Displays 56 (2019) 38–48

Contents lists available at ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Exploring touch feedback display of virtual keyboards for reduced eye movements[☆]

Huhn Kim[a], Seungyoun Yi[b], So-Yeon Yoon[c,*]

[a] Department of Mechanical System Design Engineering, Seoul National University of Science and Technology, Seoul, Republic of Korea
[b] Naver Corporation, Republic of Korea
[c] Department of Design and Environmental Analysis, College of Human Ecology, Cornell University, NY, USA

ARTICLE INFO

Keywords:
Text input display
Touch-screen keyboard
Virtual keyboard
Mobile application interface
Eye-tracking
Virtual touch feedback

ABSTRACT

When typing on smartphones or palm tablets, users generally make an effort to type correctly while simultaneously checking the small keyboard and the text display. Unlike physical keyboards that allow users to perform typing based on long-term muscle memory, virtual keyboards typically require more frequent eye movements between the keyboard and the text display areas.

This study proposes a new way of designing a virtual keyboard display to reduce the effort associated with frequent eye-movements. For this study, we developed virtual keyboard display systems featuring both static and dynamic word-by-word (WBW) feedback displays. The two display systems were examined in comparison with a more conventional method known as character-by-character (CBC) feedback display. We investigated user satisfaction, typing performance and the user's eye gaze shifts. Eye gaze shifts were measured between the keyboard and the text display areas across the three conditions using self-report, log, and eye-tracking measures. In the static WBW condition, the words being typed displayed in a fixed area at the top of the virtual keyboard; in the dynamic WBW display, the words displayed in a small popup window at the tip of the selected key.

Using a repeated measure experiment for the three display conditions, participants were asked to type fifteen phrases using a palm tablet while wearing eye-tracking glasses for each condition. We conducted a mixed-model design ANOVA with group (SLOW vs. FAST typing; men vs. women) as between-subject factors and display condition (CBC vs. WBW). We found a significant (11%) improvement in typing speed with the dynamic WBW over the CBC display for less experienced keyboard users. In addition, participants reported higher satisfaction with the two WBW conditions than the CBC condition. Eye fixations, dwell times, and heat map data also supported that WBW displays are advantageous for less experienced, slower typists by helping them stay focused more on the keyboard, thus reducing eye transitions to the text display. Our study systematically demonstrates how and to what extent the virtual keyboard display strategy influences typing performance and subjective experience based on self-reports and eye-tracking measures. The approach and findings of this study should provide useful information and practical guidance to mobile application developers and designers who are interested in improving virtual keyboard functionalities and user satisfaction.

1. Introduction

Mobile devices are becoming an integral part of our daily lives, with the time people spend on mobile devices continuing to grow. According to recent studies [1], the average American adult (18+) spends about 3 h on their smartphone every day. Younger adults are known to spend even more time on mobile devices than older demographics. The majority of those users routinely type on smartphones and palm tablets.

Mobile typing is a complex process involving vision, touch, motion, memory, learning, and other cognitive functions [2]. Most of today's mobile devices have touchscreen interfaces with virtual keyboards based on QWERTY layout. Typing on a virtual keyboard is performed by tapping virtual buttons displayed on the touchscreen. Despite the familiarity with the QWERTY layout for most people, typing on a virtual keyboard is not as easy as typing on a physical keyboard. Virtual keyboards do not provide tactile feedback, and the small-sized keys let fingers often block or go over other keys. User experience issues of mobile high-touch surfaces requiring virtual keyboards are becoming

---

[☆] This paper was recommended for publication by Richard H.Y. So.

[*] Corresponding author at: Design and Environmental Analysis, Cornell University. 3411 MVR Hall, Ithaca, NY 14853, USA.
E-mail address: sy492@cornell.edu (S.-Y. Yoon).

https://doi.org/10.1016/j.displa.2018.11.004
Received 14 April 2018; Received in revised form 2 August 2018; Accepted 21 November 2018

more critical as shared technology in classrooms, and hospitals are increasingly popular. From the public health and well-being perspectives, well-designed virtual keyboard interfaces offer a significant benefit towards the successful adoption of non-touch key input surfaces to prevent germ transmission in public service settings. Although people are mobile typing more than ever, one of the most common problems is the small virtual keyboard [3]. If mobile devices replace computers completely as some predict [4], the issues with the virtual keyboard will become more important and need greater attention.

App developers and researchers have made substantial efforts to tackle the shortcomings of virtual keyboards by exploring keyboard layouts, touch gesture recognition, word prediction, visual highlighting, and multimodal feedback. Virtual keyboards have employed various keyboard layouts, handwriting recognition approaches, word prediction, visual highlighting, and multimodal feedback in order to overcome various limitations. Despite the continuous efforts of the mobile industry and interested researchers to overcome the critical issues with virtual keyboards, to our best knowledge, no study has specifically explored visual touch feedback displays focusing on reducing cognitive loads with eye tracking analysis. In this study, we attempted to provide a new approach to improve virtual keyboards with visual feedback in the display for reduced eye movements.

2. Background

2.1. Issues with virtual keyboards

In text input related studies, the most common performance measure is typing speed using words per minute (WPM). The average input speed with physical QWERTY keyboards on desktop PCs is 40–60 WPM [5]. According to West [6], the QWERTY users reached a typing speed of approximately 80 WPM. Feit et al. [7] found that routine typists could achieve entry speeds above 70 WPM regardless of the number of fingers involved. Even with two thumbs on a physical mini-QWERTY keyboard, Clawson [8] showed that participants acquired typing expertise at almost 60 WPM with almost 95% accuracy after approximately five hours of practice. Even in a blind condition where participants could not see their hands and keyboards, the typing performance with mini-QWERTY keyboards was 46.9 WPM with 85.2% accuracy.

However, with virtual QWERTY keyboards on smartphones or palm tablets, the user can no longer use the natural ability to remember and accurately repeat muscular movements, known as muscle memory. Small screen typing with finger touches range from only 10 WPM for novice users to 20 WPM for expert users [9–12]. When the display size for the virtual keyboard is close to typical keyboards, muscle memory from touch typing tends to translate to an extent. Typing speed becomes slower when the display size is smaller [13]; for example, the average speeds with virtual QWERTY are approximately 30 WPM with 4.7-inch smartphones [14] and approximately 40 WPM with 11.6-inch tablets [15]. In addition to considerably slower typing speed, virtual keyboards induce more errors than physical keyboards [16].

