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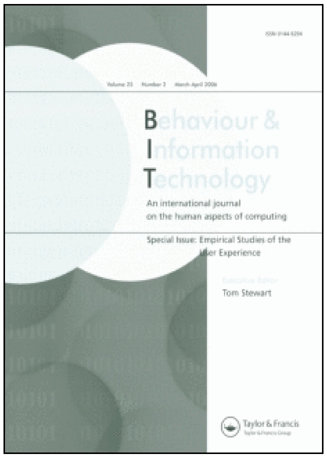

Behaviour & Information Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713736316

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Online Publication Date: 01 May 2005
To cite this Article: Wobbrock, Jacob O., Aung, Htet Htet, Myers, Brad A. and Lopresti, Edmund F. (2005) 'Integrated text entry from power wheelchairs', Behaviour & Information Technology, 24:3, 187 - 203
To link to this article: DOI: 10.1080/01449290512331321729
URL: http://dx.doi.org/10.1080/01449290512331321729

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Behaviour & Information Technology, Vol. 24, No. 3, May–June 2005, 187 – 203

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Integrated text entry from power wheelchairs

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Power wheelchair joysticks have be used to control a mouse cursor on desktop computers, but they offer no integrated text entry solution, confining users to point-and-click or point-and-dwell with on-screen keyboards. On-screen keyboards reduce useful screen real-estate, exacerbating the need for frequent window management, and impose a secondary focus of attention. By contrast, we present two integrated gestural text entry methods designed for use from power wheelchairs: one for use with joysticks and the other for use with touchpads. Both techniques are adaptations of EdgeWrite, originally a stylus-based unistroke method designed for people with tremor. In a preliminary text entry study of 7 power wheelchair users, we found that EdgeWrite with a touchpad was faster than the on-screen keyboard WiViK with a joystick, and EdgeWrite with a joystick was only slightly slower. These results warranted a multi-session comparison of text entry with EdgeWrite and WiViK using joysticks and touchpads, in which we found touchpads faster than joysticks, and EdgeWrite faster than WiViK with both devices after initial learning periods.

Keywords: Power wheelchair; Computer access; On-screen keyboard; Joystick; Touchpad; Text entry; Text input; Unistrokes; Gestures; EdgeWrite; WiViK; Pebbles.

1. Introduction

People with motor impairments, such as those caused by Muscular Dystrophy, Cerebral Palsy, Parkinson's disease, or spinal cord injuries, often cannot use a conventional mouse and keyboard. They may lack sufficient mobility to reach for these devices, sufficient motor control to switch accurately and efficiently between them, or sufficient endurance to use them for more than a few minutes. In addition, many people with motor impairments use wheelchairs. An estimated 1.4 million people in the USA depend on wheelchairs for mobility (Kraus *et al.* 1996). Of these, about 10% are in power wheelchairs, about half of whom require more than one assistive technology to participate in daily activities (Cook and Hussey 1995). A computer access solution that works with an existing device, rather than adding to the mix of encumbering devices, would be valuable (Guerette and Sumi 1994). Such solutions have previously been termed "integrated control systems" (Spaeth *et al.* 1998).

Commercial technology already exists for enabling mouse cursor control from a power wheelchair joystick (e.g. *Mouse Driver* from Switch-It, Inc.). But mouse control is only part of a computer access solution. The ability to enter text is also a cornerstone of successful human–computer interaction. However, an integrated text entry method to accompany joystick mouse control is unavailable. Instead, text entry from power wheelchairs takes the form of point-and-click or point-and-dwell with an on-screen keyboard. This can exacerbate the need for window management due to decreased screen real-estate. It also imposes a secondary focus of attention, taking users' eyes from their work. A text entry method for power wheelchair joysticks (figure 1) would give fuller access without requiring additional devices.

Though less common than joysticks, touchpads can also be used to control power wheelchairs (e.g. *Touch Drive* from Switch-It, Inc., figure 2). Touchpads require less strength to operate than joysticks and little or no calibration. The further a finger moves from the center of

Behaviour & Information Technology
ISSN 0144-929X print/ISSN 1362-3001 online © 2005 Taylor & Francis Group Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01449290512331321729

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Figure 1. The Everest & Jennings 1706-5020 power wheelchair joystick we modified for EdgeWrite text entry. Note the plastic template around the stick, which provides a square boundary.

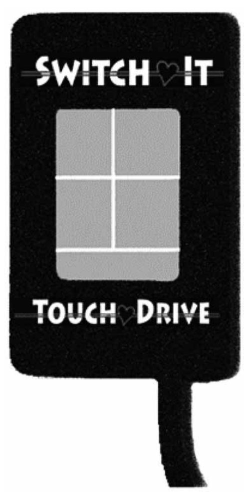

Figure 2. The Touch Drive touchpad for power wheelchairs from Switch-It, Inc. The device is proportional like a joystick: the farther a finger moves from the center of the pad, the faster the chair will move or turn in that direction. See http://www.switchit-inc.com/. Used by permission.

the touchpad, the faster the wheelchair moves. While touchpads have been studied extensively for mousing (e.g. Hinckley *et al.* 1998, Rekimoto 2003), they have not generally been considered text entry devices. People in power wheelchairs might benefit from an integrated device that could control their chair, mouse, and text entry solution. This requires a versatile text entry technique for touchpads.

As more public information terminals (i.e. kiosks) appear in building lobbies and libraries, on streets, in subways, and in community centers, the ability to access these terminals becomes more important. Just as the Americans with Disabilities Act requires that many buildings have access ramps, future terminals may be required to be accessible electronically via Bluetooth or another wireless technology. It would be advantageous to have an integrated control system where the power wheelchair joystick or touchpad could be used as the input device for mousing and text entry for such terminals.

1.1 *Our approach*

As a part of the Pebbles research project, we are investigating how handheld devices—broadly defined to include personal digital assistants (PDAs), mobile phones, joysticks, touchpads, and other similar off-desktop devices—can be used concurrently with desktop computers (Myers 2001). In our previous work (Myers *et al.* 2002), we showed that a Palm PDA could be effective for computer access for some people with motor impairments. This is because while many people with motor impairments lack gross motor control, strength, and endurance, they retain enough fine motor control and finger dexterity to negotiate the small expanse of a PDA screen. The same may be true for joysticks and touchpads.

In addition, we developed a new assistive text entry technique called *EdgeWrite* (Wobbrock *et al.* 2003b). Originally for use with a stylus, EdgeWrite enables people with tremor and reduced mobility to write on a PDA, even though many of them cannot write Graffiti, the dominant unistroke alphabet for Palm PDAs. (EdgeWrite was also over 18% more accurate than Graffiti for able-bodied users.) We also built a version of EdgeWrite for game controller joysticks, and found that able-bodied users were faster and produced more accurate text with it than with date stamp and selection keyboard, two prevalent joystick text entry methods (Wobbrock *et al.* 2004). Although game controller joysticks differ from power wheelchair joysticks, EdgeWrite is simple and versatile enough to be adapted to a variety of devices.

For the current work, we redesigned EdgeWrite to work on an Everest & Jennings power wheelchair joystick (figure 1) and a Synaptics touchpad (figure 3). We compared the use of EdgeWrite on each of these devices to a commercially available text entry method accessible using a power wheelchair joystick or touchpad—the on-screen keyboard *WiViK* from Prentke Romich, Inc. (Shein *et al.* 1991).

In our first of two investigations, we conducted participatory design sessions with 7 power wheelchair users, 6 of whom had Cerebral Palsy and 1 who had

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Figure 3. The Synaptics touchpad we used in our studies. See http://www.synaptics.com/. Used by permission.

Multiple Sclerosis. The participants entered text phrases using touchpad EdgeWrite, joystick EdgeWrite, and joystick WiViK and gave us feedback. (Due to time constraints, they did not use WiViK with a touchpad.) It was difficult for participants to learn the EdgeWrite alphabet in a single session compared to learning the on-screen keyboard, which many participants had used before. Despite this, touchpad EdgeWrite was the fastest method, joystick WiViK was second, and joystick EdgeWrite was a close third. These results were promising since participants had little time to learn EdgeWrite before testing. For this reason, we followed up with a multi-session study for our second investigation.

In the second study, 2 participants with Cerebral Palsy from the preliminary study were tested over 10 sessions on consecutive days (except weekends). Each session consisted of entering text with touchpad EdgeWrite, touchpad WiViK, joystick EdgeWrite, and joystick WiViK. The goal was to discover a "crossover point" (MacKenzie and Zhang 1999): the session at which EdgeWrite overtakes WiViK, if at all. Our results show that the touchpad methods were faster than the joystick methods, and that EdgeWrite overtook WiViK on both devices after an initial learning period. Results are discussed in depth below.

Both of these investigations confirm that gestural text entry methods often take longer to learn than selection-based methods (Wobbrock *et al*. 2004). But a quality gestural method offers a number of advantages over selection-based methods: it does not require precious screen real-estate; it can be used without looking; it can be customized (or "trained"); and it can require less motion per character, since, at least in theory, gestures can be quite small but keyboards can only be shrunk so much before their keys are too difficult to acquire.

Thus, this work takes a step toward a more complete integrated control system for computer access and wheelchair control by addressing the need for text entry from pre-existing power wheelchair joysticks and touchpads.

2. Related work

Many devices exist for computer access, some of which can be used from a power wheelchair (Anson 1997). Alternative physical and on-screen keyboards, head switches, sip-and-puff devices, voice recognition systems, and augmentative communication devices are just a few of the options available for computer access. But there are often obstacles to effective deployment. Many devices are prohibitively expensive. Others require extensive configuration or maintenance. Some might be unwieldy, even on a power wheelchair. These and other reasons may be why prior work has found that less than 60% of people who indicate they need adaptations actually use them (Fichten *et al*. 2000). Our aim in this work, by providing text entry techniques for *existing* power wheelchair control systems, is to lower the barrier to computer access by using mechanisms already present.

