Four-Key Text Entry for Physically Challenged People

Tatiana Evreinova, Grigori Evreinov, Roope Raisamo

TAUCHI Computer-Human Interaction Unit
Department of Computer Sciences
FIN-33014 University of Tampere, Finland
+358 3 215 8569
{e_tg, grse, rr}@cs.uta.fi

Abstract. For physically challenged people, learning of typing skills is essential, especially for those who are undertaking courses of study. Current user interfaces are well designed to assist an ordinary user in producing fast output and allowing customization, but can be complicated for an impaired user. The challenge is to find an efficient textual input technique making use of a small number of fingers, keys and minimal resources of the residual visual acuity. Researchers have experimented with alternative methods allowing text entry with less than four keystrokes per character using three keys. Nevertheless, the proposed strategies require strong visual and cognitive support. In this paper we describe a four-key text entry technique with three keystrokes per character. A finger memory provides complementary help and follows the style of the interaction in a natural way. We have applied the symmetric hierarchical structure with 3 levels and 4-2-4 alternatives, as the basic layout for symbol input and imaging. This method resulted in entry rate of 15 wpm. The experimental results showed that the proposed approach significantly decreases cognitive load and facilitates navigation through continuous sequence of automatic actions.

1. INTRODUCTION

People with special needs are diminished in the ability to use standard consumer products and to gain an access to information sources efficiently. According to recent statistics, prevalence of all attributes covered by manual dexterity, i.e., sleight and steadiness of hand, quickness of wrists and manual coordination, as well as diabetic retinopathy, significantly hinder computer access for the nearly eight millions of Americans [Murphy 97], [Statistics about disabled individuals]. For physically challenged people, learning of keyboard skills is essential, especially for blind and partially sighted persons who are undertaking courses of study. By virtue of ubiquitous computing, print-handicapped people with ocular pathology use alternative means for imaging textual information that rely on residual senses. In order to be useful, the conventional input-output devices should be adaptive and satisfy to specific requirements [Edwards 95]. Computer access for the physically challenged users is often hindered by the standard 101/104-key Windows keyboard, the layout of which was primarily designed for ten-finger manipulation. At the same time, the accessibility options used in Microsoft Windows system support even single-switch text entry through scanning mode and onscreen keyboard. The highlighted areas can be chosen through multiple automatic steps with reasonable typing speed provided by individually adjusted scan interval. Hence, the current user interfaces are well designed to assist an ordinary user and some part of people with special needs in producing output and allowing customization, and it can in fact be inaccessible to another user as well.

To provide productivity and easy access during communication with computer it is necessary to have a balance between flexibility of dialogue structure to make a selection, adaptability on each level of the interface, and cognitive abilities of the person. In particular, to prevent a wrong selection of the way of presenting spatial-temporal structure of the interface, mental and motor activities of the user should be strictly coordinated altogether.

There are alternative keyboards that prevent accidental key pressing for physically challenged people with ocular pathology. One-hand text entry techniques have been designed to use one, three or four fingers sequentially or in a chord. The number of keys is also varied from 3 keys up to more the 26 keys with alternative keyboards that can be programmed or customized to provide special functions. The physically challenged users still have problems when they re-learn to manipulate new computer applications, while, being healthy person, they already had typing skills with QWERTY layout but cannot use it further [Evreinova 2003 a, b]. Due to this reason, Chicago Logic returned 26 keys on cell phones with Delta II layout (slightly modified QWERTY) for single-hand operation [Keypad matrix Delta II]. The authors of almost every new system for text entry claim that his or her system is significantly faster and less stressful to use than a previous system, and lets the user write very quickly. However, a novice with limited capabilities should perform intensive work to get used to the new techniques. Nobody can guarantee that training and time will not be wasted due to individual unavailability of the technique and the user herself should make the final decision. However, an access to diverse solutions should widely be discussed and be opened for all.

Many disabled individuals use a standard keyboard but may be under the constraint of typing with one hand using only three fingers with poor manual dexterity. Reduced strength of hands and restricted movements make it difficult or impossible to use the whole keyboard area. In intensive work, a large number of switches can lead to fatigue, as there is nowhere to rest the hand during pauses. The chord keyboard requires one, two or more keystrokes per character. Unlike the multi-tap technique, when all characters have to be selected by sequentially pressing down a key, the chord requires some number of keys that need to be activated simultaneously [Matias 96]. Typing chord key combinations by one hand often leads to numbness, tingling, or loss of feeling in the pinky: carpal tunnel syndrome or ulnar neuropathy [Statistics about disabled individuals].

Instead of reducing the number of keystrokes required per typed word when a halved keyboard is used, Kushler proposed an ambiguous keyboard with multiple letter-key assignments. During the typing process, a user presses the key corresponding to the letter only once so that the ambiguous keyboard requires one keystroke per character. Kushler outlined the advantages of the ambiguous keyboard with word disambiguation, that is, users who cannot operate a full keyboard might still be able to select directly one of the fewer keys [Harbush 2003]. Apart from literacy, no memorizing of special encoding is required [Sandnes 2003]. However, insufficient electronic lexicon can aggravate the use of both strategies: prediction and disambiguation. If a word is not known to the system, the user of an ambiguous keyboard has to leave the typing mode in order to enter the word by other means [Harbush 2003].