2.2. Previous work

Many researchers and companies have proposed non-QWERTY keyboard layouts such as the DVORAK layout [16], Tap Tap keyboard (Android app), Keypurr keyboard (Android app), 8pen keyboard (http://www.the8pen.com), and TaS keyboard [16].

Another approach is to aid text entry by enlarged word prediction display [17], such as the well-known T9 technique for 3 × 4 mobile keypads. A representative word prediction feature for virtual keyboards is the regional error correction technology which, "is a dictionary-based predictive text entry method that activates not only the key corresponding to the touch point but also neighboring keys simultaneously, thereby increasing the effective virtual key size" [18].

Some researchers attempted to enhance virtual QWERTY keyboards by combining word prediction with touch gestures; such keyboards include Swype (http://www.swype.com), SwiftKey (http://swiftkey.net), SlideIT (http://www.mobiletextinput.com/Product/What_is_SlideIT/), and ShapeWriter [19]. With these types of keyboards, users can obtain the most probable word by sliding their fingers over the keys. Page [19] evaluated the usability of six commonly employed smartphone text input methods (Opti, 8pen, SwiftKey, Swype, Keypurr, and Thick buttons) and concluded that Swype and SwiftKey offer substantial benefits to users and their common typing speeds are comparable to those found on computer keyboards.

Several researchers explored the enhancement of virtual keyboards by highlighting the next likely keys or relaxing the requirement for pressing each virtual key precisely. Magnien et al. [19] found that bolding the next likely keys on unfamiliar keyboard layouts increased the typing speed. However, they did not examine the performance based on a QWERTY layout. Gunawardana et al. [20] proposed a method for dynamically resizing the touch areas for each key on QWERTY keyboards according to their likelihood based on a language model. The ThickButtons keyboard (Android app) changes the shapes of the keys based on predictions, such that they become larger and easier to select. According to Nicolau et al. [21], changing the color and size of virtual keys based on character prediction appeared to have no significant effect on the performance of experienced QWERTY typists, but these changes might be helpful for novice users and typists in attention-demanding contexts.

Some studies focused on providing multimodal feedback, such as tactile or auditory feedback, on virtual keyboards. For example, Park et al. [22] suggested the use of enhanced auditory feedback for virtual keyboards, which was generated based on the acoustic-phonetic features of human speech. Hoggan et al. [23] showed that multiple specialized actuators to provide localized tactile feedback could improve typing performance when compared with a single standard actuator that vibrates the entire device. Alternatively, Wu et al. [2] proposed virtual-physical keyboard combinations with two chording input methods called MagArea and MemoryTap. Their experiment results show that the methods reduced error rates and enhanced typing speed.

2.3. Typing behaviors by novice vs. skilled keyboard users

Typically a user visually scans the keyboard before finger movements [24]; however, skilled users can perform visual scanning and finger movements simultaneously [25,26]. Salthouse [27,28] stated that skilled users could mentally visualize characters in advance of the one currently being typed. During visual scanning, users tend to look frequently and alternately at two areas: the virtual keyboard (to press a virtual key exactly) and the phrase being typed on the screen (to ensure that the correct characters or words are being typed) [29]. This behavior can be reinforced by the absence of tactile feedback on smartphones or tablets compared with PCs. Moreover, this behavioral tendency will be stronger among novices because novice keyboard users cannot type phrases without seeing their fingers and keys. Frequent eye movements between the two areas can make typing inefficient when the two areas are in different fields of view. Thus, the assumption can be made that reduced eye movements on the smartphone or small size table display while using a virtual keyboard can improve typing performance.

2.4. Visual touch feedback display scenarios

The typical keyboards found on smartphones or tablet PCs present visual touch feedback based on the corresponding character whenever the user presses a virtual key. The display of a touch feedback system is often a magnifier or popup view, which floats over the key (see Fig. 1) to attenuate the occlusion of virtual keys by the fingers. This type of touch feedback allows users to know if the correct character has been selected. Users can also ensure that the typed words are correct while

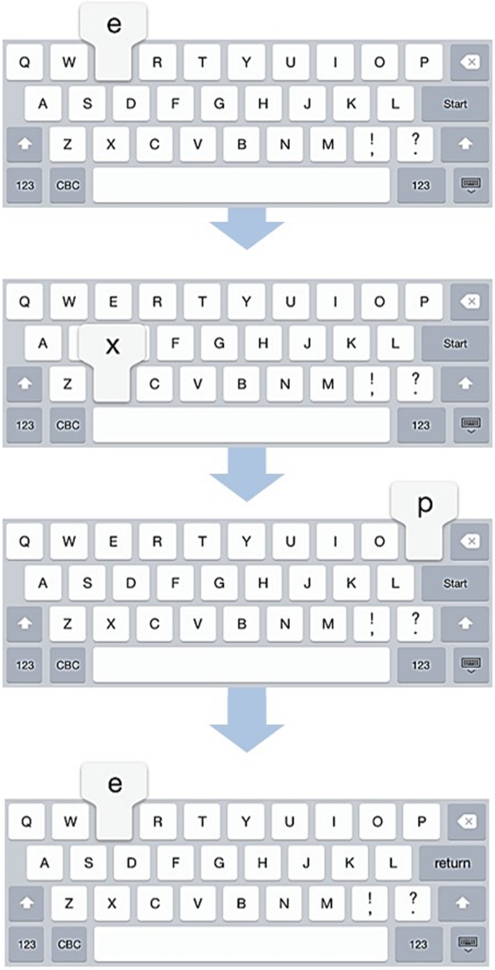


Fig. 1. CBC (Character by character) touch feedback display.

typing them [29]; therefore, it is preferable to place the touch feedback in a location and form that allows users to see the currently typed word easily. In this study, we developed and evaluated two types of touch feedback display scenarios for virtual keyboards based on an eye-tracking experiment: static word-by-word (WBW) and dynamic WBW feedback displays (Fig. 2). The two virtual keyboard display systems are developed to help less experienced and slow typists to remain more focused on the virtual keyboard while typing.