Stylus-based EdgeWrite is related to other unistroke text entry methods, most notably the original Unistrokes (Goldberg and Richardson 1993) and Graffiti (Blickenstorfer 1995). Few methods besides EdgeWrite have been devised for "writing" with a joystick, but a notable exception is *myText*, a commercial system from Co-operwrite, Ltd. (http://www.my-text.com/) for miniature mobile phone joysticks.

EdgeWrite uses physical edges to provide stability of motion. Other work has explored using edges in interaction techniques, such as placing controls along edges for easier target acquisition (e.g. Farris *et al*. 2001, Wobbrock *et al*. 2003a). The classic Lisa and Macintosh user interfaces had their menus along the top of the screen for easy target acquisition using the screen's edge (Ludolph and Perkins 1998).

Mouse cursor control using a power wheelchair joystick has been recently studied (Romich *et al*. 2002, LoPresti *et al*. 2004), but not with an integrated text entry technique. Like the current work, the study by LoPresti *et al*. also used the on-screen keyboard WiViK.

Touchpad interaction techniques have existed for some time, but surprisingly few text entry techniques have been developed for them. Two limited exceptions are a touchpad used for a television remote control (Enns and MacKenzie 1998) and for numeric entry using a clock-face metaphor (Isokoski and Kaki 2002). Neither of these, however, is a generic touchpad text entry technique like EdgeWrite. Most touchpad techniques focus on control and selection tasks (e.g. Hinckley *et al*. 1998, MacKenzie and Oniszczak 1998, Rekimoto 2003). Similar to EdgeWrite, templates have been used before on touch surfaces to guide finger motion (Buxton *et al*. 1985).

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3. Edgewrite design and implementation

3.1 *Stylus EdgeWrite for PDAs*

EdgeWrite was originally designed as a stylus-based text entry method for people with motor impairments, especially tremor, since Graffiti proved difficult for this population (Wobbrock *et al.* 2003b). The properties of EdgeWrite and the EdgeWrite alphabet (figure 4) make it well-suited for deployment on other devices for assistive text entry, like power wheelchair joysticks and touchpads.

Specifically, EdgeWrite relies on physical edges and corners to provide stability during motion (Wobbrock 2003). A user moves his or her stylus, finger, or joystick along the physical edges and into the corners of the square. Recognition does not depend on the whole path of motion, but only on the order the corners are hit. This means that moderate wiggle and tremor do not deter good recognition. It also means that to add a custom gesture, a user only needs to perform it once, indicating the desired order of corner-hits. EdgeWrite is not a pattern-matcher and does not require a training set, so recognition occurs without ambiguity.

3.2 *Joystick EdgeWrite for power wheelchairs*

We implemented a version of EdgeWrite in C++ for the Everest & Jennings 1706-5020 power wheelchair joystick, which was removed from the chair (figure 1). Wires were attached to the joystick outputs and the left auxiliary switch in order to access the voltage signals corresponding to the absolute (x, y) position of the stick and the state of the switch (figure 5). A National Instruments 6024E DAQCard read the voltage signals and made them available to our software.

The joystick was polled for its position every 5 milliseconds. When the (x, y) position entered one of the four EdgeWrite corners, a character trace began. When the (x, y) position returned to the center of the square for a short duration, the trace was deemed complete and recognition of the corner sequence occurred. Using this approach in a previous study of able-bodied game controller users, we observed no segmentation errors for thousands of characters (Wobbrock *et al.* 2004).

The joystick's coordinate plane was restricted to the square hole that bounded the stick. One design consideration was how big to make this square (figure 6). In our design iterations, we found that an edge length of 13.75 mm worked well. It was small enough to reduce the amount of necessary movement, but big enough to reduce the risk of accidental corner-hits. The template was mounted on three bolts which we installed from the underside of the joystick chassis.

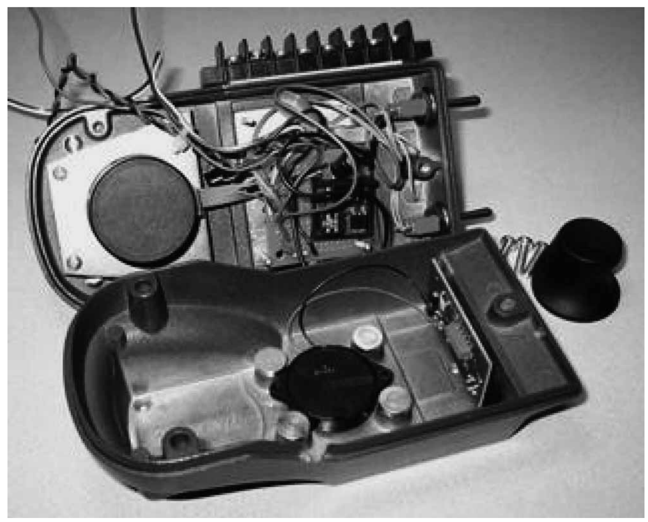

Figure 5. A view inside the Everest & Jennings joystick. We added wires to emit the absolute (x, y) joystick position and the state of one depressible switch. Bolts coming up from the underside of the chassis hold the plastic template.

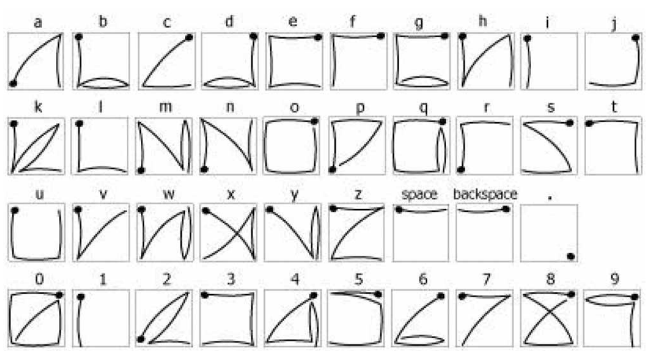

Figure 4. EdgeWrite letters and numbers. A full character chart is available elsewhere (Wobbrock *et al.* 2003b). Note that the bowed line segments are for illustrative purposes only. Actual motion is in straight lines.

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The (x, y) position of the joystick was very noisy, in essence containing a great deal of electronic "tremor" (figure 7a). To filter out this noise, we took the last n points and computed a running average, treating the result as a single point (figure 7b). Trial and error yielded $n = 12$ as the value that removed sufficient noise while decreasing the inevitable lag introduced by a running average.

3.3 *Touchpad EdgeWrite for power wheelchairs*

We implemented another version of EdgeWrite in C++ for a Synaptics touchpad (figure 3). Like the stylus and joystick versions, the touchpad version used a plastic template to provide a square boundary (figure 8). While joystick EdgeWrite was found to be highly sensitive to the size of the square boundary, the touchpad version was not; the square shown in figure 8 is 30 mm wide and worked well.

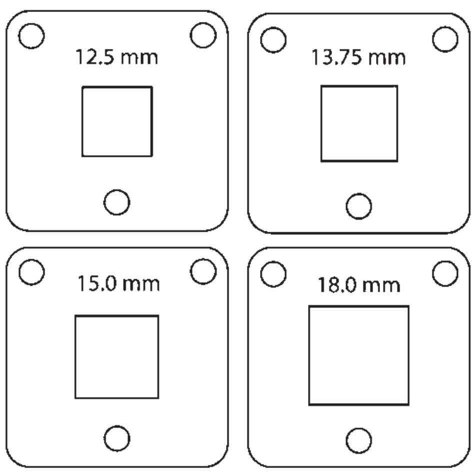
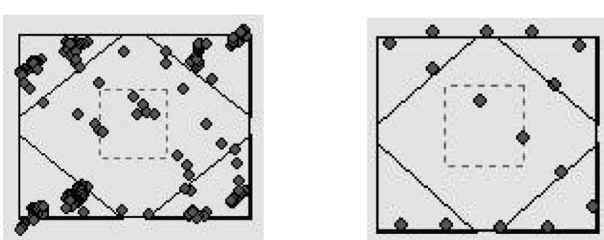


Figure 6. Template diagrams that impose different square sizes in which the joystick can move. Measurements indicate the square holes' edge length. In pilot testing we found the 13.75 mm size to offer the best speed-accuracy tradeoff.



Figures 7a, 7b. An unfiltered (left) and filtered trace of "s" with the joystick. Note the triangular corners and center area used for segmentation.

Touchpad EdgeWrite is similar to stylus EdgeWrite in that letter segmentation is accomplished when the finger (or pen) is lifted. Before a finger goes down on the touchpad, the corners are considered rectangular. Once a finger enters a corner, however, the corners *deflate* into triangles, preventing diagonal strokes from accidentally hitting unintended corners (figure 9).

The edges of the touchpad's plastic template aid tremulous finger motion in the same way that physical edges aid stylus motion on a PDA (Wobbrock *et al.* 2003b). Users can feel the smooth plastic edges as they move, exerting pressure against them for stability. The touchpad surface is a capacitive sensor that senses human skin, so pressure on the plastic template does not interfere.

Figure 8. The Synaptics touchpad with square EdgeWrite template.

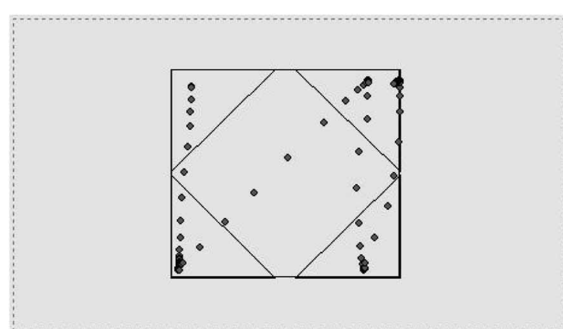


Figure 9. An EdgeWrite "w" traced on the touchpad. The touchpad's surface maps to the whole image, while the EdgeWrite area within the plastic template is the square in the center.