Trying to overcome this drawback, Harbush [Harbush 2003] proposed novel communication aid for physically challenged people called as UKO-II method. This technique was adopted in two ways. First, the system is customizable to differing keyboard layouts and to the selection of word suggestions or additional editing commands. Second, a layered structure of language models controls a disambiguation process and adapts to the text input of the user. However, this technique increases cognitive load imposed on users while typing the word, so they may be unable to see the letters of the word already typed and have to memorize the input position [Harbush 2003].

Both imperfection and lack of adaptability of the prediction systems and optimizing algorithms require that the user should permanently watch the prediction list and make selections from it. As mentioned by Zagler, by such a way "the user spends the time – sometimes to a greater extent than s/he has gained by the prediction itself" [Zagler 2002].

MacKenzie [MacKenzie 2002 b] studied a 3-key mobile text entry technique called as Date Stamp. This method assumes that left and right arrow keys maneuver a cursor over a linear sequence of letters and a Select key enters the letter. He found that such a text entry method on average requires 10.66 keystrokes per character (KSPC) for normal English text. By making minor optimizations the number of keystrokes per character can be reduced by as much as 6.45 KSPC. The Date Stamp technique is suitable for casual use only because it also requires high concentration from the user navigating a constantly changing wheel-of-letter. Attempts for improving this technique have resulted in requiring only 4.23 keystrokes per character.

Table 1 shows text entry performance comparison for the techniques discussed above. The problem is in the necessity to provide anyone who has limited finger dexterity and cannot see well with an efficient textual input method using the small number of fingers, keys and blind-manipulation as the basic technique. Thus, our work was devoted to development of the text entry technique based on a simple hierarchical structure, the finger memory and kinesthetic feedback. The method was also designed adhering to the principle to escape lateral movements and use two or three fingers and four keys only. We supposed that the solution could accelerate teaching physically challenged persons including the contingent with ocular pathology to type.

Table 1. The performance comparison of keyed text entry techniques.

Text entry technique	Keys number	Number of fingers used	KSPC	Keystrokes per alphabet
QWERTY	26 + space	10	1	27
Braille.6 [BRAILLEX®]	6 + space	7	2.524	85
Twiddler chord Keyboard [Twiddler keyboard]	12	5	1.503	45
UKO-II [Harbush 2003]	4	4	1.007	29
4-key UDRL	4	2-3	3	84
Date Stamp, [MacKenzie 2002]	3	3	10.66 – 4.23	288 –115

Note, that the goal of this work was only to explore design and interaction issues for new text entry technique without linking these to the specific form factor so it is by no means suggested as the preferred choice of text entry method.

2. METHOD DESIGN

A usability study was undertaken to evaluate the novel text entry UDLR technique when using four keys (Up, Down, Left, Right) on the 101-key Windows keyboard manipulated by three fingers (forefinger, middle and fourth finger). The goal of our research was to explore the efficiency of typing performance and the learning trend over whole experiment.

2.1. Participants

Eight volunteers (five males and three females) from staff and students at the University of Tampere were involved in the testing. All participants were right-handed. The age of the subjects ranged from 22 to 50 years with a mean age of 32. All used computers on a daily basis, reporting 7 to 12 hours of usage per day. The average computing experience of all participants was 4.2 years. All had low visual acuity and wore prescription glasses.

2.2. Apparatus

The experimental software was designed in Microsoft Visual Basic 6.0 under Windows 2000. The task implemented in the software was the retyping of the presented and memorized test word. As shown in diverse studies, such an approach simulates a *text creation task* in that the user knows exactly what to enter. This is in contrast to a *text copy task* wherein the focus of user attention is continually switched between the source text and the keyboard [MacKenzie 2002 a], [MacKenzie 99 a, b]. The test word was displayed on the first line and user input was on the second line (Figure 1). The prompter frame was placed in the lower right field of the testing program and intended to visualize the current level and alternatives of hierarchical structure (label-indicator) to choose the necessary character; four labels indicated the key states to facilitate input. When the key on the keyboard was pressed down, the corresponding label changed its color. Novice performance was measured in order to see how intuitive this method was. In addition to calculating the mean of typing speed, execution time of the exercise, and error rates, the software recorded clicks per word, the time needed to enter the whole word and each character. The tested and entered characters were both recorded. We also did not admit typing wrong characters; certainly, this influences in data dispersion, but allows detecting other problems dealing with layout. The testing was performed using four arrow keys (Up, Down, Left, Right) on the 101-key Windows keyboard (Figure 2). Finger manipulations of the user with using the UDLR method are shown in the Figure 3.