3. Visual touch feedback display

Typical virtual keyboards on smartphones or palm tablets provide visual touch feedback similar to what is shown in Fig. 1, where the typed character appears as a popup when the user touches a key. We refer to this type of touch feedback display as character-by-character (CBC) display. The popup is usually located to the upper right of the key the user's finger touches. However, with this type of touch feedback, users look frequently and alternately at both the keyboard and the text to check the words are typed correctly. Fig. 3 is eye-tracking results showing frequent eye movements between the keyboard and the text display areas with a CBC display.

The feedback displays shown in Fig. 2 are intended to reduce the distance between the keyboard and the word being typed. We propose two scenarios of WBW display. One is for static word-by-word (WBW) touch feedback display, and the other is for dynamic word-by-word (WBW) touch feedback display (Fig. 2). With the static WBW feedback, the characters that the users are typing display in a fixed area at the top of the keyboard, as well as the touch feedback provided by CBC. The SPACE bar clears typed characters; therefore, the fixed view shows every word that is being typed.

As shown in Fig. 2, the dynamic WBW touch feedback display shows the word in the upper side popup of the selected key. The static WBW display is always in a fixed location, whereas the dynamic WBW display changes the location according to the figure location. One limitation with the popup display is in showing long words. The width of the popup view expands to six characters in the dynamic WBW feedback, which is close to the average length of English words [30]. However, the font size of the popup view becomes smaller when seven or more characters are typed, which ensures that the word in the popup display is legible for users (Fig. 2).

We refer to the proposed virtual keyboard display as a word-by-word (WBW) display because a word is a natural information-processing unit in reading and typing [28,31]. According to the two-loop theory of skilled typewriting [32], the outer loop encodes words and passes them to the inner loop, and the inner loop activates keystrokes for the letters comprising the word. Yamaguchi and Logan [33] mentioned, "The outer loop monitors visual feedback from the display, detecting errors in the words typed on display; the inner loop monitors haptic feedback from the keys and tracks finger positions on the keyboard." Therefore, we use the word as a unit of processing in our displays.

4. Methods

4.1. Materials and procedure

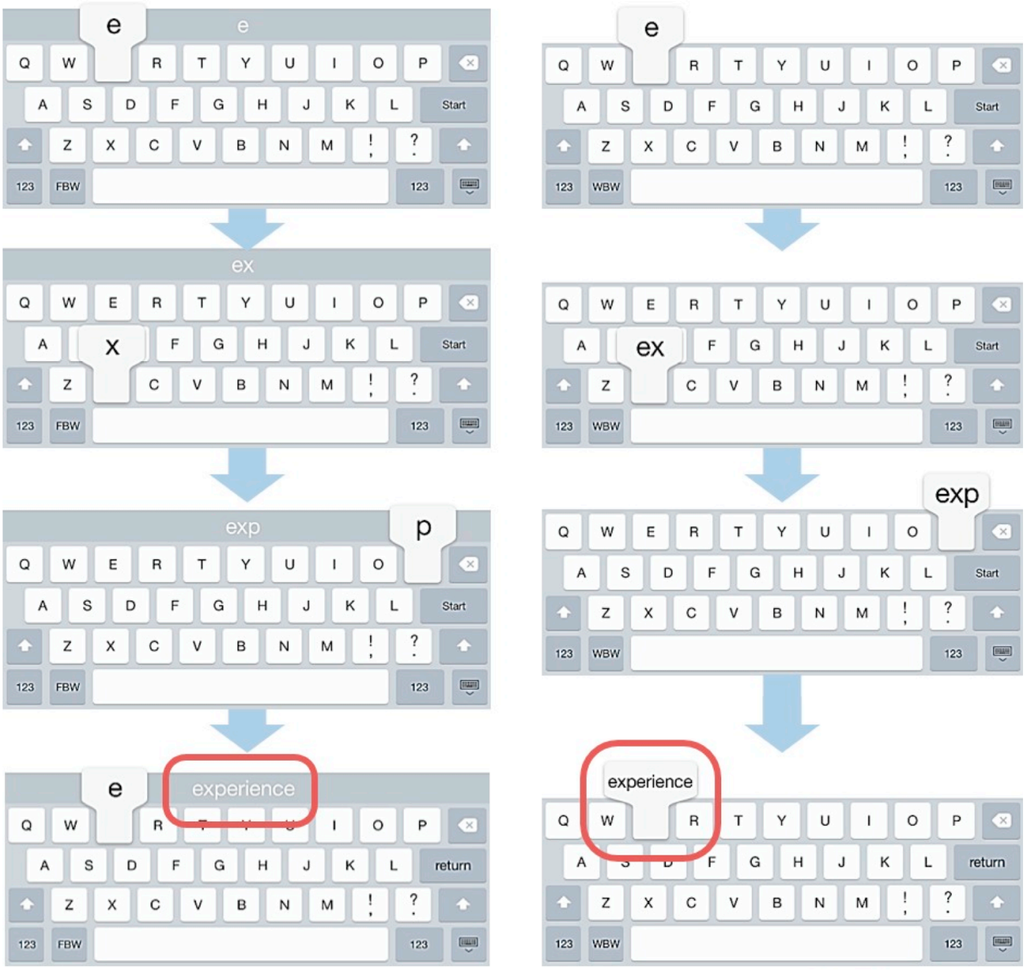
In addition to a control system representing a more conventional display with character-by-character (CBC) feedback, two proposed display systems were developed with an identical virtual keyboard (Fig. 4). Participants were asked to follow and type the exact phrase on the screen using the virtual keyboard. The participant could see the text being typed between the given phrase and the keyboard.

Depending on the mobile app, the space between the keyboard and the text may vary. Most chatting apps have the text area and the virtual keyboard close to each other. The experimental system for this study represents other types of apps (such as email, word processors, or note-taking apps) where the keyboard and the text areas are apart from each other.