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3.4 *Expert performance with three EdgeWrite versions*

To appreciate the differences among these text entry methods, an able-bodied EdgeWrite expert, the first author on this paper, was given a text entry test using phrases from MacKenzie and Soukoreff (2003). He entered 10 phrases with each EdgeWrite implementation: the PDA stylus, the Everest & Jennings joystick, and the Synaptics touchpad. His respective speeds were 23.0, 12.8, and 19.1 words per minute (WPM). His respective error rates were 6.2%, 8.4%, and 11.4%. All errors made during entry were corrected (though this hindered speeds), so these data represent perfect transcription. While this only reflects one expert, it gives a ballpark comparison consistent with other studies (Wobbrock *et al.* 2004).

4. Study 1: Participatory design & evaluation

This section describes our design and evaluation sessions with participants, in particular the lessons we learned and the parameters we identified. Throughout the process we worked closely with real power wheelchair users.

4.1 *Mouse control and the WiViK keyboard*

In order to compare EdgeWrite to a currently available means of text entry with a wheelchair joystick, we compared the EdgeWrite techniques described above to the on-screen keyboard WiViK (Shein *et al.* 1991) in conjunction with the wheelchair joystick. In order to allow participants to use the WiViK software, we implemented proportional mouse control for the wheelchair joystick. We also enabled a switch on the joystick to simulate a mouse click. When the switch was pressed, it acted as a mouse-down. When the switch was released, it acted as a mouse-up.

We used the WiViK keyboard with the default settings, which included no spacing between the keys, no word prediction, and click-triggering of keys rather than dwell-triggering. The keyboard consumed the entire width and about 1/3 of the height of a 1024 × 768 screen. We chose the WiViK keyboard because of its familiarity as a mouse-driven on-screen keyboard.

Prior research (LoPresti *et al.* 2004) shows that among the possibilities for joystick-driven mouse control, a rate-controlled approach is both fastest and most accurate for on-screen keyboard text entry, as opposed to absolute positioning or a hybrid mode. We implemented a rate-controlled joystick, the velocity and acceleration of which were comparable to that used in the prior work. When using WiViK with the joystick, we removed the plastic template used by EdgeWrite (figure 1) because it would otherwise greatly restrict the joystick's normal range of motion.

4.2 *Participants*

We improved the three techniques that we evaluated—joystick and touchpad EdgeWrite, and joystick WiViK—with the help of 7 power wheelchair users. (We initially had 8 participants, but one was too impaired to perform any of the techniques.) Six of the 7 were from the United Cerebral Palsy Center of Pittsburgh and had Cerebral Palsy. One participant had Multiple Sclerosis. The average age of the participants was 25.9 years, with a low of 21 and a high of 67. Participants had been in wheelchairs for an average of 14.0 years, with a low of 3 and a high of 30. Two of the 7 participants were male. Four of the 7 participants were right-handed. All but one of them used a conventional QWERTY keyboard for text input, but nearly all of them said that they could only do so for short periods of time before becoming fatigued. Two of the participants had used a PDA only a little, and the other 5 had never used one at all. None of the participants had ever used EdgeWrite with a joystick or touchpad.

4.3 *Procedure*

In order to involve participants in the design of the techniques, we had them practice each technique before entering a single test phrase (about 30 letters). Practice consisted of entering each letter 4 times in a row with a given technique (e.g. "*aaaa bbbb … zzzz*"). This took 25–35 minutes with the EdgeWrite techniques, and about 10–20 minutes with WiViK, since there was no gestural alphabet to learn. The whole test duration did not exceed 2 hours. All 7 participants used joystick WiViK and joystick EdgeWrite, but only 4 participants used touchpad EdgeWrite because of time constraints. A comparison of the joystick data from these 4 participants to the other 3 participants shows similar results, suggesting that touchpad results for all 7 participants would not be substantially different.

An EdgeWrite character chart was visible during the test (figure 10). With the slow pace of practice and the limited endurance of participants, we did not want to unduly burden them with memorizing the EdgeWrite characters. Instead, we taught them how to read the chart and observed their behavior. Reading the chart greatly slowed them compared to their use of WiViK, which required no chart. The *inter-character time*—the time from the end of one character to the start of the next—gives us some idea of the delay caused by reading the chart. The average inter-character time was 6.23 seconds. With more practice, this value would go down, since participants would be familiar with the letters. Our second study confirms that by the 10th session, the inter-character time was down to 3.74 seconds.

All text input was logged on the PC by a text entry test program that we wrote. It was later analyzed with recently

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Figure 10. This participant is entering text with the joystick using the WiViK on-screen keyboard. To the right of the laptop screen is the EdgeWrite character chart used in the two EdgeWrite conditions.

developed measures (Soukoreff and MacKenzie 2003), which allow participants to enter text in an unconstrained, real-world fashion, where they can choose to fix errors or not. Participants are merely instructed to ''proceed quickly and accurately.''

We solicited responses from participants in between text entry phrases and more formally using questionnaires. In addition, many participants offered ideas while practicing with the techniques.

4.4 *Results*

In this first investigation, slow performance and rapid fatigue meant that only one test phrase could be entered by each participant for each method. Thus, we do not have sufficient data for statistical significance. However, we can compare the means for the 3 techniques (using 4 participants for touchpad EdgeWrite) and correlate performance with participants' comments.

For text entry speed, touchpad EdgeWrite proved fastest, joystick WiViK second, and joystick EdgeWrite third (figure 11).

Three error rates characterize unconstrained text entry. Corrected errors are those fixed during entry, uncorrected errors are those left in the transcribed string, and total errors are the sum of the other two (figure 12).

Clearly, participants made more errors with the EdgeWrite methods than with joystick WiViK. This is to be expected of a gestural input technique compared to a selection-based one, since when learning new gestures, users often perform them incorrectly. On the other hand, to make an error with WiViK, a user would have to place the mouse cursor over the wrong key and still choose to press and release the switch, a lengthy perceptual-motor task that is easily avoided most of the time.

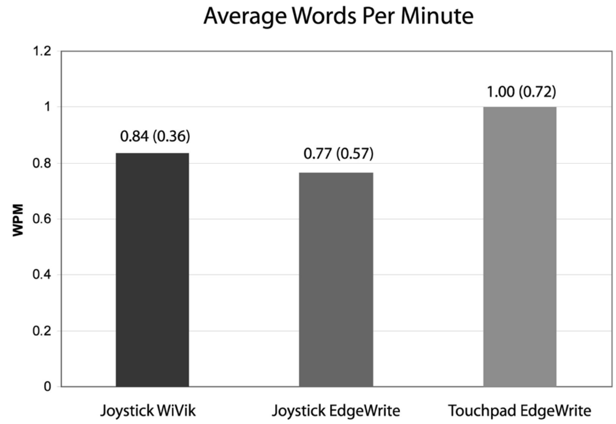

Figure 11. Average words per minute for the 3 techniques tested in the first study. (Bigger values are better.)

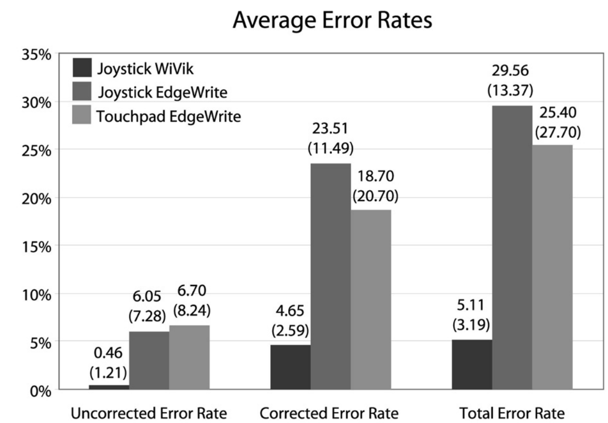

Figure 12. Average error rates for the 3 techniques tested in the first study. Uncorrected errors appear in the final text but corrected errors are fixed with backspace during entry. Total errors are the sum of uncorrected and corrected errors. (Smaller values are better.)

The questionnaire results showed that, of the 3 methods, participants felt that touchpad EdgeWrite was the easiest to use, easiest to learn, fastest, most accurate, most enjoyable, most comfortable, and most liked. They rated joystick WiViK second in all of these categories, and joystick EdgeWrite third. These ratings are shown in figure 13.

4.5 *Lessons from participants*

Participant #1 was a 67-year-old retired school teacher with Multiple Sclerosis. He was notable for two reasons: he was the only person without Cerebral Palsy, and he was only one of two participants who was faster with joystick EdgeWrite than WiViK (1.91 *vs.* 1.22 WPM). The other was Participant #8, who was a 22 year-old female with

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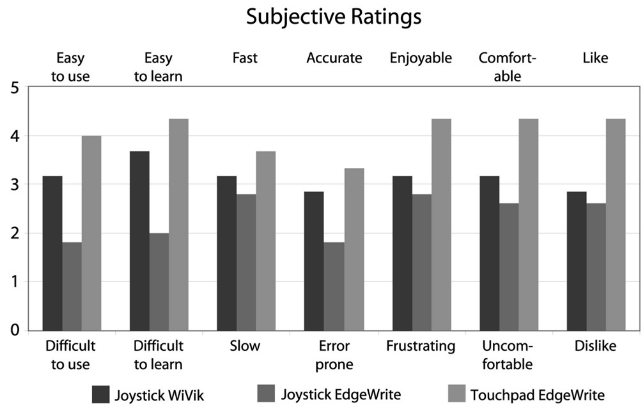

Figure 13. Average questionnaire ratings from the first study reveal a preference for touchpad EdgeWrite over joystick EdgeWrite and joystick WiViK. (Bigger values are better.)

good fine motor control. She was only slightly better with joystick EdgeWrite than WiViK (0.52 *vs.* 0.50 WPM). Participant #1 showed us that the plastic template should be thicker to prevent the exposed spring on the joystick post from catching the template's edge. After using WiViK for a few minutes he said, ''It takes the patience of Job to do this.'' Upon switching from WiViK to EdgeWrite, he said, ''I'm much faster with this; don't you think I'm much faster?'' indicating his first impression of joystick EdgeWrite.