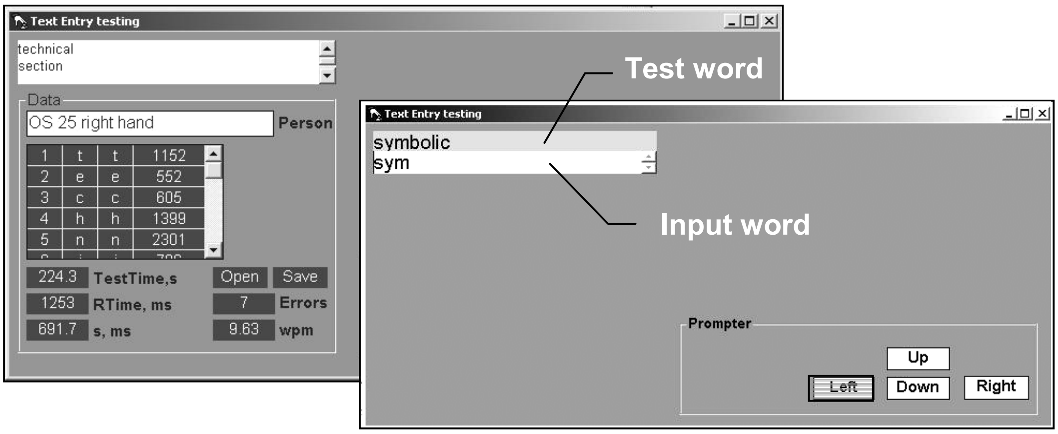

Figure 1. Screenshot of the UDLR text entry technique

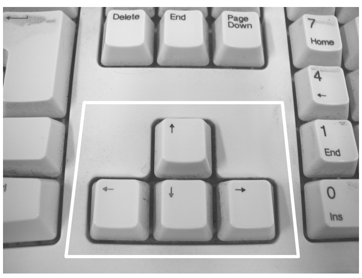

Figure 2. Key layout used on the 101-key Windows keyboard marked by thick white line

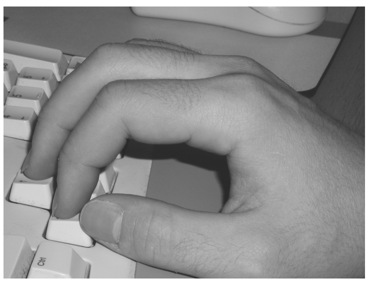

Figure 3. Finger manipulations with using the UDLR method

2.3. Character Selection

We have applied the symmetric hierarchical structure with 3 levels and 4-2-4 alternatives, as the basic layout for symbol input and imaging. Four functional groups (I-IV) were used to combine three keys per each alphabet character and two keys for additional operations such as editing (Space, Backspace and Next Line) to involve two or three fingers when typing these combinations (see Table 2). That is, the length of path from start position to character key-node is constant, three keystrokes, and typing speed depends on the individual fingers mobility.

Table 2. The UDLR technique

Left (I)		**Right (II)**		**Up (III)**		**Down (IV)**	1 selection order 2 3
Up	**Down**	**Up**	**Down**	**Left**	**Right**	**Left**	
A	E	I	M	Q	U	Y	**Left (3)**
B	F	J	N	R	V	Z	**Right (3)**
C	G	K	O	S	W		**Up (3)**
D	H	L	P	T	X		**Down (3)**

1 2 3 – the selection order of the keys (in the upper right cell)

Below, the samples of a character selection through a sequential input with UDRL method are presented:

A	left – up - left	**S**	up – left – up
J	right – up - right	**Z**	down – left – right

Space	up – down
Backspace	right – left
Next Line	left – right

Numerous variations of the UDLR method are possible, such as combinatory variation of functional groups with three key arrangements according the most frequently used characters and the limited joint mobility of the fingers.

2.4. Procedure

The experimental evaluation took place in a usability laboratory. The entire testing took seven days. During the test session, the task of test person was to listen to a wave file of the test word or look at the test word, memorize it, and type the words which were provided by the software. One test session consisted of five blocks. Each block had twenty words appearing in a random order from a sample set of 150 words. Each subject completed 7 sessions, with no more than one session per day.

The test words were 6 – 13 characters in length with the mean of 8.5 characters, and every letter of the alphabet was included, at least several times during the block. Words were not repeated within blocks but repetitions were allowed from block to block. The correlation of relative frequency of the characters used during the test with English letter frequencies was about 0.91.

Before the test, subjects were given fifteen minutes to familiarize themselves with text entry method. Subjects were handed out a paper of the coded combinations for creating characters as practice guidance for using this technique. The subjects were told the logic of the method and advised to memorize the coded combinations. The subjects were allowed to use a paper with listed key combinations during the two days of testing to facilitate understanding the character selection sequence with the help of four keys. After a two-day practice, the paper was taken away when the test started. The subjects were instructed to aim at both speed and accuracy when entering words. They were also told to avoid long pauses of thought. If they were unsure of a given letter, they should guess and continue typing. Subjects could rest as they desired between trials. When they selected the right character, there was a short clicking sound indicating that the subject could move to the next symbol. When a wrong character was entered, corresponding sound (earcon) was heard to indicate the subject should try again.

