passage. Note that the targets are surrounded by ∗ on the PDA (written in bold and underlined in the following paragraph). Please note that you are not allowed to change your errors, so please be careful. When you finish, please click the link below the textbox and go to the next task.

<u>1984</u>

It was a bright cold day in <u>**April**</u> and the clocks were striking thirteen. Winston Smith, his chin nuzzled <u>**intpo**</u> his breast in an effort to escape the vile wind, slipped quickly through <u>**teh**</u> glass doors of <u>**Victory Mansions**</u>, though not quickly enough to prevent a swirl of gritty dust from entering along with him.

The hallway smelt of boiled cabbage and old rag mats. At one end of it a coloured poster, too large for indoor display, had been tacked to the wall. It depicted simply <u>**a n**</u> enormous face, more than a meter wide: the face of a <u>**mat**</u> of about forty-five, with a heavy black moustache and ruggedly handsome features. Winston made for the stairs. <u>**It was no use trying the lift**</u>. Even at the best of times it was seldom working, and at present the electric current was cut off during daylight hours. It was part of the economy drive in preparation for Hate Week. The flat was seven flights up, and Winston, who was thirty-nine and had a varicose ulcer **avobe** his right ankle, went slowly, resting several times on the way. On each landing, opposite the lift shaft, the poster with the enormous eyes gazes from the **roof**. It was one of those pictures which are so contrived that the eyes follow you about when you move. BIG BROTHER IS WATCHING YOU, the caption beneath it ran.

Outside, even through the shut window-pane, the world looked cold. Down in the street little eddies of wind were whirling dust and torn paper into
spirals, and though the sun was shining and the sky a harsh blue,
there seemd to be no colour in anything, except the posters that were plastered everywhere. The black moustachio'd face gazing down from every commanding corner. There was one on the house-front
immediately opposite. BIG BROTHER IS WATCHING YOU, the captionsaid, while the dark eyes looked deep into Winston's own. Down at street level another poster, torn at one corner, flapped fitfully in the wind, alternately covering and uncovering the single word INGOC. In the far
distance a helicopter skimmed between the roofs, hovered for an
instant like a bluebottle, and darted away again with a curving flight.

Editing Tasks

(a) Double click on the word "April" at the beginning of the passage.

(b) Do key combination "Shift + b".

(c) Drag the mouse to select the word "mat" in the second paragraph.

(d) Type "man", which will replace the selected word.

(e) In the first paragraph, change "intpo" to "into".

(f) In the first paragraph, change "teh" to "the".

(g) Use the arrows on the scroll bar to move down the document until the top of the third paragraph is exactly at the top of the screen.

(h) Click at the end of the text, and type the sentence: "It was the police patrol, snooping into people's windows."

(i) Use the box in the scroll bar to move the document back up so that the top of the second paragraph is at the top of the screen.

(j) Double click to select 'avobe', half way down the second paragraph, at the right hand side.

(k) Type "above", to replace the selected word.

(l) Go to the 'Edit' menu, choose 'Find/Change'.

(m) Click on the 'Close' button on the pop-up box to close it.

(n) Change "roof" into "wall" at the end of the second paragraph.

(o) Drag the mouse to select "Victory Mansions", in the first paragraph, excluding the following comma.

(p) Go to the 'Style' menu, and choose 'Underline'.

(q) Use the arrows on the scroll bar to move down the document until the top of the third paragraph is exactly at the top of the screen.

(r) Click at the end of the text, and type the sentence: "The patrols did not matter, however."

(s) Drag the box in the scroll bar to move the document back up so that the top of the second paragraph is at the top of the screen.

(t) Drag the mouse to select "It was no use trying the lift.", including the full stop.

(u) Go to the 'Style' menu, and choose 'Bold'.

(v) Change "a n" into "an",in the second paragraph.

(w) Go to the 'Outline' menu, choose 'Outline View'.

(x) Use the arrows on the scroll bar to move down the document until the top of the third paragraph is exactly at the top of the screen.