Participant #2 was a 21-year-old student. She initially had trouble with the diagonal strokes with joystick EdgeWrite because she would move too slowly through the center, and EdgeWrite would try to recognize what she had already done. She motivated us to change the center dwell time required for segmentation. If a polled joystick point falls outside the center area before the dwell time has elapsed, the dwell time counter resets. The time that worked well for Participant #2 was 500 ms. This participant also thought it would be *easier* to do the WiViK keyboard with the EdgeWrite template still on the joystick because it would help prevent target overshooting. This suggests joystick mouse control and joystick EdgeWrite could co-exist on the same device without having to remove the EdgeWrite template.

A long dwell time was not sufficient for Participant #4, a 40-year-old volunteer. She moved inconsistently with joystick EdgeWrite, sometimes making letters very quickly, other times pausing for many seconds to think. For her we added the ability to trigger recognition with the switch, removing the need for center dwell. She enjoyed touchpad EdgeWrite because it was the easiest method with which to fix mistakes. Of touchpad EdgeWrite she said, ''Once you understand what you are doing, it goes completely well.'' Participant #7 echoed this when she said, ''If you get used to it, you'd be really fast I suppose.''

While the females tended to interact too gingerly with the joystick, the males, Participants #1 and #3, were too forceful at first. Discovering the right speed and pressure to exert against the joystick template was an obvious part of learning joystick EdgeWrite.

A common problem was that participants did not always start in the corner of the plastic template before making their gestures with the joystick. This was less of a problem with the touchpad. The reason may be that the joystick had to be pushed *from* somewhere (i.e. the center) to reach the starting corner, whereas a finger could *begin* in the corner of the touchpad.

Participant #4 gave us an important insight into the design of the touchpad template. We originally smoothed the edge of the touchpad template so that it was slightly beveled. But this caused participants' fingers to slip up onto the template's surface, actuating a ''finger up'' and prematurely triggering recognition. This insight led to the fabrication of a thicker touchpad template, the edges of which we left vertical and unbeveled. We also added a settable tolerance to lift for the second investigation, discussed below.

Participant #6 highlighted the importance of end-user customizability. While using touchpad EdgeWrite, this participant's finger did not always press against an edge of the square. Having defined the square for her along the plastic edges, we saw that her fingers moved inside this square, and that the actual square in which she moved was smaller than the one we had defined. When we had *her* redefine the EdgeWrite square, her accuracy improved tremendously.

Finally, the diagonal strokes were difficult for many users of joystick EdgeWrite. This is not surprising, because it is along the diagonals that the user does not have an edge to press against. The letter ''k'' (figure 14a) was particularly problematic because of its two diagonals in a row. For our second study, we designed a new form of ''k'' (figure 14b) that is still reminiscent of a Roman ''k'' but without a diagonal. This new ''k'' proved much easier to perform and has become a permanent part of the alphabet in all versions of EdgeWrite.

6. Study 2: Multiple sessions with two users

The findings from the first study, which largely represent ''walk up and use''-ability, warranted a second investigation over multiple sessions. Such a study can identify a ''crossover point'' where EdgeWrite, though initially harder to learn, overtakes WiViK in speed or accuracy. Participants #2 and #4 from the first investigation agreed to partake in a 10-session study over consecutive days (except

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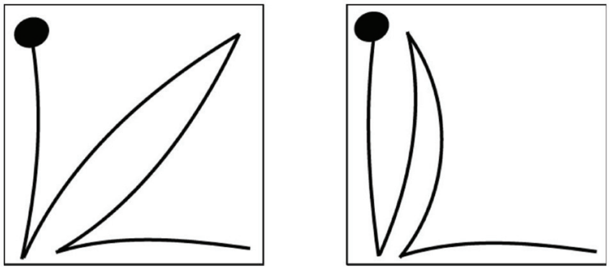

Figures 14a, 14b. The original design of the letter ''k'' (left) was difficult for joystick users in the first study because of the diagonal strokes. An alternate ''k'' was designed for the second study that contains no diagonals. This ''k'' was much easier to make with a joystick. Note that arcs are only illustrative. Actual motion is in straight lines.

weekends). There was about 3 months separating Study 1 and Study 2.

6.1 *Participants*

Participant #2 is female and 22 years old. She uses a computer more than a few hours a day, largely for email, surfing the Web, and word processing. She reports being able to use a standard physical QWERTY keyboard for up to 1 hour, after which point she switches to an alternative method, usually a WiViK on-screen keyboard accessed with a standard mouse, because of fatigue. She is able to write her name with a pen, though it takes her many seconds, and it is legible about 4 out of 5 times. The joystick on her power wheelchair has a short stick with a plastic ball at the top.

Participant #4 is female and 41 years old. She uses a computer only about once a week for email, surfing the Web, or word processing. She, too, reports being able to use a standard physical QWERTY keyboard for up to 1 hour, after which she either stops using the computer or uses the WiViK on-screen keyboard with a standard mouse. She can write her name legibly with a pen but it takes many seconds if not minutes, and is legible about 4 out of 5 times. The joystick on her power wheelchair is about twice as long as and a great deal skinnier than the one we used in the study (figure 1). It also had a much weaker spring. Participant #4 was a great deal weaker than #2, which affected her ability to move the joystick snugly into the corners while using joystick EdgeWrite.

6.2 *Design improvements*

Before conducting the second investigation, we made some design changes to the techniques based on our observations from the first study. For example, we added tolerance for a brief lifting of the finger from the touchpad surface during EdgeWrite. Previously, when a finger was lifted the stroke was immediately ended and recognition commenced. The new tolerance, which took the form of a customizable lift-delay, allowed participants' fingers to lift briefly from the surface and return, thereby continuing the stroke without triggering unwanted recognition. Both participants worked well with a 275 ms tolerance.

The triangular corner regions in touchpad EdgeWrite were also reduced slightly from 47.5% of the square's width and height in each dimension to 42.5%. This was because participants would sometimes hit an unwanted corner while making a diagonal, particularly from the bottom-left corner to the upper-right. Both of study 2's participants were right-handed.

The area considered the center for joystick EdgeWrite (figure 7b) was reduced by about 11% to make accidental recognitions less common, since participants would often move too slowly through the center region while making a diagonal. In the first study, this caused the software to think the joystick had been returned to center for segmentation between letters. We also found that participant #2 required a 500 ms center dwell segmentation threshold, while participant #4 required 1000 ms. Lesser values resulted in some unwanted attempts at recognition while moving through the center region.

Finally, as noted above, a new form of ''k'' that contains no diagonals was added to the EdgeWrite alphabet (figure 14b). We also added a new form of ''e'' that is tolerant to the omission of the bottom-left corner, since this corner was also missed fairly often.

As stated above, the joystick used with WiViK was rate-controlled, so the farther it was moved from its center, the faster the mouse cursor moved. The acceleration transfer function was linear from the center of the joystick to its extremes. For joystick WiViK, we reduced this acceleration from a maximum of 1.2 pixels/ms to 0.8 pixels/ms. We made this change because of some occasional target overshooting while participants tried to acquire keys on the WiViK keyboard during the first study. With the reduced acceleration, target overshoots in the second study were rare.

6.3 *Procedure*

The experiment was a 2 × 2 × 10 within-subjects factorial design with factors for *method* (EdgeWrite or WiViK), *device* (joystick or touchpad), and *session* (10 sessions). With only 2 participants, the experiment was aimed less at achieving statistical significance and more at observing how long it took users to learn EdgeWrite, and whether EdgeWrite could outperform WiViK given repeated practice.

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Each participant performed all 4 techniques (method × device) during each session. Technique order was assigned randomly by the software for each session. Participants practiced each technique before testing by entering a short 2-word phrase ($\sim$10 letters). During the test, participants transcribed 2 phrases of about 6 words ($\sim$30 letters) each. This took from 10–30 minutes per technique, depending on the session, technique, technique order, and other factors. Thus, a session consisted of about 70 characters for each method × device combination. Figure 15 shows the user test program (top) and the WiViK keyboard (bottom).

The test phrases were drawn randomly from the published test corpus of 500 phrases by MacKenzie and Soukoreff (2003). These phrases only contain letters, but as MacKenzie and Soukoreff argue, unless the entry of numbers or punctuation involves a qualitatively different mechanism (e.g. two hands instead of one), letters alone should be representative. In the case of EdgeWrite and WiViK, numbers and punctuation are accessed in the same general manner as letters, so only letters were tested.

Unfortunately, Participant #2 was unable to finish all 10 sessions due to intervening commitments. She finished 6 sessions with joystick WiViK due to technical problems during the 7th and 8th sessions. She finished 8 sessions with the other 3 techniques. These limitations are taken into account in our analyses.

6.4 *Results*

We analyzed this data as a mixed model with a random effect for *subject*. Random effect models give wider confidence intervals (i.e. larger standard errors) than fixed models and therefore set a higher bar for determining statistically significant differences. They also result in greater denominator degrees of freedom. We accommodated the aforementioned imbalance in our number of sessions by using least squares estimates for our means (LS Means).