Difficulties in error tabulation have pushed some researchers to ignore errors altogether [Lewis, 99], or to force the subject to enter correct text only [Venolia 94]. That is why we did not use “Backspace” to delete a character but the subject had to try until s/he got the right character, while the selection time was restricted to 10 s. Every missed or wrong symbol was counted as an error.

We aimed at practicing participants toward expert performance. Therefore, to motivate the subjects, the results of each user's performance were displayed at the end of each block. Performance expectations were not explained, however. Instead, participants were constantly reminded to do their best on the tested system.

3. RESULTS

Our research was focused on the measurement of a lower bound of the text entry speed, which was recorded at the beginning of learning the UDLR technique, and an upper bound, which was recorded in the end of each experimental session.

3.1. Text entry speed

The average performance and standard deviation of the text entry for 8 participants through 35 blocks are shown in Figure 4. Text entry speed was converted to “words per minute” by using of the typists’ definition of a word – five characters including spaces.

The results for entry speed seemed low and somewhat disappointing at the beginning of the testing. The typing speed with using the UDLR method faired poorly initially (4.53 wpm). We have considered several reasons for the low entry rates. First, our tested words included different letters of the alphabet. Second, this is good because it ensures of the subjects to exploit all coded combinations during the task. The appearance of different letters can essentially aggravate the learning progress in typing performance. That is, text entry speed failed to yield a significantly higher throughput during about of four sessions.

Significant increase in text entry speed was observed only after the 5th session or after selection about 4250 characters. This happened after four hours of practice. The performance continued to improve at the 7th session (about 5950 characters were entered). It is likely due to the subjects getting accustomed to the typing method and, which is a more important, fingers’ motor memory was activated to provide a complementary help in selecting of the key sequences. The average text entry rate reached about 15 wpm during 7th session.

By comparison, MacKenzie [MacKenzie 2002 a] reported text entry rates of 10-11 wpm for two pager-style five-key techniques, but these were achieved on the tenth session of testing. Rates were only 5 – 6 wpm on the first session with a strong visual feedback. Similarly, MacKenzie et al. [MacKenzie 99 a, b] tested two text entry techniques for mobile phones and measured rates of 15 – 20 wpm after 20 sessions of practice. However, on the first session, the rates were just over 7 wpm. MacKenzie and Zhang [MacKenzie 99 b] measured three-key text entry rates in mobile systems. The overall results for text entry speed seemed to be quite low, just in the range of 9.1 – 9.61 wpm. However, another Mackenzie's experience related to the testing of one-handed touch-typing on a QWERTY keyboard [Matias 96] had shown that subjects were able to adapt to Half-QWERTY typing very quickly. The first session already resulted in the average speed of 13.2 wpm, with over 84% accuracy. Considering the above examples in the research literature, the results in Figure 4 seem quite reasonable.

The full data analysis overall the test blocks showed that the lower average value of text entry speed was 4.42 wpm, $s < 0.75$, and an upper bound for the text entry speed was 14.82 wpm, $s < 0.52$.

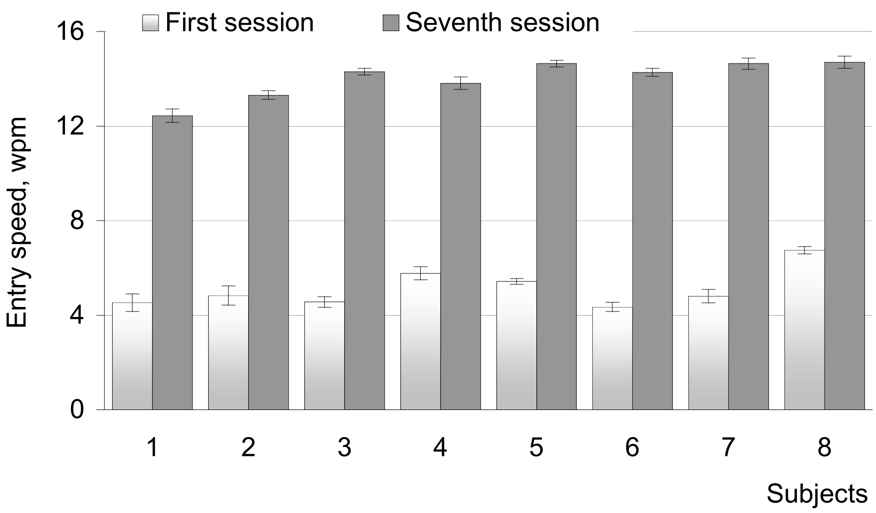

Figure 4. The average performance and standard deviation of the text entry speed without training (1st session) and in the end of testing (7th session)

3.2. Error rate

To investigate our results further, we constructed confusion matrix with rows identifying test characters and columns identifying input characters. The matrix in Figure 6 shows which of the input characters (along the X-axis) were misrecognized and entered as another character (along the Y-axis). The cells which have a gray color represent this occurrence.