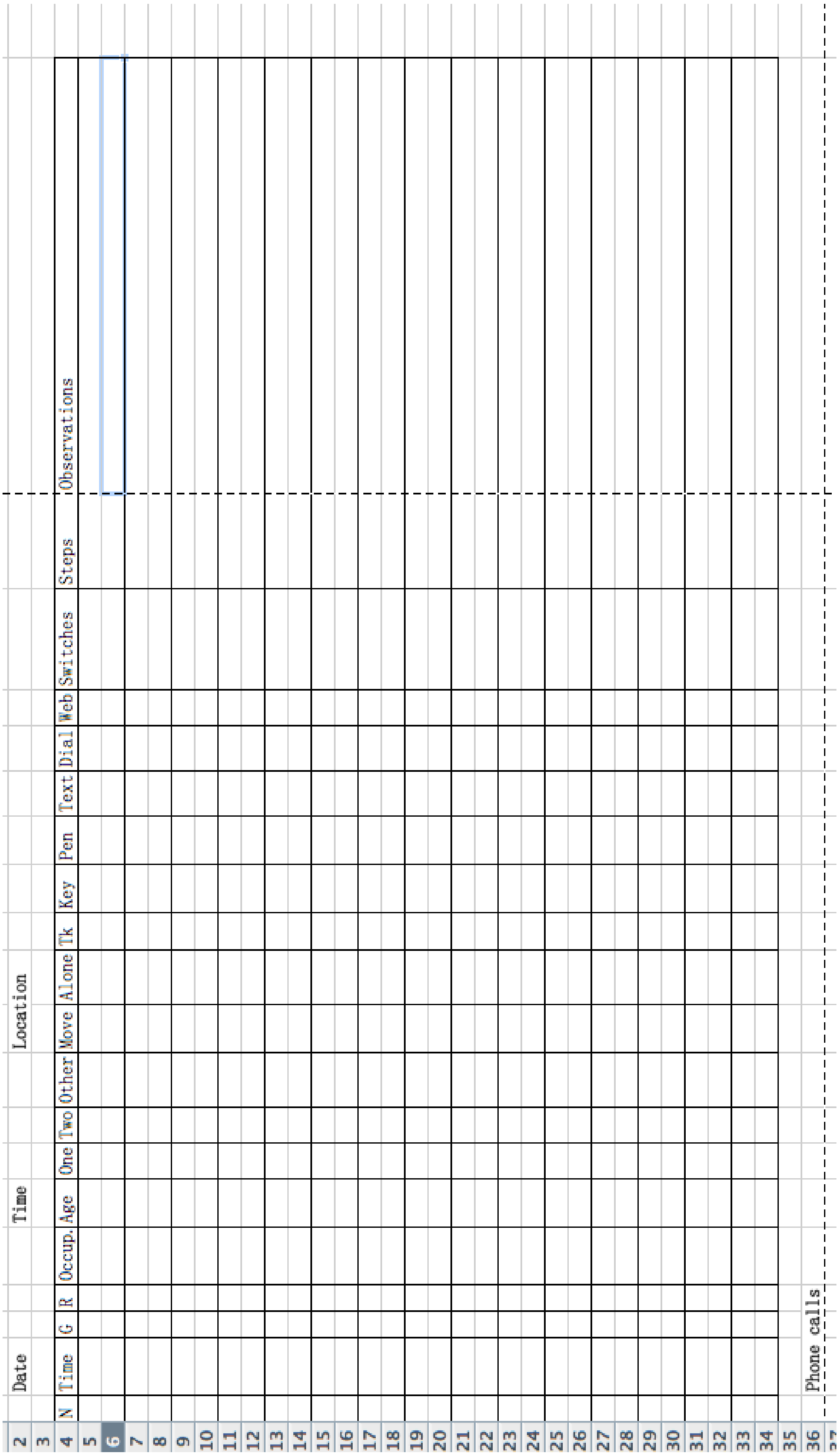
(y) Click at the end of the text, and type the sentence: "Only the Thought Police mattered."

(z) Click on the Save page button below the textbox.