A repeated measure experiment for the three display conditions was used for the study. Each participant was invited individually to a quiet research lab. As shown in Fig. 4, the participant was asked to hold a palm tablet (iPad mini with 7.9″ screen) while sitting on a comfortable chair while wearing a pair of eye-tracking glasses (ASL mobile eye XG). After an instruction, the participant was asked to complete typing tasks while wearing eye-tracking glasses for three conditions, CBC, static WBW, and dynamic WBW, in a random order. Each participant was asked to type a given phrase with the assigned QWERTY keyboard display systems. When the participant selected the "Start" button, the screen displayed a random phrase from a list of 500 phrases developed by MacKenzie and Soukoreff [34].

These phrases comprise the most frequently used words in English, and are often used as stimuli in text entry research [35]. If the participant pressed the "End" button upon the completion of the given typing task, the "Result log" (Fig. 4) appeared on the screen to confirm the task is completed. The log includes the completion time, the number of characters in the presented and typed phrases, and the number of times the delete key was pressed. The log data was stored in the system for analysis. Before the experiment started, the experiment administrator informed each participant to ignore the log display. Immediately after each condition, the participant was asked to complete a survey on his/her typing experience.

All the participants typed phrases using a two-thumb typing style while sitting on a chair and wearing ASL mobile eye-tracking glasses (see the picture on the right of Fig. 4). According to an observational



Static WBW showing the word being typed at the top of the keyboard

Dynamic WBW showing the word over the selected key

Fig. 2. Proposed WBW (Word by word) touch feedback displays.

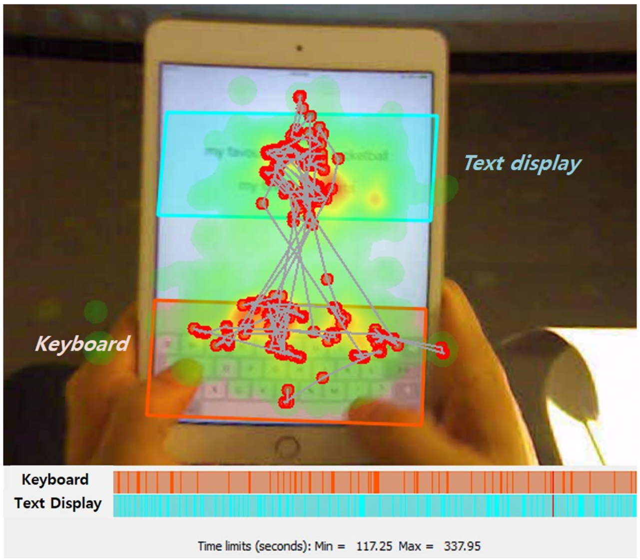
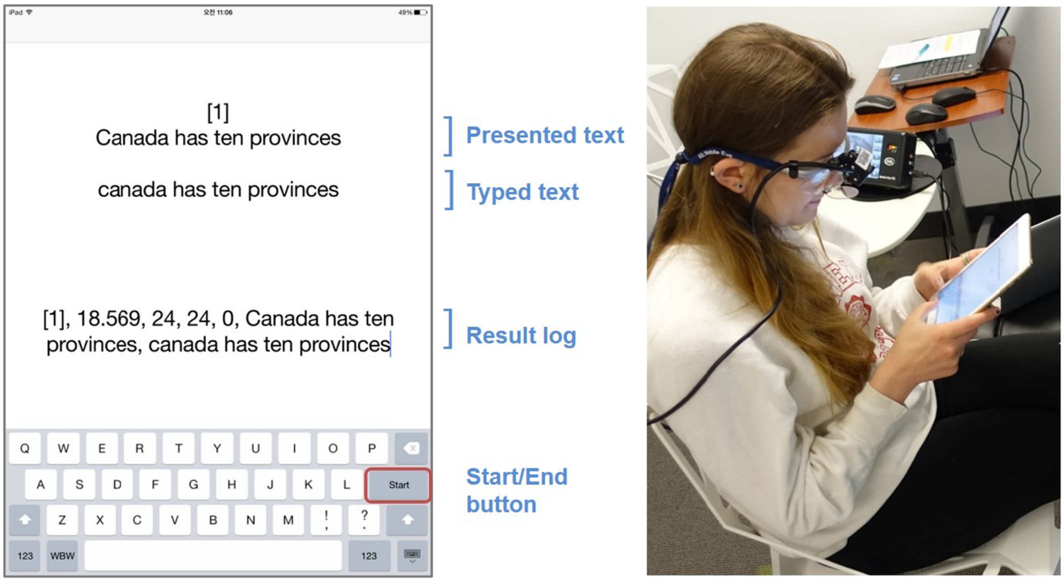


Fig. 3. Example of a typical eye movement pattern. The lower bar graphs indicate time span for eye fixations between the keyboard and the text display areas.

study by Gold et al. [36], the most frequent typing styles are both hands holding the device with both thumbs typing (46.1%) and one thumb typing while holding the device with the same hand (44.1%). Karlson et al. [37] showed that the users of keypad-based devices employ one-hand typing almost exclusively, whereas smartphone users prefer to employ both hands, especially during text entry. Moreover, two thumb-typing requires less wrist extensor muscle activity than one thumb-typing [38]. Thus, the participants in the present study used the two-thumb typing style. In addition, the eye-tracking data was automatically recorded with the ASL mobile eye-tracking and analyzed using “ASL results plus GM” software.

4.2. Participants

Participants were recruited on the campus of Cornell University in the US with the offer of extra credit or an Amazon gift card. After excluding those whose eye-tracking data were not reliable, the study had a total of 21 participants (six men and 15 women) ranging in age from 18 to 54 years. Participants performed the experimental tasks wearing ASL mobile XG eye-tracking glasses (Fig. 4). Each participant was taken through a calibration procedure prior to the experiment for successful eye-tracking recording. For six participants, the eye-tracking device failed to calibrate or track the eye movements throughout the



[1]
Canada has ten provinces

canada has ten provinces

[1], 18.569, 24, 24, 0, Canada has ten provinces, canada has ten provinces

Fig. 4. Experimental system and environment.

experiment. Thus we excluded their eye-tracking data from the analysis, but their self-report and objective performance data were analyzed.

4.3. Task and procedure

When participants arrived at the experiment site, they were provided a detailed explanation of the experiment by the administrator and presented with an informed consent form to sign. The participant was then asked to wear the mobile eye-tracking glasses. The administrator assisted the participant with wearing and adjusting the device. The eye-tracking glasses were calibrated to accurately record the participant's eye movement using a prepared calibration aid chart with markers.