Figure 5 demonstrates that the most frequent misrecognition pairs were caused by the inversion of the key sequences which test letters had included in relation to each other. For instance, the letter "b" was frequently misrecognized as "i", because of the letter "b" had to be typed starting from pressing the Left key following by the Up and Right keys while the letter "i" had to be typed in the inverted sequence in the relation to the letter "b". The typing was started from pressing the Right key following by Up and Left keys. The same situation was observed with the letters "f" and "m", "u" and "i", "y" and "h". It is possible that a small modification in the coding of alphabet characters could improve the overall performance. Although it is not obvious, it would bring benefits for other symbols, as a modification might break the logic of the method.

Another misrecognition set was caused by the user mistakes. Some of the subjects reported that it was very hard for them to memorize such letters as "q", "u", "y" and "z" (see Table 2). Since these characters are the least used in English language and only in about 10% in the test words, the subjects had fewer possibilities to experiment with these characters (see also Figure 8). Thus, they could not benefit from accumulating experience. When the subjects forgot how to type these letters, they started to recollect the logic of the method and often entered characters incorrectly.

The results from Figure 6 are also present in the results from Figure 5. The characters that had a mirror copy of finger movements to code another character showed fairly high misrecognition rates (5 % for the letter “f” and 10% for the letter “n”). Errors may also have occurred because text entry speed increased over the sessions. Besides that, the subjects might miss typed combinations and add an extra character or tangle neighboring keys.

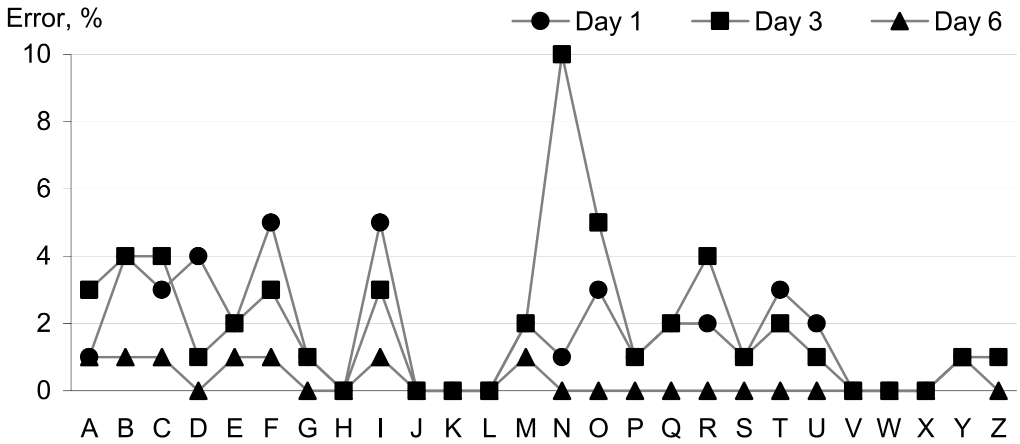

Figure 5. Substitution errors of test characters by another ones.