<u>End of Editing Tasks</u>

Appendix D

Field Study Data Recording Form



	Date				Time				Location										
N	Time	G	R	Occup.	Age	One	Two	Other	Move	Alone	Tk	Key	Pen	Text	Dial	Web	Switches	Steps	Observations

Phone calls

Figure D.1: The data recording form used in the field study

Appendix E

Webpages Used in the Study

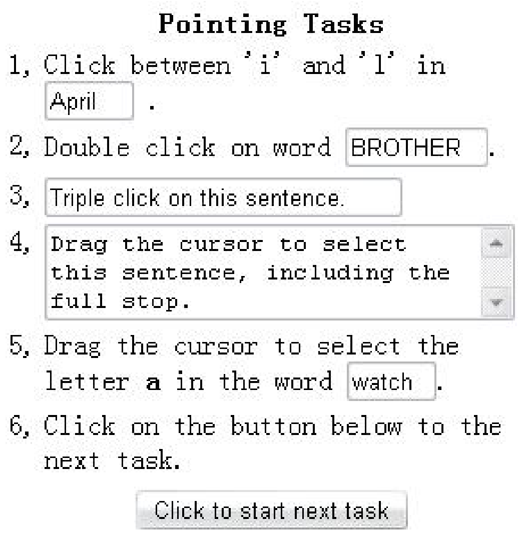


Figure E.1: Webpage for the pointing task T1

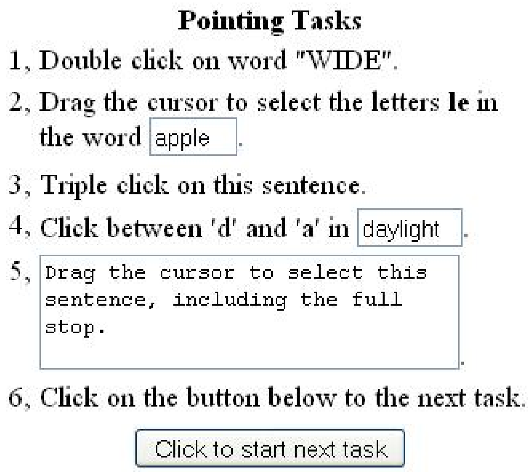


Figure E.2: Webpage for the pointing task T4

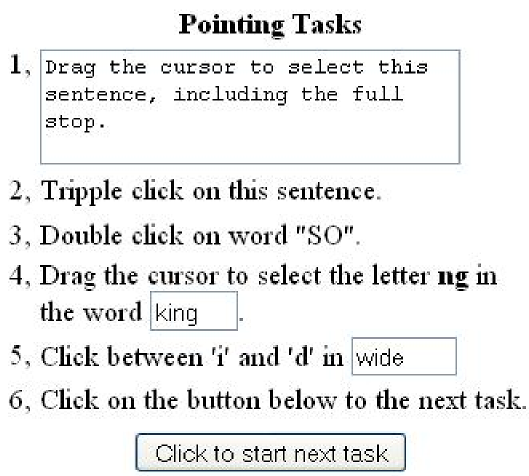


Figure E.3: Webpage for the pointing task T7

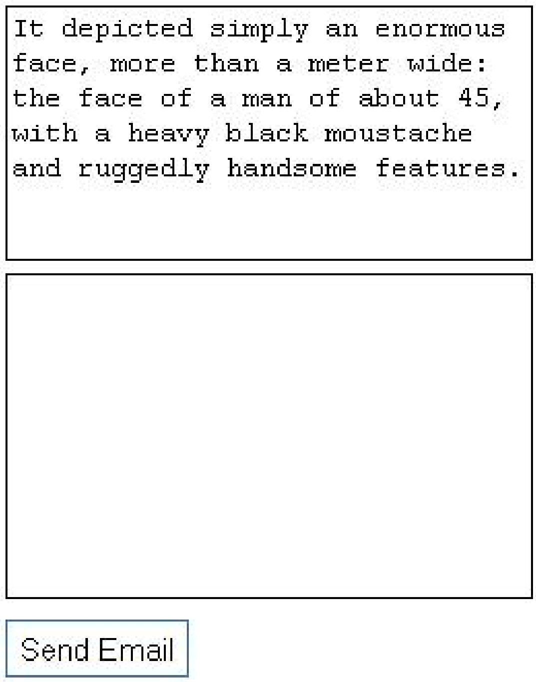


Figure E.4: Webpage for the typing task T8

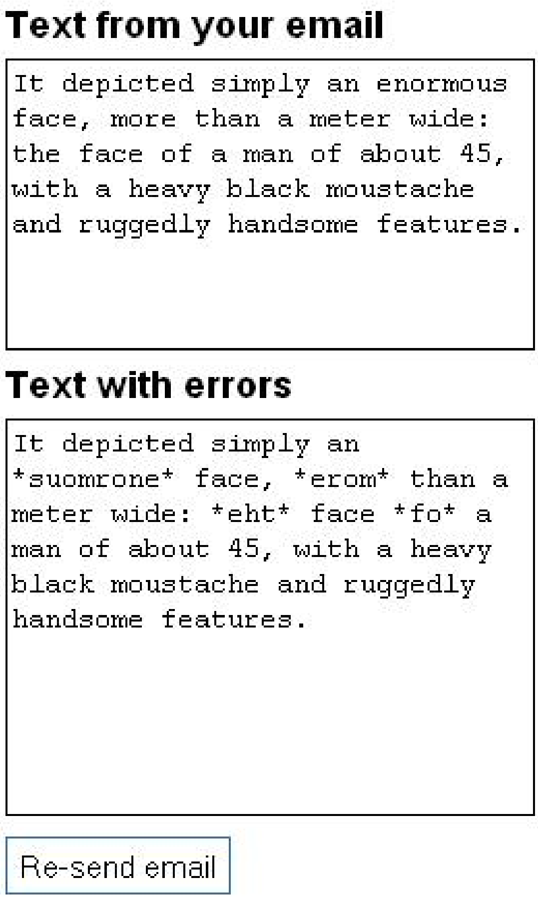