After calibration, the participant was instructed to perform the typing task as if he or she was writing a short message to a friend that involves typing 15 phrases with each touch feedback display (total of 15 phrases × 3 touch feedback displays = 45 trials; within-subjects design). The system randomly selected and presented phrases from the database. The participant practiced for the first five trials with each touch feedback display. The order of the three touch feedback display systems was randomized and balanced for every participant.

After the participant pressed the "START" key, a phrase appeared on the device (Fig. 4). Then, the participant was asked to read the phrase aloud, to type when ready, and to press the "END" key when he or she was satisfied with the result. The recording time started when the first key was touched. The participant was instructed to ignore capitalization and punctuation to type the presented phrase as quickly and accurately as possible. Furthermore, the participant was allowed to make corrections, but not obliged to correct every error. This type of text entry is known as unconstrained text entry [8].

After typing 15 phrases with each type of touch feedback display, the participant was asked to subjectively evaluate the touch feedback system regarding effectiveness, satisfaction, and preference based on a seven-point Likert scale.

4.4. Performance measures

Objective performance data was gathered and analyzed. First, words per minutes (WPM) was calculated using Mackenzie's equation [39]. WPM is a general calculation of how fast a person can type with no error penalties. WPM = (T-1)/S × 60/5 [39], where T is the length of the typed text and S is the time required to type the entire phrase in seconds. The constants 60 and 1/5 are used because there are 60 s in a minute and the average word length including spaces in English is five characters.

Secondly, the type and number of errors were measured, which were counted and tabulated regarding insertion errors (unnecessary letters inserted), omission errors (missing letters), word spacing errors (missing or extra spaces), and substitution errors (erroneous letters substituted for intended letters). These types of errors are common typing errors [27,31,40]. Using the counts for each error, the error rates were calculated, which has been used in several studies related to text entry [35,41]:

$$\text{Error rate} = \text{MSD}(A, B)/\max(|A|, |B|) \times 100\%,$$

A is the presented text, B is the typed text, and MSD is the minimum string distance [42], which is a sequence comparison algorithm that calculates the minimum number of operations (e.g., substitutions, insertions, and deletions) required to convert the presented text (A) into the typed text (B). For instance, if we consider the following string:

Presented:	my watch fell in the water	(= 26 letters)
Typed:	mywatch fall into the water	(= 27 letters)

The length of the typed text is 27 letters, including spaces. The errors in the typed string include omission of space, a substitution of "a" for "e," and the insertion of an additional "to." The MSD calculated for this pair is 4 and the error rate = (4/27) × 100% = 14.81%.

We also analyzed the number of deletions, which includes the number of times that a participant pressed the delete key while revising typed the text. The error rate can reflect uncorrected errors, whereas the number of deletions can reflect corrected errors.

4.5. Eye-tracking measures

Additionally, we acquired and analyzed eye-tracking data to obtain a more comprehensive understanding of participants' experiences with the proposed feedback displays. An area of interest (AOI) in eye-tracking data analysis represents a researcher's defined area within a display or visual environment. In this study, we determined two areas of interest; the keyboard area and the text window area displaying the presented and typed phrases (Fig. 3). The text display AOI contained the presented and typed phrases. Using this information, the participants could type the presented phrases and ensure the accuracy of the typed phrases by comparing the two. The keyboard AOI contained the virtual QWERTY keyboard and the visual touch feedback display. The participant viewed and touched keys on the keyboard to perform the given typing tasks. The eye-tracking metrics for the two AOI analysis are described below.

First, we measured the number of eye fixations on two AOI. Eye fixation is defined as a spatially stable gaze that lasts approximately 200–300 ms, where the visual attention is directed to a specific area in the visual display [43]. Fixations represent the elements or areas where information acquisition and processing can occur. Thus, if the number of fixations on a particular area of interest is higher, the importance of that element or area is greater [44].

Secondly, the total dwell time, i.e., gaze duration, on each AOI was measured. The total dwell time means the total time spent fixated on each AOI during the entire experiment trial, i.e., the sum of all the individual gaze durations for a particular AOI. The total dwell time can predict whether gazes at a specific element or area are longer when the participant experiences difficulty extracting or interpreting information from a display element or area [44]. The total dwell time typically includes several eye fixations, and it can include a relatively small amount of time for short saccades between fixations.

Finally, we analyzed the average pupil sizes of the participants with each AOI, which were recorded automatically by the ASL mobile eye-tracking system. Pupil dilation is typically used as a metric for assessing an individual's interest or arousal relative to the element or area that the individual is observing [43].

5. Results

5.1. Subjective ratings

The average subjective ratings given by the participants regarding the effectiveness, satisfaction, and preference for each type of touch feedback display as shown in the graph below (Fig. 5).

5.1.1. Effectiveness

The subjective ratings for effectiveness were significantly different among the CBC, dynamic WBW, and static WBW (Friedman test: $\chi^2(2) = 6.125$, $p = 0.047$). The average for the static WBW was higher than the values for both the CBC and dynamic WBW (5.05, 4.24, and 4.24, respectively).

5.1.2. Satisfaction

The subjective ratings for satisfaction differed significantly among the CBC, dynamic WBW, and static WBW (Friedman test: $\chi^2(2) = 6.25$, $p = 0.044$). On the average, the static and dynamic WBW were reported more satisfactory than the CBC (4.86, 4.38, and 3.76, respectively).

5.1.3. Preference

There was no significant difference in preference among the CBC, dynamic WBW, and static WBW found (Friedman test: $\chi^2(2) = 3.877$, $p = 0.144$). However, the average for the dynamic WBW was lower than the values for both the CBC and static WBW (3.90 vs. 4.33 and 5.19, respectively). Seven of the 21 participants indicated that the touch feedback provided by the dynamic WBW was confusing because its location kept changing.