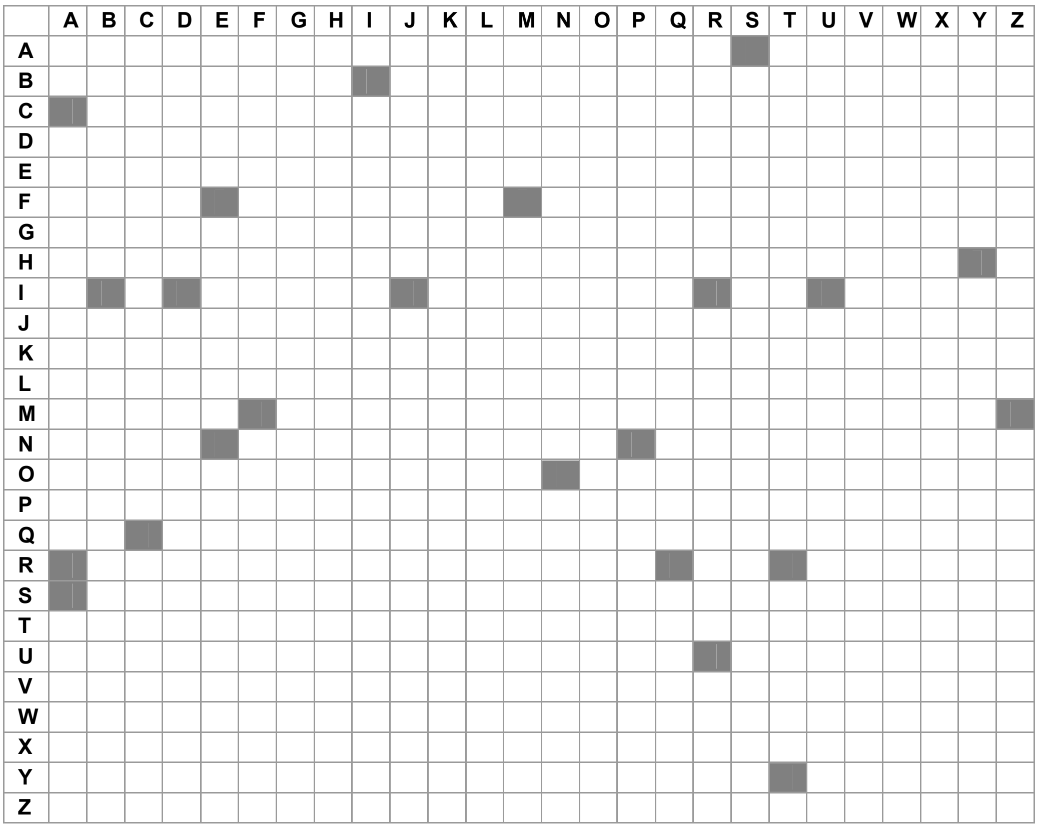

Figure 6. Confusion matrix for the four key input data set.
The test character is shown along X-axis (the top row).
The entered character is shown along Y-axis (the left column).

3.3. Dynamics of the typing training

Figure 7 shows the completion time of the test blocks decreased from 480 s, in the beginning, to 156 s in the end of testing, due to acquiring the experience with new technique. Obtained experimental results indicated that the subjects could gain familiarity with the UDLR technique fast enough.

The subjects indicated that typing throughput could be significantly improved if more sufficient practice was given. The high error rate during the first and second experimental session was probably related to the deficient knowledge of the alphabet characters coding, and motor memory still was not activated to provide a complementary help in selecting key sequences.

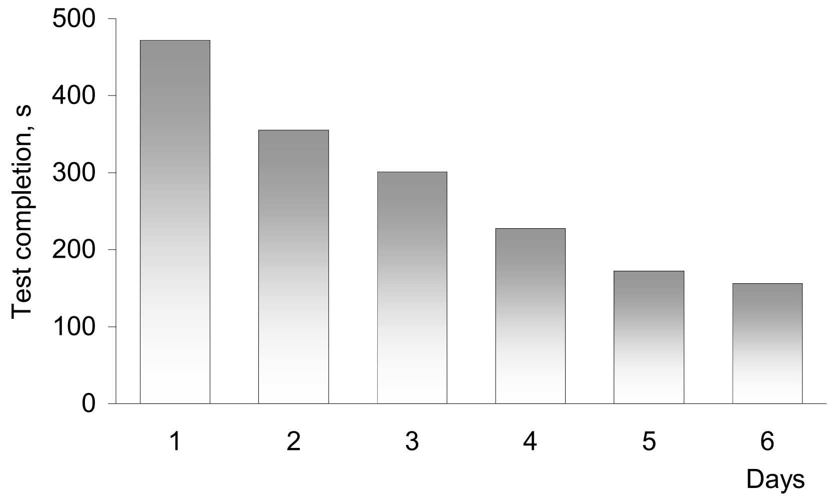

Figure 7. The total test completion time for the experimental sessions

3.4. Average reply time per character

There is no clear definition for the term "complexity" in motor control. Not only factors such as speed and accuracy, the involvement of different joints and muscles, different modes of movement preparation or movement selection, and the degree of experienced practice can make a movement more or less "complex". It is obvious that even a linear simple keystroke sequences of "index-middle-ring fingers" and "ring-middle-index fingers" will be differed in respect to their individual performance complexity. Meanwhile, the complexity of motor sequences might be reflected by different acquisition times (defined as the actual practice times necessary to reach the required performance level), as reported in detail [Gerloff 1997; Karni 1995].

We examined the average reply times per each test character within each test block. The pattern of results (Figure 8) follows our observations of the participants' behavior from the section 3.2. If the motor sequences were composed by a "natural" way and their performance was convenient for the subject, a lower time per character was required and participants easily memorized such motor patterns. The reply time for simple test sequences seemed to be lower (about 1500 ms) than for the hardest ones (about 3500 ms).

Since software keyboards lack kinesthetic and tactile feedback, on-going visual feedback is required, even for experts. That is, the reply time has to be always greater before the novice-to-expert process will happen. The logic of the UDLR method assumes that the visual scan time for text entry sets to zero. Nevertheless, in our case the reply time was lowered up to 1000 ms per character only at the end of the testing. This fact means that a typing in a great extent depends on motor skills rather than follows to the logic of the method.