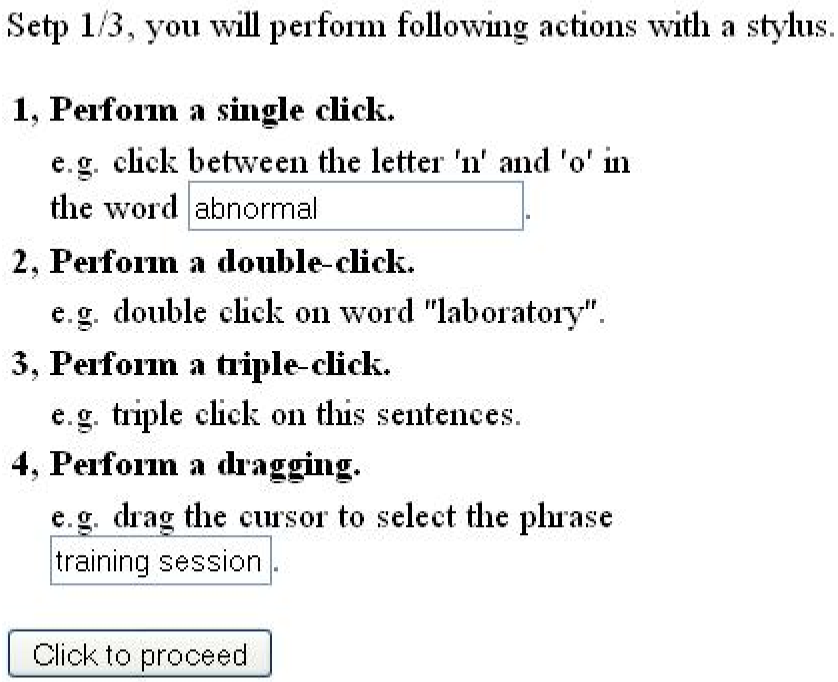


Figure E.5: Webpage for the editing task T9


Setp 1/3, you will perform following actions with a stylus.

1, Perform a single click.

e.g. click between the letter 'n' and 'o' in the word abnormal.

2, Perform a double-click.

e.g. double click on word "laboratory".

3, Perform a triple-click.

e.g. triple click on this sentences.

4, Perform a dragging.

e.g. drag the cursor to select the phrase training session.

Click to proceed

Figure E.6: Training page for pointing task


Step 2/3, you will type some texts.

1, Enter an email address to the address bar below.

Email adress: abc@yousushi.com

Adress bar:

2, Enter the text shown in the first box to the box below.

1+1=3? Make your own JUDGEMENT!