6.4.1 Speed. Overall results show a main effect of *device* on speed ($F_{1,131} = 142.05$, $p < 0.001$). The touchpad was faster than the joystick at 1.28 and 0.82 WPM, respectively. There was no significant *method* × *device* interaction ($F_{1,131} = 0.01$, n.s.), since touchpads were similarly faster than joysticks for both EdgeWrite and WiViK.

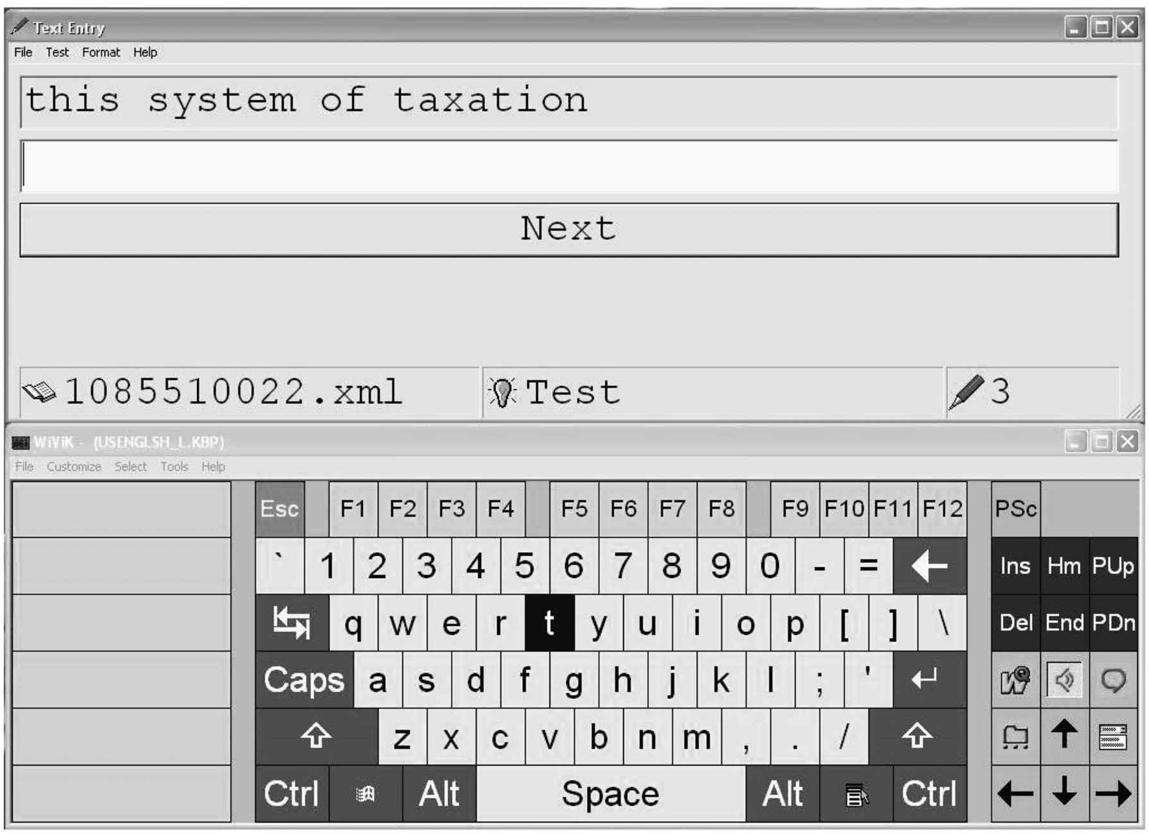

Figure 15. The 1024 × 768 laptop screen on which we tested was consumed by the text entry program (top) and the WiViK on-screen keyboard for the WiViK methods. For EdgeWrite methods, the bottom area showed the EdgeWrite square. WiViK image used by permission.

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There was no main effect of *method* on speed ($F_{1,131} = 2.95$, n.s.). This is because the EdgeWrite methods were slower in the early sessions but faster at the end. A significant *session* × *method* interaction shows that methods did indeed improve over sessions ($F_{1,131} = 10.35$, $p < 0.002$). However, contrast tests show that this improvement was due mostly to EdgeWrite and not to WiViK, as there was significant speedup from the first 5 sessions to the second 5 sessions for EdgeWrite ($F_{1,99} = 25.61$, $p < 0.001$) but not for WiViK ($F_{1,99} = 1.73$, n.s.). Figure 16 depicts this improvement and gives a sense of the rate at which EdgeWrite was learned. As noted above, sessions 7 and 8 lack joystick WiViK for Participant #2. This actually *improves* WiViK's speed for those 2 sessions because touchpad WiViK was significantly faster than joystick WiViK ($F_{1,131} = 70.07$, $p < 0.001$).

As we would expect, there was a main effect of *session* on speed ($F_{1,131} = 9.84$, $p < 0.003$), with Participant #2 improving her overall average from 0.91 WPM in session 1 to over 1.17 WPM by session 6. (Sessions 7 and 8 were even faster at 1.41 and 1.22 WPM, respectively, but these lacked data for joystick WiViK.) Participant #4 improved her overall average from 0.87 WPM in session 1 to 1.11 WPM in session 10. There was no significant *session* × *device* interaction ($F_{1,131} = 0.03$, n.s.), since the touchpad and joystick were learned at a similar rate. There was also no significant *session* × *method* × *device* interaction ($F_{1,131} = 2.19$, n.s.).

6.4.2 Accuracy. The total error rate is the addition of the uncorrected error rate (errors left in the transcription) and the corrected error rate (errors fixed with backspace during entry). Readers are directed to Soukoreff and MacKenzie (2003) for more details.

Overall results show a main effect of *device* on total error rate ($F_{1,131} = 23.39$, $p < 0.001$). The touchpad was more accurate than the joystick at 5.56% and 10.74% errors, respectively. A significant *method* × *device* interaction suggests that each method's accuracy was affected differently by the devices ($F_{1,131} = 15.58$, $p < 0.001$). Contrast tests show that joystick EdgeWrite was significantly less accurate than touchpad EdgeWrite ($F_{1,131} = 39.94$, $p < 0.001$) at 19.39% and 9.98% errors, respectively; but joystick WiViK was not significantly less accurate than touchpad WiViK ($F_{1,131} = 0.38$, n.s.) at 2.09% to 1.14% errors, respectively. This interaction is shown in figure 17.

There was a significant main effect of *method* on total error rate ($F_{1,131} = 148.99$, $p < 0.001$). As in the first study, WiViK was more accurate than EdgeWrite at 1.62% and 14.69% errors, respectively. There was a significant *session* × *method* interaction ($F_{1,131} = 10.14$, $p < 0.002$), indicating method accuracy improved over time. Contrast tests show this was due to EdgeWrite improving from the first 5 tasks to the second 5 tasks ($F_{1,99} = 26.92$, $p < 0.001$), but WiViK remained about the same ($F_{1,99} = 0.39$, n.s.). With more sessions and further refinements, particularly to the joystick's physical parameters (e.g. spring strength, stick

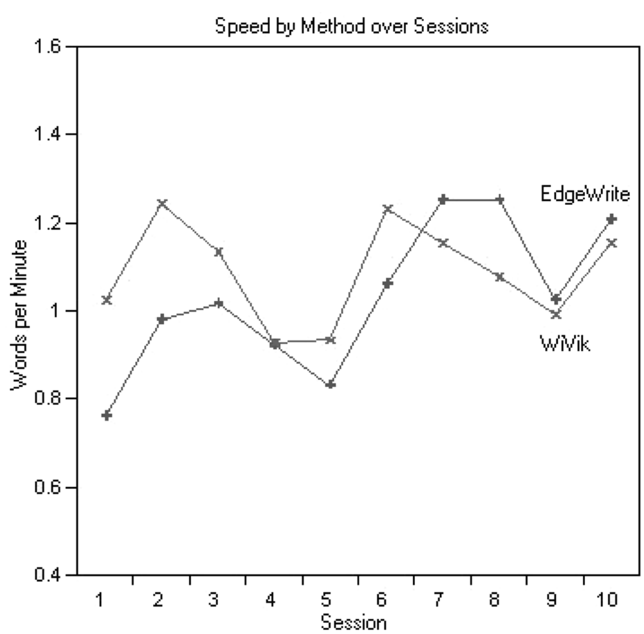

Figure 16. Over the 10 sessions, participants' speeds improved with EdgeWrite more than they improved with WiViK. This is confirmed by contrast tests which are significant for EdgeWrite but not for WiViK.

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length), EdgeWrite error rates would probably drop further. Figure 18 shows the improvement in accuracy over sessions for each method.

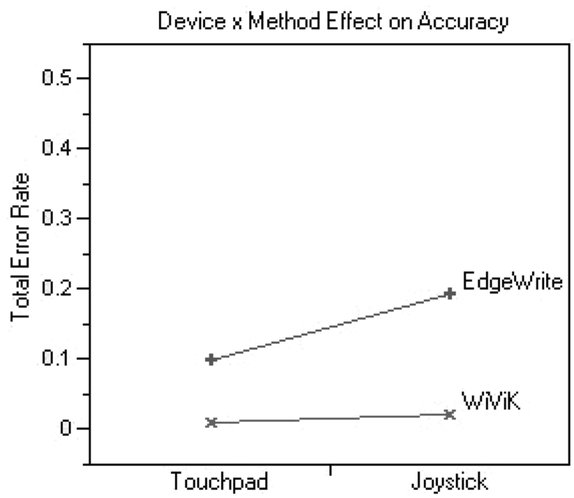

Figure 17. The device type did not significantly affect the accuracy of WiViK, but the touchpad was significantly more accurate than the joystick for EdgeWrite. This may be because gesture-making in EdgeWrite is more sensitive to the parameters of devices than is simply moving a cursor for WiViK.