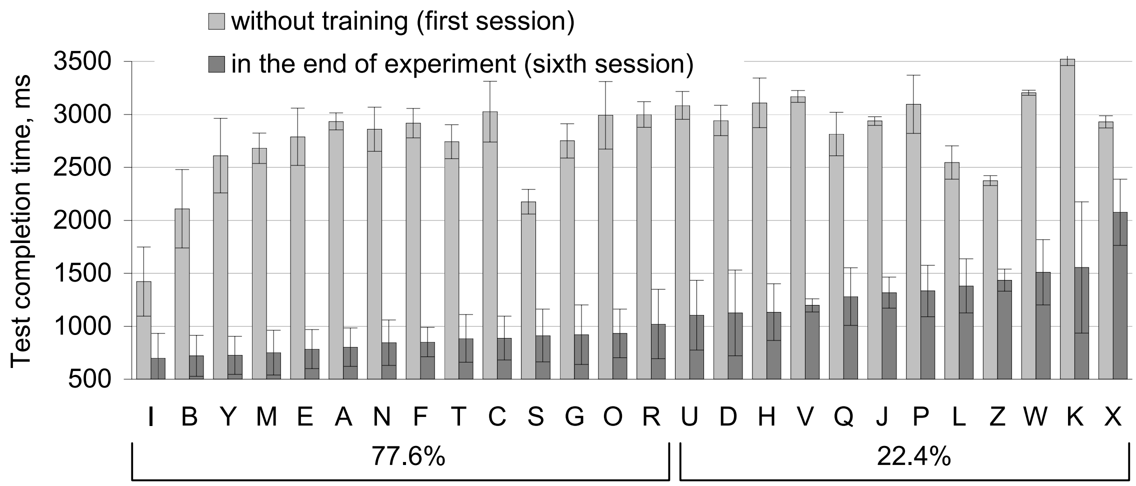

Figure 8. Average times (and standard deviation) needed to choose any character within one test block.

3.5. Preferences

The subjects were asked to rate the UDLR method and their impressions about perceived performance. The five statements and responses of the subjects are shown in Figure 9. When the subjects had an insufficient knowledge of the UDLR method logic in the beginning of the experiment, five participants found this method very frustrating and three participants found it moderately frustrating. Some participants felt that the typing still required more concentration during the third session. One participant noticed that changing the behavioral stereotype previously shaped by sequential typing on the QWERTY layout might cause the high cost of mistakes with the given method. Another participant expressed extreme frustration with the logic of the method, feeling that the method was trying “to put you out by shuffling the keys” after each letter entry.

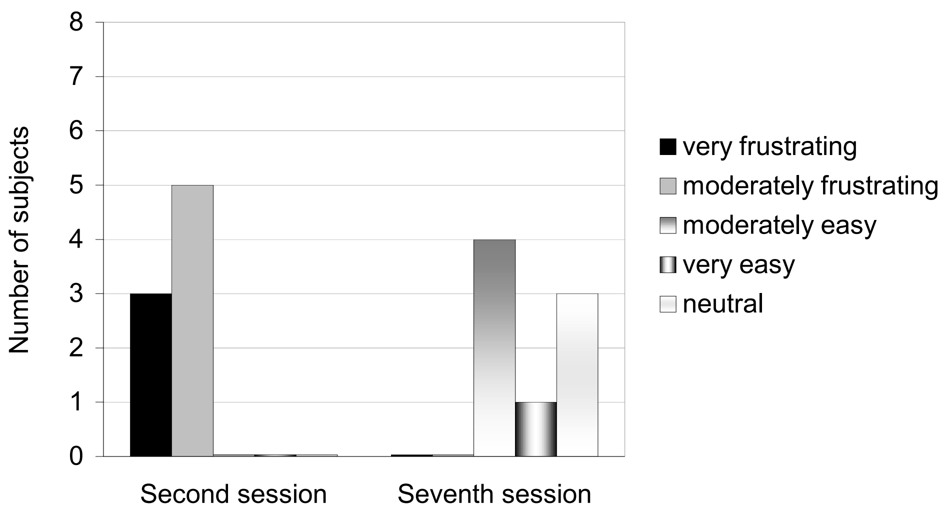

Figure 9. Post-test questionnaire results

However, by the end of the test, four of the eight subjects indicated they would use such a method as freely as typing on a QWERTY keyboard. The other three demonstrated neutral reaction to the proposed method. One subject indicated that typing was just easy and felt that his typing was almost like expert performance with the UDLR method.

CONCLUSION

The majority of physically challenged people use a standard keyboard but may be under the constraint of typing with poor manual dexterity. In this paper, we described a four-key text entry technique with three keystrokes per character. A finger memory provides complementary help and follows the style of the interaction in a natural way. The method requires the use of a small number of fingers, keys and minimum resources of the residual visual acuity.

The technique uses the Left, Right, Up and Down arrow keys on the 101-key Windows keyboard. We have applied the symmetric hierarchical structure with 3 levels and 4-2-4 alternatives, as basic layout for symbol input and imaging. Four functional groups were used to combine three keys per each alphabet character and two keys for additional operations such as editing (Space, Backspace and Next Line) to involve two or three fingers when typing these combinations.

The full data analysis of the typing learning with the UDLR method overall the test blocks showed that the lower average value of text entry throughputs was 4.42 wpm, $s < 0.75$ and an upper bound for the text entry speed was 14.82 wpm, $s < 0.52$ respectively. Obtained results indicated that the subjects could gain familiarity with the UDLR method fast. Subjects indicated that typing throughput using this text entry system could significantly be improved if more sufficient practice were given. The high error rate during the first and second experimental session was probably related to the insufficient practice and a complexity of motor sequences that were reflected by different acquisition times per character.