Click to proceed

Figure E.7: Training page for typing task

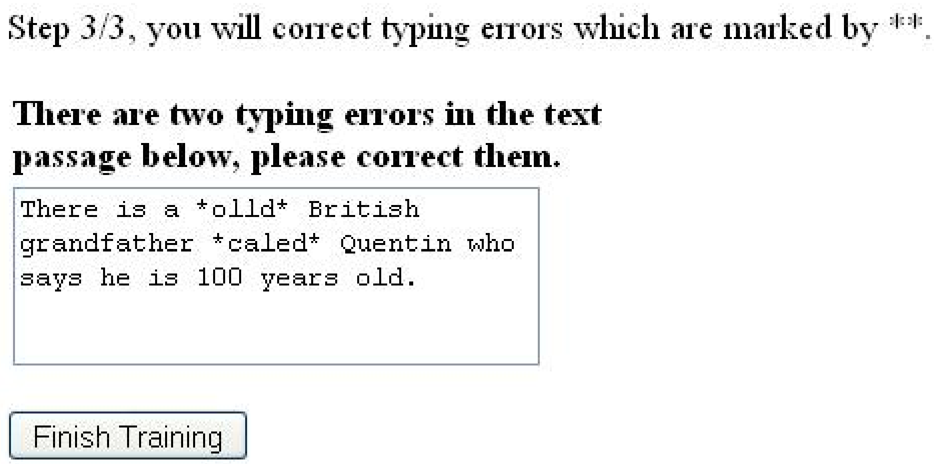


Figure E.8: Training page for editing task

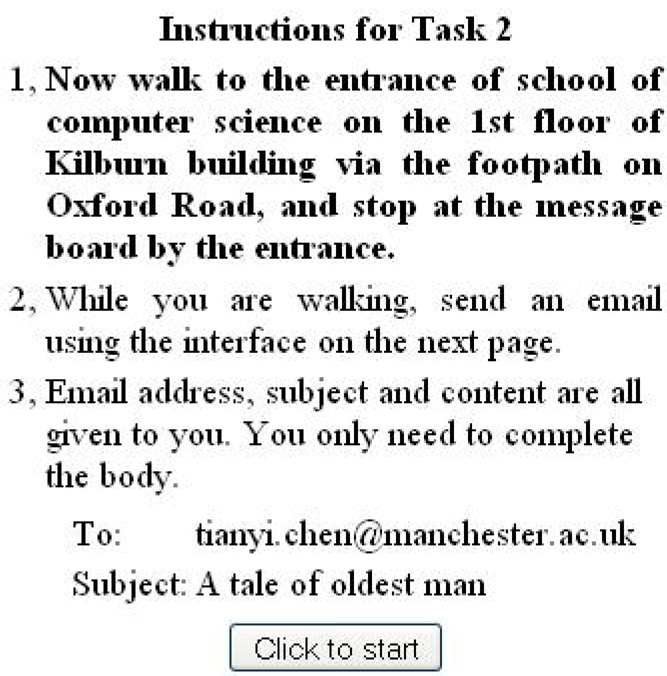


Figure E.9: Instruction page for task T2

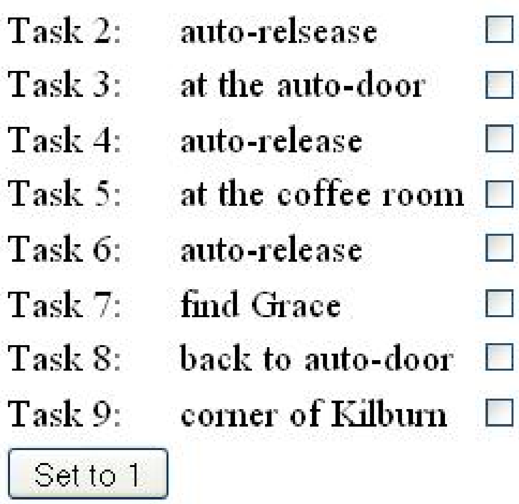


Figure E.10: The control panel

Appendix F

Demographic Form

Mobile Usage Interview Questionnaire

Participant Index
Location
Time
Gender **Male** **Female**

Age Range | 15-35 | 35-50 | 50-65 | 65+ |

Occupation

	none	a little	moderate	good	expert
previous experience in mobile texting					
previous experience in mobile Web					