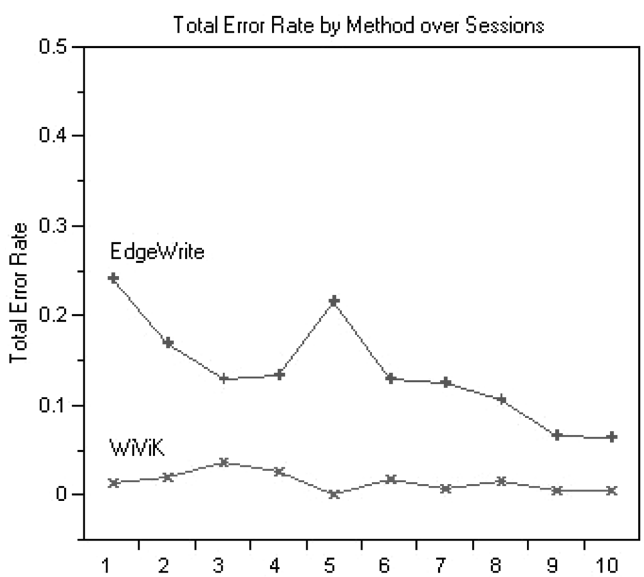

Figure 18. Over the 10 sessions, participants' total error rates improved significantly with EdgeWrite. This was not the case with WiViK, which maintained a low error rate over all sessions.

That the overall error rates are higher for EdgeWrite than WiViK is not unexpected, since learning and performing a gestural entry technique will usually be more error prone than selecting from an on-screen keyboard (Wobbrock *et al.* 2004). But results for each participant show dramatic improvements in accuracy from the first session to the last for EdgeWrite: 21.2% in session 1 to 11.7% in session 8 for Participant #2, and 26.8% in session 1 to just 6.0% in session 10 for Participant #4.

As expected, there was a main effect of *session* on total error rate ($F_{1,131} = 15.75$, $p < 0.001$). There was also a significant *session* $\times$ *device* interaction ($F_{1,131} = 5.55$, $p < 0.02$), since from the first 5 tasks to the second 5 tasks, participants became more accurate over sessions with the joystick ($F_{1,99} = 18.42$, $p < 0.001$) but not with the touchpad ($F_{1,99} = 1.76$, n.s.). There was no significant *session* $\times$ *method* $\times$ *device* interaction ($F_{1,131} = 1.21$, n.s.).

With only 2 participants and a high degree of variation from one session to the next, these overall results are less illuminating than the detailed results for each participant. We report these in the next two sections.

6.4.3 Participant #2. Participant #2 showed a main effect of *device* on speed ($F_{1,52} = 41.39$, $p < 0.001$), being faster with the touchpad than the joystick at 1.30 and 0.91 WPM, respectively. There was not a significant main effect of *method* on speed ($F_{1,52} = 0.75$, n.s.), though on average she was faster with EdgeWrite than WiViK at 1.13 and 1.08 WPM, respectively. There was no significant *method* $\times$ *device* interaction ($F_{1,52} = 3.21$, n.s.).

A plot of her WPM over sessions (figure 19) shows that touchpad EdgeWrite overtook touchpad WiViK on session 4 and again on sessions 7 and 8, suggesting a possible crossover point at session 7. The graph shows an increase in the speed of touchpad EdgeWrite over sessions, while touchpad WiViK remains relatively unimproved. The graph also shows that joystick EdgeWrite quickly overtook joystick WiViK by session 2, maintaining a small but consistent advantage thereafter through session 6. Although we lack data for joystick WiViK beyond session 6, the improvement of joystick EdgeWrite in sessions 7 and 8 suggest it is unlikely that joystick WiViK would have overtaken it. A contrast test between joystick EdgeWrite and joystick WiViK supports this trend ($F_{1,52} = 3.11$, $p = 0.08$) at 0.99 and 0.83 WPM, respectively. With more sessions, the advantage of joystick EdgeWrite would likely reach significance.

Participant #2's total error rates for the 4 techniques are shown over sessions in figure 20. Though both EdgeWrite methods improve over the sessions, their accuracy still falls far short of WiViK. The trends imply, however, that with more practice, even better accuracy can still be achieved.

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6.4.4 Participant #4. Participant #4 showed a main effect of *device* on speed ($F_{1,72} = 137.64$, $p < 0.001$), being faster with the touchpad than with the joystick at 1.25 and 0.72

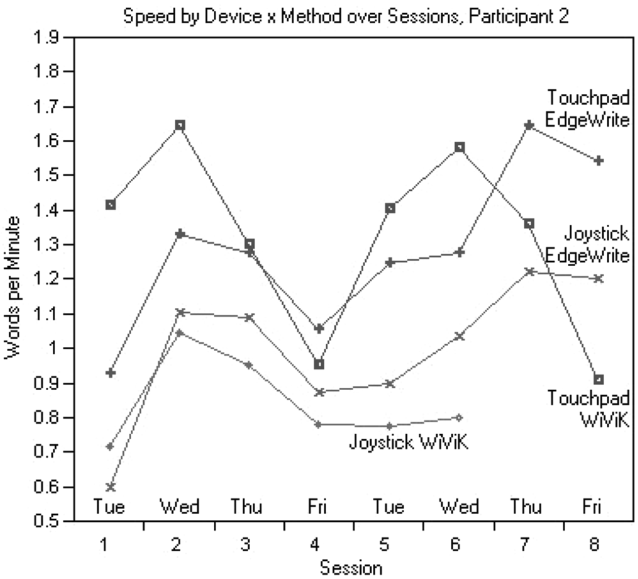

Figure 19. Speed in words per minute over sessions for Participant #2. The participant's speed decreases on Fridays. The performance after a three day weekend was better than the performance on Friday and comparable to that of the previous Thursday, suggesting that the break helped the participant's performance.

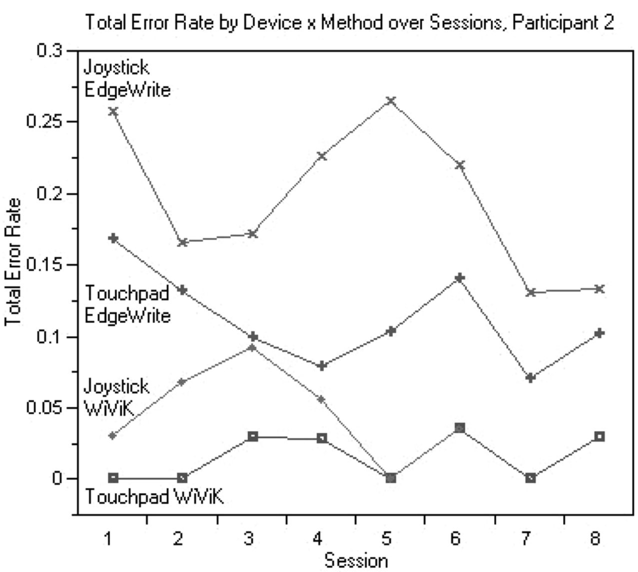

Figure 20. Accuracy as total error rates over sessions for Participant #2. The graph shows improvements for EdgeWrite.

WPM, respectively. Unlike Participant #2, this participant showed a main effect of *method* on speed ($F_{1,72} = 11.46$, $p < 0.002$), being faster with WiViK than EdgeWrite at 1.06 and 0.91 WPM, respectively. She showed no significant *method* $\times$ *device* interaction ($F_{1,72} = 1.80$, n.s.). A contrast test between touchpad WiViK and touchpad EdgeWrite shows no significant difference ($F_{1,72} = 2.08$, n.s.). A similar test between joystick WiViK and joystick

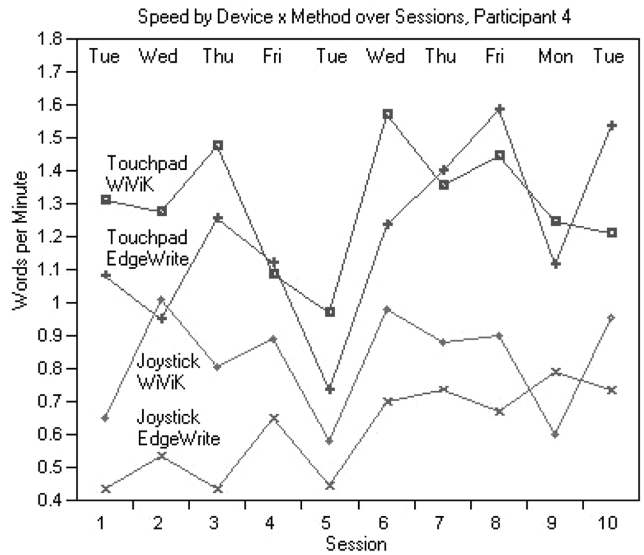

Figure 21. Speed in words per minute over sessions for Participant #4. Notice the overall trend for the two EdgeWrite methods to overtake their respective WiViK methods.

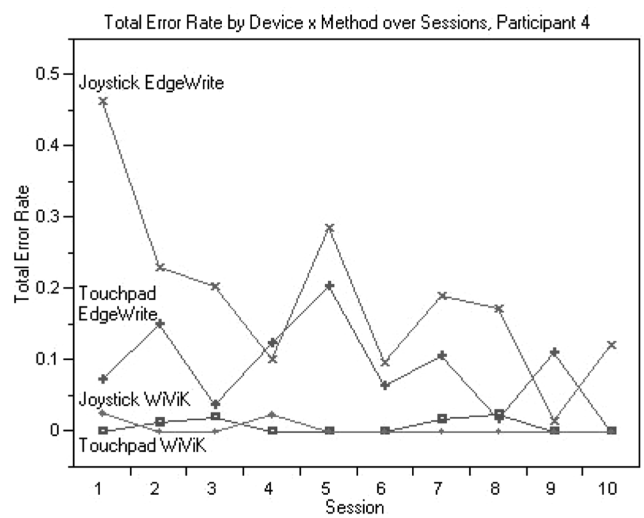

Figure 22. Accuracy as total error rates over sessions for Participant #4. EdgeWrite's accuracy improves dramatically for both the joystick and touchpad versions.