5.2. Objective performance

5.2.1. Words per minute

During the experiment, we observed that rapid typing participants tended not to observe the virtual keyboard frequently. Yamaguchi et al. [26] also noted that skilled typists can type sentences without looking at the fingers and keys they control (i.e., touchscreen typing). Thus, the feedback methods, such as the dynamic WBW or the static WBW, might not be beneficial for them. Therefore, to investigate typing proficiency, we analyzed whether the three touch feedback display systems impacted participants' typing speed. Participants were divided into two speed groups based on the average Words per Minute (WMP) of all participants (36.99 WPM): the SLOW and the FAST typing groups. Ten out of the 21 participants were included in the slow group while the remaining participants were in the FAST group (average WPM: 27.76 for the SLOW group and 45.38 for the FAST group). The three-way ANOVA showed that the substantial difference between the speed groups was significant (F(1,623) = 1204.191, $p = 0.000$).

We found significant differences in the average WMP among the dynamic WBW, static WBW, and CBC (F(2,623) = 2.924, $p = 0.045$). The means and standard deviations for the dynamic WBW, static WBW, and CBC were 37.76 (10.54), 36.91 (10.89), and 36.31 (11.56) WMP, respectively. Duncan's test indicated that the dynamic WBW was faster than the CBC (Fig. 6). Furthermore, a significant effect of the interaction between the feedback display type and SLOW/FAST speed group was found (F(2, 623) = 3.037, $p = 0.049$). Differences in WPM among the touch feedback display systems were found only in the SLOW group (Fig. 6). Thus, we reanalyzed only the SLOW group's WPM data (excluding the FAST group data). The results clearly showed the superiority of WBW over CBC (F(2,296) = 6.901, p = 0.001). In addition, men were significantly faster than women (F(1, 623) = 35.120, $p = 0.000$; average, 27.63 vs. 27.77 WMP).

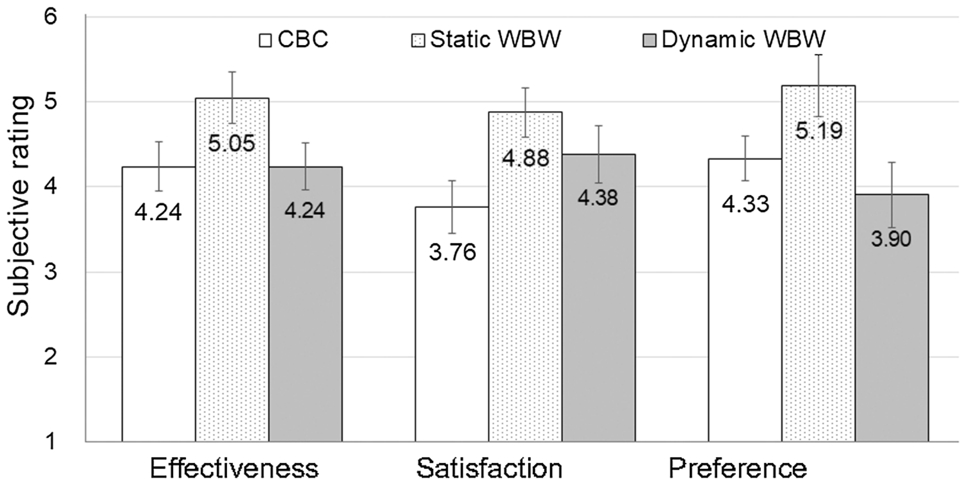


Fig. 5. Subjective ratings for each type of touch feedback method. The error bar indicates the standard error of the mean ($N = 63$).

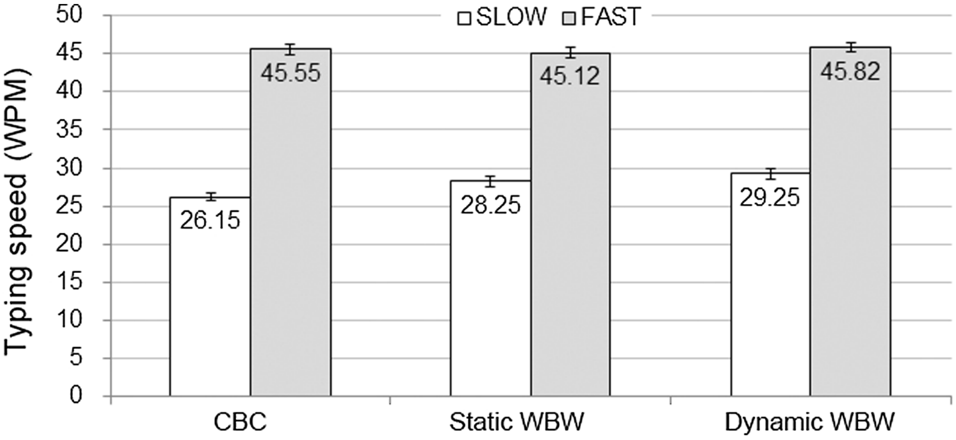


Fig. 6. Differences in typing speed between the SLOW and FAST groups by feedback display type. The same letters indicate no significant difference at α = 0.05 according to Duncan's test.

5.2.2. Error rate

We did not find a significant difference in error rates among the three types of touch feedback display systems (F(2,623) = 0.950, *p* = 0.387); however, the average error rates were noticeably lower for the static WBW (Fig. 7). The average error rates (and standard deviations) for the CBC, dynamic WBW, and static WBW were 2.15% (4.80), 2.18% (5.65), and 1.63% (3.18), respectively. The difference between the FAST and SLOW groups was not significant in the error rates (F(1, 623) = 1.330, *p* = 0.249; average, 2.20 vs. 1.75%), and there were no significant interaction effects between the feedback type and speed group (F(2, 623) = 0.340, *p* = 0.712). Meanwhile, women made more typing errors than men (F(1, 623) = 6.265, *p* = 0.013; average, 2.28 vs. 1.24%).

Regardless of the feedback display type, we found substitution errors were the most frequent type of error, followed by omission, insertion, and spacing (average, 1.18, 0.58, 0.18, and 0.06%, respectively). As shown in Fig. 7, omission error rates were much lower with the static WBW than with the CBC and dynamic WBW, although the difference was not statistically significant (F(2, 623) = 2.226, *p* = 0.109). The fixed location of words in the static WBW display may have helped to prevent missing characters.