1. Do you normally use your mobile phone while you are walking?	**Yes**	**No**		
2. If so, do you normally use it for phone call or text messages or internet or something else?	**Phone calls**	**Txt msg**	**internet**	**Other:**
3. When using the mobile phone, do you normally type with one hand or both hands?	**One hand**	**Both hands**		
4. Do you use your thumb to press the keys or other fingers?	**Thumb**	**Other:**		
5. Do you normally correct your typing errors when you use your mobile phone?	**Yes**	**No**	**Other**	
6. Do you normally use predictive text? (For example, T9).	**Yes**	**No**		
7. Do you normally use abbreviations when typing with your mobile phone?	**Yes: R U OK?**	**No: Are you okay?**		
8. Have you used stylus (pen) and touch-screen on a PDA before?	**Yes**	**No**		
9. Do you normally type very long text messages?	**Yes**	**No**		
10. Do you use your mobile phone to do text editing task besides sending messages?	**Yes**	**No**		
11. When you are typing while walking, which keypad do you prefer, stylus/touch-screen or physical keypad? Why?	**Physical**	**On-screen keypad**	**why?**	
12. Comparing with typing while standing still, do you think you have more attention switches between the mobile phone and the surroundings when you are typing while walking?	**More walking**	**More standing**		

Figure F.1: The demographic form used in background session, part I

13. Comparing with typing while walking with friends, do you think you have more attention switches between the mobile phone and the surroundings when you are typing while walking alone?	**More accompanied**	**More alone**		
14. Does your mobile phone have the function to access the Internet?	**Yes**	**No**		
15. Do you use the Internet on your mobile phone?	**Yes**	**No**		
16. How often do you use it?	**Daily**	**Weekly**	**Monthly**	**Other:**
17. What do you use it for, news reading, entertainment, emails, maps or something else?	**News**	**Games**	**Email**	**Maps**
	Other			
18. If you do not use the Internet on your mobile phone, why not?				
19. Where do you normally use your mobile phone to access the Internet? Do you normally do that while you are out, walking or do you mostly use it at home?	**Home**	**Outside**	**Bus**	**Driving**
	Other			

Figure F.2: The demographic form used in background session, part II

Appendix G

Session Record Form

Feedback Session

1. Did you become tired at any point?

2. Did you press the right key but enter the wrong character? How easy did you find avoiding key ambiguity error (1 to 7, 1 stands for impossible and 7 for very easy)?

3. Did you press a key too long that generates unwanted copy? How easy did you find releasing a key (1 to 7)?

4. Did you press any key(s) adjacent to the target key? How easy did you find avoiding additional key error (1 to 7)?

5. Did your finger bounce when you press a key which generates additional copy of the intended key? How easy did you find avoiding finger bounce (1 to 7)?

6. Did you press the neighbouring keys in wrong order? How easy did you find avoiding transposition error (1 to 7)?

7. Did you miss any key? How easy did you find avoiding missing key error (1 to 7)?

8. Is there any comment that you want to make regarding typing using a PDA keypad?

9. Did you experience any difficulty in performing single clicking? How easy did you find clicking an on-screen item (1 to7)?

Figure G.1: Session Record Form Part I

10. Did you experience any difficulty in performing multiple clicking? How easy did you find performing multiple clicking (1 to 7)?

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11. Did you experience any difficulty in performing dragging tasks? How easy did you find performing dragging with a stylus (1 to 7)?

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10. Is there any comment that you want to make regarding clicking and dragging using a PDA stylus?

Figure G.2: Session Record Form Part II

Appendix H

Technical Reports

A list of technical reports written throughout the project:

(a) CHEN, Tianyi (2007) RIAM D1: Review Document
http://wel-eprints.cs.manchester.ac.uk/10/

This report is intended to be the conduit by which information is passed from the PhD student to the RA (who started 6 months after). It contains a review of the current literature on the Accessible Web and the Mobile Web. The report discusses approaches and guidelines on achieving and evaluating Web Accessibility. It also explains characteristics of the Mobile Web and discusses related accessibility issues. Based on the knowledge gained from this report, further investigation on the interoperability between the Accessible Web and the Mobile Web can be conducted.