The experimental results showed that proposed approach significantly decreases cognitive loading and facilitates navigation through continuous sequence of automatic actions. The proposed technique could be useful for developing wearable assistive devices and educational applications for blind and partially sighted typists having restricted manual dexterity.

ACKNOWLEDGMENTS

The research reported here was conducted at the Usability Laboratory of the Tampere Unit for Computer-Human Interaction (TAUCHI) at the Department of Computer Sciences in the University of Tampere. We wish to thank every volunteer test subject at TAUCHI for making our testing possible. Our gratitude is also extended to the students of the University of Tampere for participating in the experiment. We gratefully acknowledge the financial support of the Graduate School in User-Centered Information Technology (UCIT), and Academy of Finland (grant 200761).

REFERENCES

[BRAILLEX®] *BRAILLEX® EL Braille Assistant*, available at: http://www.sighted.com/

[Edwards 95] A. Edwards, *Extra-Ordinary Human-Computer Interaction: Interfaces for Users with Disabilities*, Cambridge University Press, 1995.

[Evreinova 2003, a] T. Evreinova, G. Evreinov. The text input training system through touch screen and color blinking imaging for people with low vision, in *the 1st Nordic Symposium on Multimodal Communication*, Copenhagen, Denmark, 25-26 September 2003, pp 169-182.

[Evreinova 2003, b] T. Evreinova, G. Evreinov, R. Raisamo, The text entry self-training system with color blinking imaging, in *AAATE 2003*, Dublin, IOS Press, Netherlands, 2003, pp 989-993.

[Gerloff 1997] C. Gerloff, B. Corwell, R. Chen, M. Hallett, L.G. Cohen, Stimulation over the human supplementary motor area interferes with the organization of the future elements in complex motor sequences. *Brain*, 120, 1997, pp 1587-1602.

[Harbush 2003] K. Harbush, M. Kuhn, Toward an Adaptive Communication Aid with Text Input for Ambiguous Keyboards, in EACL'03, Demo Sessions, Budapest, pp 4.

[Karni 1995] A. Karni, G. Meyer, P. Jezzard, M.M. Adams, R. Turner, L.G., Ungerleider, Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature*, 377, 1995, pp 155-158.

[Keypad matrix Delta II] Keypad matrix Delta II. Available at: http://www.chicagologic.com/

[Lewis 99] J. R. Lewis, P. J. Kennedy, M. J. Lalomia, Development of a diagram-based typing key layout for single-finger/stylus input, in *the Human Factors and Ergonomics Society 43rd Annual Meeting*, (Santa Monica, CA: HFES), 1999, pp 415-419.

[MacKenzie 99, a] I. S. MacKenzie, S. X. Zhang, The design and evaluation of a high-performance soft keyboard, in *the ACM Conference on Human Factors in Computing Systems - CHI*, New York, ACM Press, 1999, pp 25-31.

[MacKenzie 99, b] I. S. MacKenzie, S. X. Zhang, R. W. Soukoreff, Text entry using soft keyboards. *Behaviour & Information Technology*, 18, 1999, pp 235-244.

[MacKenzie 2002, a] I. S. MacKenzie, KSPC (keystrokes per character) as a characteristic of text entry techniques, in *the Fourth International Symposium on Human Computer Interaction with Mobile Devices*, Heidelberg, Germany: Springer-Verlag, 2002, pp 195-210.

[MacKenzie 2002, b] I.S. MacKenzie, Mobile Text Entry using Three Keys, in *NordiCHI 2002*, ACM Press, 2002, pp 27-34.

[Matias 96] E. Matias, I. S. MacKenzie, W. Buxton, One-handed typing with a QWERTY keyboard. *Human-Computer Interaction*, 11, 1996, pp 1-27.

[Murphy 97] C. Murphy, Computers Assisting the Handicapped, 1997. Available at: http://courses.cs.njit.edu/~cs3604/lib/Disabilities/murhpy.AT.html

[Sandnes 2003] F. E. Sandnes, H. W. Torkildssen, A. Arvei, J. O. Buverud, Fast text-entry on miniature mobile devices, in *the Nordic Information Conference (NIC),* Oslo, 2003, pp 12.

[Statistics about disabled individuals] Statistics about disabled individuals. Available at: http://www.breaktheglassceiling.com/

[Twiddler keyboard] Twiddler chord keyboard. Available at: http://www.handykey.com/

[Venolia 94] D. Venolia, F. Neiberg, T-Cube: A fast, self-disclosing pen-based alphabet, in CHI '94, ACM Press, 1994, pp 265-270.

[Zagler 2002] W.I. Zagler, Matching Typing Persons and Intelligent Interfaces, in *ICCHP 2002*, LNCS Vol. 2398, Springer-Verlag Berlin Heidelberg, 2002, pp 241-242.