5.2.3. Deletion/error correction

There was no significant difference in deletion among the feedback display types (F(2,623) = 0.474, *p* = 0.623). The average (and standard deviations) deletion numbers with the CBC, dynamic WBW, and static WBW were 1.70 (3.38), 1.80 (3.15), and 1.99 (3.17), respectively. There were no interaction effects between the feedback type and speed group (F(2, 623) = 0.039, *p* = 0.962). Interestingly, we found that females revised sentences more frequently than males (F(1, 623) = 21.785, *p* = 0.000; 2.18 vs. 0.93, respectively), which was consistent with our finding that females made more erroneous typing actions than males. The SLOW group made more deletion actions than the FAST group (F(1, 623) = 24.363, *p* = 0.000; average, 2.45 vs. 1.25). Frequent deletion is likely to cause slower typing speed.

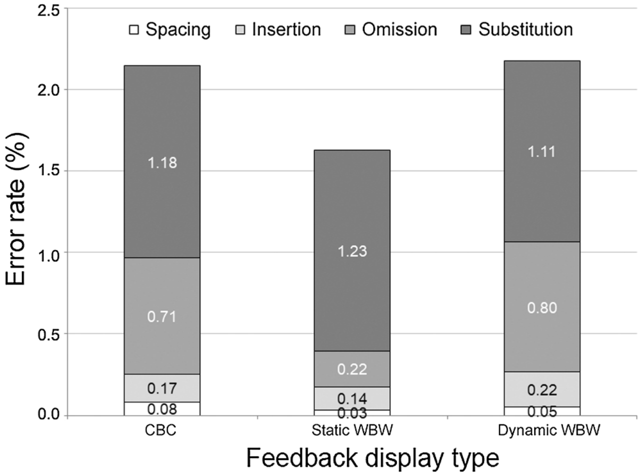


Fig. 7. Error rates for each error type according to the type of touch feedback method.

5.3. Eye-tracking data analysis

5.3.1. Heat map

Fig. 8 shows the heat maps generated from participants' eye movement data for the three touch feedback displays. Participants tended to look at both keyboard and text display areas while typing in the CBC condition. However, participants focused more on the keyboard than the text display for the static WBW condition. This demonstrates that the static WBW helped participants verify the words better while typing. This tendency also appeared to a lesser degree in the dynamic WBW condition (Fig. 8). We also analyzed the heat maps by the FAST and SLOW typing speed groups. There was no noticeable difference observed between the two groups.

5.3.2. Eye fixation count

Eye fixation analysis results show that the participants focused more on the keyboard area than the text display area while typing (F(1,80) = 6.974, p = 0.010; average, 191.11 vs. 151.07); this behavior was stronger in the SLOW group than in the FAST group as shown in Fig. 9. The SLOW group looked at the keyboard area and the text display area much more frequently than the FAST group (F(1,80) = 37.184, *p* = 0.000; average, 237.47 vs. 126.83), and the interaction effect between the speed group and AOI was also significant (F(1,80) = 4.706, *p* = 0.033). The SLOW group looked at the keyboard more frequently than the text display area. As expected, unfamiliarity would have influenced high visual dependency on the virtual keyboard.

We did not find a significant difference in eye fixation counts across the touch feedback displays (F(2,80) = 0.477, *p* = 0.622; average, 161.60, 179.53, and 172.13 for CBC, static WBW, and dynamic WBW, respectively). However, the participants focused more often on the keyboard than the text display when using the static and dynamic WBW feedbacks (Fig. 10). The heat map for each feedback display also supports this interpretation (Fig. 8). More specifically, the participants looked much less at the text display area when using static WBW.

Fig. 8. Heat map comparison (all participants).

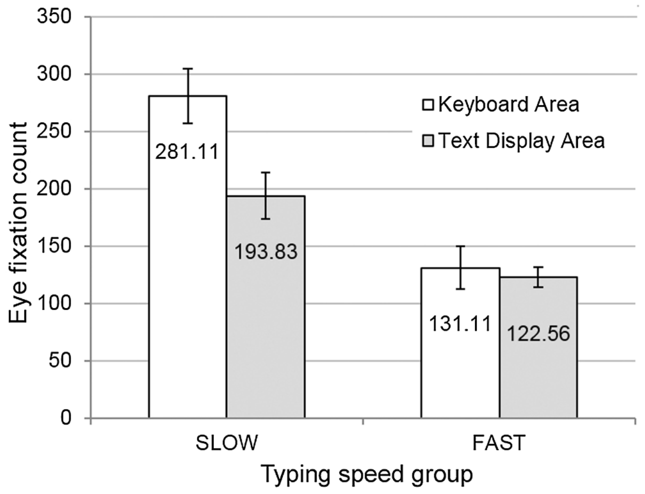


Fig. 9. Eye fixation comparison by SLOW and FAST groups.

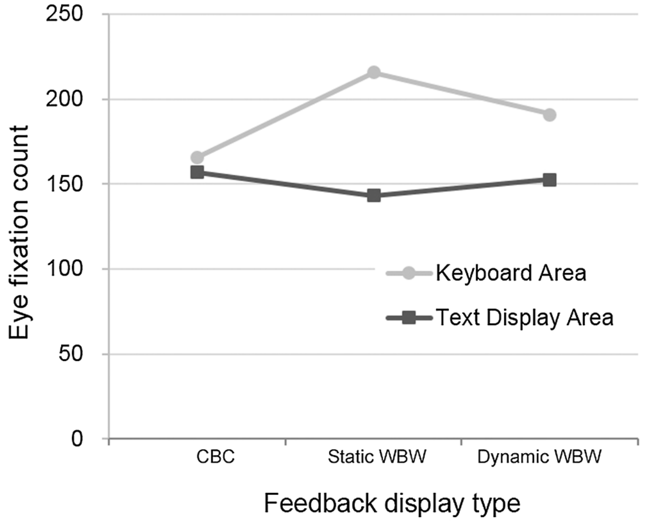


Fig. 10. Interaction effects between feedback display conditions and keyboard/text display areas on eye fixation.