(b) CHEN, Tianyi and Yesilada, Yeliz and Harper, Simon (2009) RIAM Framework: Output.
http://wel-eprints.cs.manchester.ac.uk/119/

This report presents a literature survey on output problems experienced by both disabled desktop users and small device users. We focused on seven user domains: motor-impaired desktop users, blind desktop users, low-vision desktop users, hearing-impaired desktop users, cognitive-impaired desktop users, small device users and aged desktop users. The survey identified 15 common output problems and 24 corresponding solutions. It also revealed gaps in the literature where certain problems are likely to affect different user domains but have not been well supported by the existing research. In addition, different solutions to the same problem are seen across user domains, which motivate solution migrations. The survey results motivate further cross domain studies, and also serve as a knowledge base of user agent accessibility guidelines.

(c) CHEN, Tianyi and Yesilada, Yeliz and Harper, Simon (2008) Rerunning Trewin and Pain's experiment with mobile users.
http://wel-eprints.cs.manchester.ac.uk/81/

Accessibility of the mobile Web is affected by poor input facilities of mobile devices, such as compact keypads and inefficient pointing tools. But empirical study on input problems experienced by mobile Web users is rare. Here we presents a study that investigates the performance errors of mobile Web users in text entry and pointing. The study is conducted with 15 able-bodied participants. We adopt an existing methodology from Trewin and Pain's 1999 study which was originally used to investigate the input difficulties of motor-impaired computer users. We have identified six categories of typing errors and three pointing errors from mobile users. With regard to typing, mobile users are mainly affected by key ambiguity error. Additionally, we find that the more experienced mobile users rate themselves in text entry, the fewer key ambiguity errors they experience. From the aspect of pointing errors, dragging is more error-prone than clicking and multi-clicking. Further, we find that mobile users have significantly fewer multi-clicking error when they repeat the pointing task. Comparing our results with those of motor impaired users, we find four common typing error categories. In addition, the three pointing errors identified on mobile users also affect motor impaired users.

(d) CHEN, Tianyi and Yesilada, Yeliz and Harper, Simon (2008) How do people use their mobile phones while they are walking?
http://wel-eprints.cs.manchester.ac.uk/98/

This report presents a field study that investigates how small device users use their mobile phones and PDAs in their daily lives. The field study consists of a series of participant observations and unstructured interviews. Results from the observational study show that small device users normally type on their mobile phones or PDAs and walk at the same time. They normally type with one hand and press the keys with thumbs. In addition, small device users have significantly more attention switches between the device screen and the surrounding environment when they type while walking. Results from the interviews show that small device users usually correct typing errors, use abbreviations, and prefer physical keypads over on-screen keyboards. Few use the mobile Web due to bad interface and high cost. Based on the usage patterns obtained from this field study, we propose a set of guidelines that can be used to design small device user studies in more realistic settings.

(e) CHEN, Tianyi and Yesilada, Yeliz and Harper, Simon (2009) Investigating Small Device Users' Input Errors under Standing Walking Conditions.
http://wel-eprints.cs.manchester.ac.uk/118/
This report presents a user study that investigates small device users' typing and pointing errors under standing and walking conditions. The aim of the study is to find out whether typing and pointing errors identified with small device users under sitting condition still exist when the users are mobile, and whether the error rates will increase in magnitude. The study is designed based on a field study of real world small device users, so that the settings and tasks are close to real-life scenarios. Results of the study show that small device users have more typing and pointing errors when they are walking, and the magnitude of error rates are close to, in some cases higher than, that of motor-impaired desktop users.

(f) CHEN, Tianyi and Yesilada, Yeliz and Harper, Simon Solution migrations for Input from disabled desktop users domain to mobile Web users domain.
http://wel-eprints.cs.manchester.ac.uk/97/
Results of our study with small device users suggest that these users experience common typing and pointing errors with motor-impaired desktop users. This report reviews existing solutions and highlights the ones that can be migrated from the motor-impaired desktop users

domain to the small device user domain. Six technical solutions have been reviewed; two for typing errors and four for pointing errors. We propose to migrate Dynamic keyboard and TrueKeys system from motor-impaired domain to address the common typing errors of small device users. Similarly, target expansion, Steady Clicks system, Sticky Icons, and SUPPLE++ system are proposed to address the pointing errors of small device users.