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EdgeWrite is significant ($F_{1,72} = 11.18$, $p < 0.002$) at 0.83 and 0.61 WPM, respectively. An examination of speeds over sessions (figure 21) shows potential crossover points within devices in the last few sessions. For example, touchpad EdgeWrite overtakes touchpad WiViK in sessions 8 and 10, while joystick EdgeWrite briefly overtakes joystick WiViK in session 9. It would be informative to see how the techniques compare past session 10; the upward trends of the EdgeWrite curves suggest they may overtake their flatter WiViK counterparts with more sessions.

Participant #4's EdgeWrite error rates drop dramatically over sessions as seen in figure 22. In fact, by the 10th session, her accuracy with touchpad EdgeWrite is perfect (0.0% errors). This graph is encouraging because it suggests that with enough practice, users can achieve reasonable accuracy.

6.5 *Discussion*

It is customary in studies of human performance and learning to fit a regression curve in the form of the power law of learning (MacKenzie and Zhang 1999, Card *et al.* 1978). Such a curve is of the form $y = bx^c$ and allows us to predict how a participant might perform in future sessions. Fitting such curves is speculative for the current data, however, since we only have 2 participants and only 2 trials per technique per session. Nonetheless, the curves give a sense of how performance may continue past session 10.

The *speed* × *session* regression curves and correlations (r^2) for the 4 *method* × *device* combinations for Participant #2 are shown in figure 23. As figure 19 shows, the data are of highly variable, so obtaining high values for r^2 on such few points is not possible. But the learning curves show clear upward trends for the two EdgeWrite methods. The slightly negative slopes for the WiVik graphs and low r^2 values may be explained as follows: since the participant was already familiar with WiViK from extended prior use, her performance data does not represent initial use. Furthermore, learning an on-screen keyboard is rather trivial, offering little room for improvement. (In fact, the WiViK curves suggest she grew worse, possibly due to fatigue or boredom with the WiViK methods.)

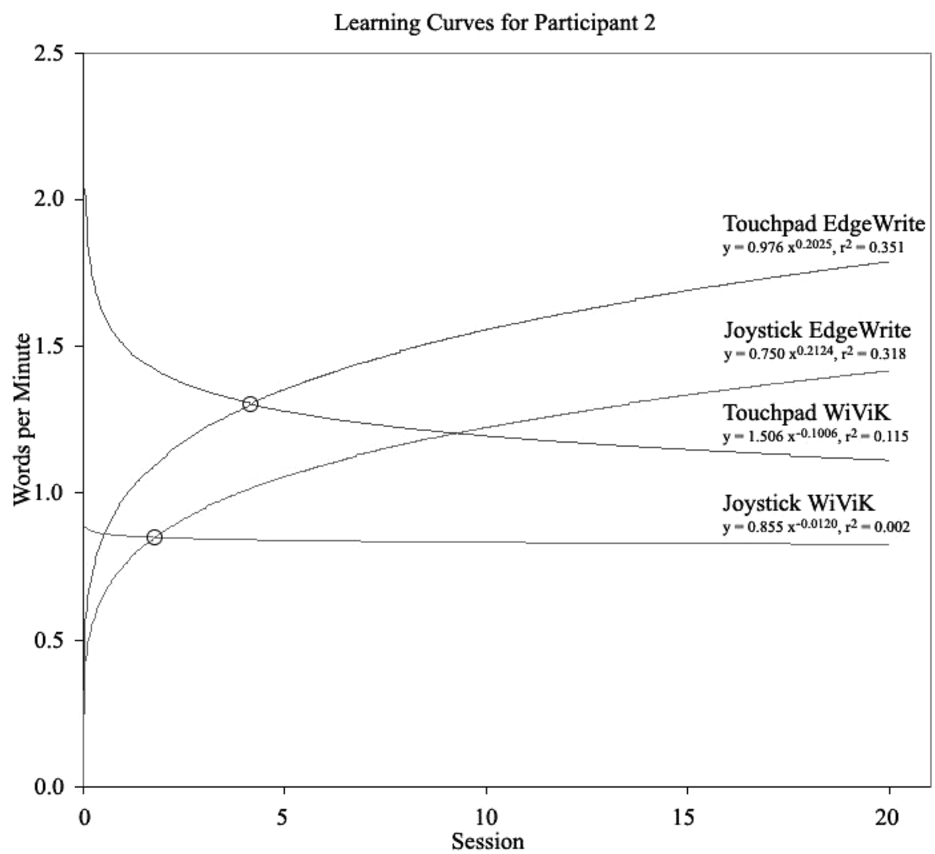

Figure 23. Learning curves for participant #2 show improvement for EdgeWrite but not for WiViK. This is probably because this participant had prior familiarity with WiViK and because selection-based methods require little practice. Circles indicate crossover points for the joystick and touchpad techniques at sessions 2 and 4, respectively.

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Crossover points for the joystick and touchpad techniques occur at around sessions 2 and 4, respectively, with EdgeWrite overtaking WiViK. While these curves are speculative, they do give a sense of the overall trends.

Similar curves for Participant #4 are shown in figure 24. Again we see nearly flat graphs for the WiViK methods, suggesting that very little learning took place. The EdgeWrite techniques overtake their WiViK counterparts by session 7 for the touchpad and session 17 for the joystick. The latter is certainly speculative since it is far out on the curve. As before, the learning models better fit the EdgeWrite data than the WiViK data, judging from the r^2 values.

Overall, the results for speed and accuracy confirm both the challenge of learning a gestural text input method and the potential benefits. The initially poor accuracy of EdgeWrite, particularly the joystick version, is not surprising, and might be mitigated with further design. For example, both participants' own power wheelchair joysticks were longer and had much weaker springs than the one used in the study, requiring less strength and diligence during motion. Optimizing parameters such as these might be one way to improve users' experiences. The general advantage of the touchpad over the joystick points to this device for future inclusion in computer access solutions.

A post-test questionnaire showed similar results for the 2 participants as from the first study (figure 13). Both participants preferred touchpad EdgeWrite overall, followed by touchpad WiViK, joystick EdgeWrite, and joystick WiViK. For both devices, the WiViK methods were considered easier to learn but the EdgeWrite methods were preferred for their perceived speeds.

7. Future work

The success of input systems depends largely on numerous physical and psychological factors (Ehrlich 1997), many of which can still be identified and optimized for the EdgeWrite versions under investigation. The joystick we used for the study had a stronger spring and was shorter than many of the joysticks on our participants' wheelchairs. This meant that more force was required to move it than many

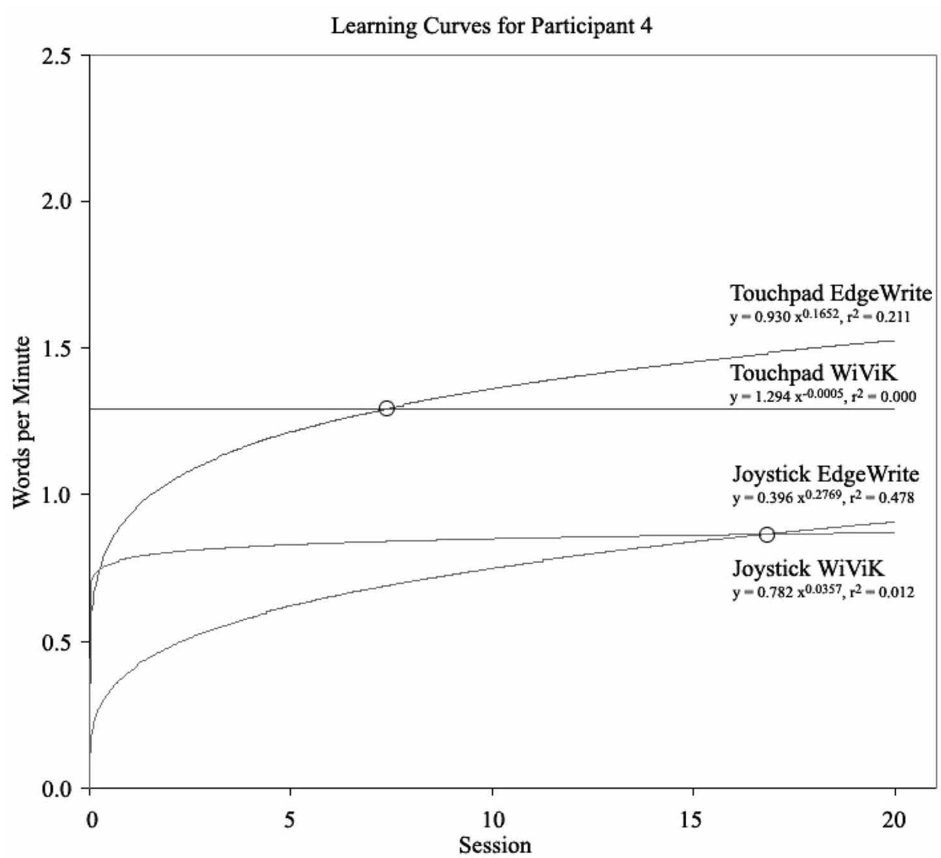

Figure 24. Learning curves for participant #4 show learning occurred with EdgeWrite more than it did with WiViK, probably due to more prior familiarity with WiViK. Circles indicate crossover points for the touchpad and joystick methods at sessions 7 and 17, respectively.

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of our participants were used to applying. Further alphabetic refinements may be warranted as well, since participants often had trouble with diagonals in some letters. Speed may be increased by adding word prediction and completion, preferably not as a secondary point of interaction but as part of the EdgeWrite strokes themselves. Such ''in-stroke'' word completion could enable word-level stroking, rather than just character-level stroking. A similar concept is under investigation for stylus keyboards on a PDA (Zhai and Kristensson 2003).

Once the design is improved, the next step is to integrate mouse control into both devices and provide for switching among mouse, text, and wheelchair control. We can then study the integrated control system in a holistic fashion. For example, we could have participants move between terminals where they would do mouse and text entry tasks. Other design issues arise here, for example, if we have more than one person attempting to control a terminal at a time. Techniques for coordinating multiple interfaces to a single desktop computer have been explored (Myers *et al.* 1998) and could be employed.

8. Conclusion

We described two means of integrating text entry into preexisting controls on power wheelchairs: one using a wheelchair joystick, the other a touchpad. Both devices are small, light, inexpensive, and require minimal configuration, giving them significant practical advantages as integrated control systems over dedicated computer access technologies. We described our design and implementation of EdgeWrite and the participatory role real power wheelchair users played in our development process. We presented results for a multi-session study in which EdgeWrite seemed to overtake WiViK in speed while improving dramatically in accuracy with practice. While these techniques have room for improvement, this work has opened the way for their future refinement, and ultimately, better computer access from power wheelchairs.

Acknowledgments

The authors thank Janis Thoma-Negley and our participants from the UCP of Pittsburgh, Steve Hayashi, John A. Kembel, Ryan S. Baker, Darren Gergle, Rich Simpson, John Springsteen, A.T. Sciences for the joystick, and Elaine Wherry and Synaptics, Inc. for the academic touchpad kit. This work was supported in part by grants from the NEC Foundation of America, General Motors, Microsoft Corporation, and the National Science Foundation under Grant No. UA-0308065. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

References

Anson, D.K., 1997, *Alternative Computer Access* (Philadelphia: F. A. Davis Co.).

Blickenstorfer, C. H., 1995, Graffiti: wow! *Pen Computing Magazine*, January, pp. 30–31.

Buxton, W., Hill, R. and Rowley, P., 1985, Issues and techniques in touch-sensitive tablet input. Proceedings of the ACM Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '85), 22–26 July 1985 (New York: ACM Press), pp. 215–224.

Card, S.K., English, W.K. and Burr, B.J., 1978, Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. *Ergonomics*, **21,** pp. 601–613.

Cook, A.M. and Hussey, S.M., 1995, *Assistive Technologies: Principles and Practice* (St. Louis: Mosby Press).

Co-operwrite, Ltd. myText. http://www.my-text.com/

Ehrlich, K., 1997, A conversation with Ted Selker. *interactions*, **4** (5), pp. 34–47.

Enns, N.R.N. and MacKenzie, I.S., 1998, Touchpad-based remote control devices. Summary for the ACM Conference on Human Factors in Computing Systems (CHI '98), 18–23 April 1998 (New York: ACM Press), pp. 229–230.

Farris, J.S., Jones, K.S. and Anders, B.A., 2001, Acquisition speed with targets on the edge of the screen: An application of Fitts' Law to commonly used web browser controls. Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting (HFES '01), 8–12 October 2001 (Santa Monica, California: Human Factors and Ergonomics Society), pp. 1205–1209.

Fichten, C.S., Barile, M., Asuncion, J.V., and Fossey, M.E., 2000, What government, agencies, and organizations can do to improve access to computers for postsecondary students with disabilities: Recommendations based on Canadian empirical data. *International Journal of Rehabilitation Research*, **23** (3), pp. 191–199.

Goldberg, D. and Richardson, C., 1993, Touch-typing with a stylus. Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '93), 24–29 January 1993 (New York: ACM Press), pp. 80–87.

Guerette, P. and Sumi, E., 1994, Integrating control of multiple assistive devices: A retrospective review. *Assistive Technology*, **6** (1), pp. 67–76.

Hinckley, K., Czerwinski, M. and Sinclair, M., 1998, Interaction and modeling techniques for desktop two-handed input. Proceedings of the ACM Symposium on User Interface Software and Technology (UIST '98), 1–4 November 1998 (New York: ACM Press), pp. 49–58.

Isokoski, P. and Kaki, M., 2002, Comparison of two touchpad-based methods for numeric entry. Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '02), 20–25 April 2002 (New York: ACM Press), pp. 25–32.

Kraus, L.E., Stoddard, S. and Gilmartin, D., 1996, *Chartbook on Disability in the United States* (Washington, D.C.: National Institute on Disability and Rehabilitation Research).

LoPresti, E.F., Romich, B.A., Hill, K.J. and Spaeth, D.M., 2004, Evaluation of mouse emulation using the wheelchair joystick. Proceedings of the 27th Annual Conference of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA '04), 18–22 June 2004 (Washington, D.C.: RESNA Press), electronic proceedings.

Ludolph, F. and Perkins, R., 1998, The Lisa user interface. Summary for the ACM Conference on Human Factors in Computing Systems (CHI '98), 18–23 April 1998 (New York: ACM Press), pp. 18–19.

MacKenzie, I.S. and Oniszczak, A., 1998, A comparison of three selection techniques for touchpads. Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '98), 18–23 April 1998 (New York: ACM Press), pp. 336–343.

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MacKenzie, I.S. and Soukoreff, R.W., 2003, Phrase sets for evaluating text entry techniques. Extended Abstracts of the ACM Conference on Human Factors in Computing Systems (CHI '03), 5 – 10 April 2003 (New York: ACM Press), pp. 754 – 755.

MacKenzie, I.S. and Zhang, S.X., 1999, The design and evaluation of a high-performance soft keyboard. Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '99), 15 – 20 May 1999 (New York: ACM Press), pp. 25 – 31.

Myers, B.A., 2001, Using hand-held devices and PCs together. *Communications of the ACM*, **44** (11), pp. 34 – 41.

Myers, B.A., Stiel, H. and Gargiulo, R., 1998, Collaboration using multiple PDAs connected to a PC. Proceedings of the ACM Conference on Computer Supported Cooperative Work (CSCW '98), 14 – 18 November 1998 (New York: ACM Press), pp. 285 – 294.

Myers, B.A., Wobbrock, J.O., Yang, S., Yeung, B., Nichols, J. and Miller, R., 2002, Using handhelds to help people with motor impairments. Proceedings of the ACM Conference on Assistive Technologies (ASSETS '02), 8 – 10 July 2002 (New York: ACM Press), pp. 89 – 96.

Prentke Romich Company. WiViK On-Screen Keyboard, version 3. http://www.wivik.com/

Rekimoto, J., 2003, ThumbSense: Automatic input mode sensing for touchpad-based interactions. Extended Abstracts of the ACM Conference on Human Factors in Computing Systems (CHI '03), 5 – 10 April 2003 (New York: ACM Press), pp. 852 – 853.

Romich, B.A., LoPresti, E.F., Hill, K.J., Spaeth, D.M., Young, N.A. and Springsteen, J.P., 2002, Mouse emulation using the wheelchair joystick: Preliminary performance comparison using four modes of control. Proceedings of the 25th Annual Conference of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA '02), 27 – 1 June/July 2002 (Washington, D.C.: RESNA Press), pp. 106 – 108.

Shein, F., Hamann, G., Brownlow, N., Treviranus, J., Milner, M. and Parnes, P., 1991, WiViK: A Visual Keyboard for Windows 3.0. Proceedings of the 14th Annual Conference of the Rehabilitation Engineering and Assistive Technology Society of North America (RESNA '91), 21 – 26 June 1991 (Washington, D.C.: RESNA Press), pp. 160 – 162.

Soukoreff, R.W. and MacKenzie, I.S., 2003, Metrics for text entry research: An evaluation of MSD and KSPC, and a new unified error metric. Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '03), 5 – 10 April 2003 (New York: ACM Press), pp. 113 – 120.

Spaeth, D.M., Jones, D.K. and Cooper, R.A., 1998, Universal control interface for people with disabilities. *Saudi Journal of Disability Rehabilitation*, **4** (3), pp. 207 – 214.

Switch-It, Inc. Mouse driver. http://www.switchit-inc.com/pages/MouseControls.html

Switch-It, Inc. Touch drive. http://www.switchit-inc.com/pages/TouchDrive.html

Wobbrock, J.O., 2003, The benefits of physical edges in gesture-making: Empirical support for an edge-based unistroke alphabet. Extended Abstracts of the ACM Conference on Human Factors in Computing Systems (CHI '03), 5 – 10 April 2003 (New York: ACM Press), pp. 942 – 943.

Wobbrock, J.O., Myers, B.A. and Aung, H.H., 2004, Writing with a joystick: A comparison of date stamp, selection keyboard, and EdgeWrite. Proceedings of Graphics Interface 2004 (GI '04), 17 – 19 May 2004 (Waterloo, Ontario: Canadian Human–Computer Communications Society), pp. 1 – 8.

Wobbrock, J.O., Myers, B.A. and Hudson, S.E., 2003a, Exploring edge-based input techniques for handheld text entry. Third International Workshop on Smart Appliances and Wearable Computing (IWSAWC '03). In Proceedings of the 23rd IEEE Conference on Distributed Computing Systems Workshops (ICDCSW '03), 19 – 22 May 2003 (Los Alamitos, California: IEEE Computer Society), pp. 280 – 282.

Wobbrock, J.O., Myers, B.A. and Kembel, J.A., 2003b, EdgeWrite: A stylus-based text entry method designed for high accuracy and stability of motion. Proceedings of the ACM Symposium on User Interface Software and Technology (UIST '03), 2 – 5 November 2003 (New York: ACM Press), pp. 61 – 70.

Zhai, S. and Kristensson, P., 2003, Shorthand writing on stylus keyboard. Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI '03), 5 – 10 April 2003 (New York: ACM Press), pp. 97 – 104.