5.3.3. *Total dwell time*

There was no significant difference observed in the total dwell times among the three touch feedback display conditions (F(2,80) = 0.584, $p = 0.560$; average, 48.80, 55.33, and 54.37 s for the CBC, static WBW, and dynamic WBW, respectively). Consistent with the eye fixation analysis results, participants viewed the keyboard more than the text display while typing (F(1,80) = 4.951, $p = 0.029$; average, 58.34 and 47.33 s for the keyboard and the text display areas), and this tendency was stronger with the SLOW group than in the FAST group as shown in Fig. 11. This was supported by the significant interaction effect between the speed group and AOI (F(1,80) = 5.147, $p = 0.026$). While it is obvious the SLOW group viewed the screen longer overall than the FAST group, the SLOW viewed the keyboard area substantially longer than the text display area compared to the FAST group (F(1,80) = 20.744, $p = 0.000$; average, 69.81 vs. 41.51 s).

In the CBC condition, there was no significant difference found in the total dwell times between the keyboard area and the text display area. However, between CBC and WBW display conditions, participants dwelled longer on the keyboard area than the text display area in WBWs conditions (Fig. 12). This result is consistent with the eye fixation results.

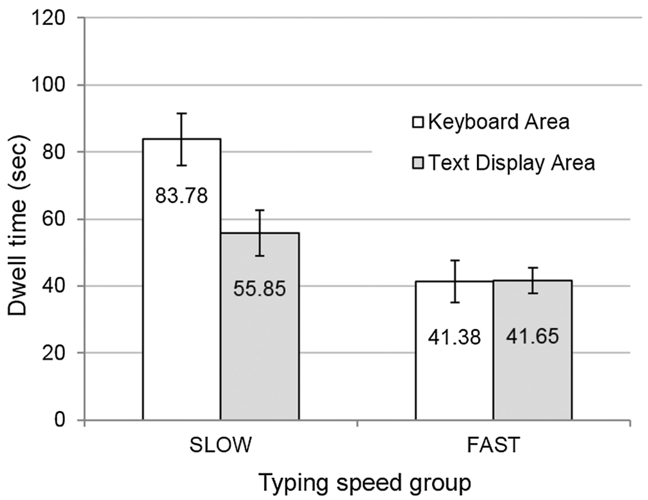


Fig. 11. Total dwell time comparison by SLOW and FAST groups.

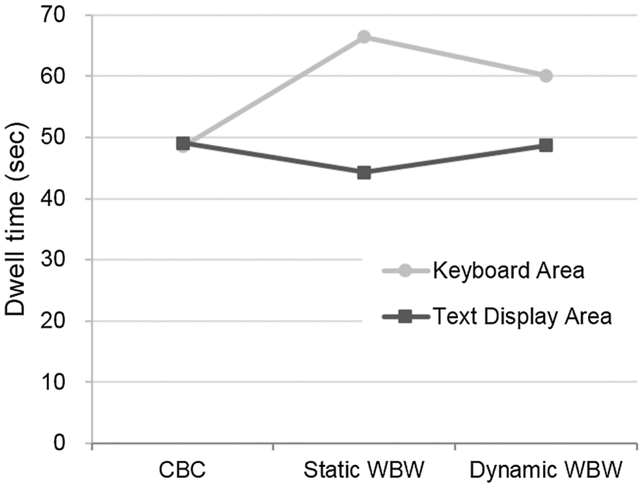


Fig. 12. Interaction effect between feedback displays and keyboard/text display areas on total dwell time.

In addition, the average pupil size was analyzed. The average pupil size for the text display area was significantly larger than that for the keyboard area (F(1,80) = 4.632, p = 0.034; average, 129.17 vs. 109.60 pixels). This can be interpreted as when the participants were looking at the text display area, their pupil sizes were enlarged to make sure they are typing correctly. However, the average pupil size did not differ significantly among the three types of touch feedback methods (F (2,80) = 0.374, p = 0.689; average, 118.67, 116.05, and 123.42 pixels for the CBC, static WBW, and dynamic WBW, respectively).

5.3.4. *Transitions between keyboard and text display*

Fig. 13 shows the transition probabilities between the keyboard and the text display AOI. The probabilities were calculated by ASL results plus GM software. In terms of the transitions within the keyboard, both the static and dynamic WBW displays had greater probabilities than the CBC on average (0.66, 0.65 vs. 0.54). This implies that the participants could stay more focused on the keyboard with static and dynamic WBWs than with the CBC. Meanwhile, the probability of switching from keyboard to text display was higher in the CBC than in both WBWs (0.26 vs. 0.19, 0.22). This means that participants had to see what they are typing more often in the CBC condition, whereas WBW displays allowed participants to stay with the keyboard without having to look at the text display area as much.

6. Discussion

From a series of analysis, we found that the dynamic and static WBW displays allow higher typing performance than the commonly used character-by-character (CBC) system especially in the SLOW group. However, we did not find significant differences in the WPM or error rate between the static and dynamic WBW displays by the SLOW group. This could be because the user can better detect errors when typing slower on a word-by-word basis with the WBW feedback displays when typing while viewing the keyboard area.

Expert typists tend to perform text input without looking at the virtual keyboard. Therefore, providing visual feedback, such as WBW, had little effect on their typing performance. On the other hand, novice typists enter each character while looking at both the keyboard and the input sentence area while also checking the word being typed. The longer the distance between the two areas, the longer the eye movement time and the slower the input speed. Thus, the visual feedback of WBW reduces the distance between the two areas, while also reducing the necessary eye movement and text input time.

For the slower typists, the typing speed on the dynamic or the static WBW systems were 11% and 8% faster than the CBC, respectively. While the speed improvement may seem marginal, participants were more satisfied with the static and dynamic WBW than the CBC. Participants rated higher effectiveness for the static WBW than both the dynamic WBW and CBC. Compared to the static WBW, the dynamic WBW requires more effort to keep up with the moving feedback display. Therefore, the dynamic WBW had the lowest preference ratings. On the other hand, we assume that participants were familiar with the static WBW. Most of all, the position of the static WBW could be more helpful because it was on the same line as the moving line of sight when trying to see the sentence to be entered.

Among error rate measures, substitution errors were consistently the most common error type across the conditions. Rodrigues et al. [15] reported similar results. However, omission error rates were lower in the static WBW condition than CBC and dynamic WBW conditions.

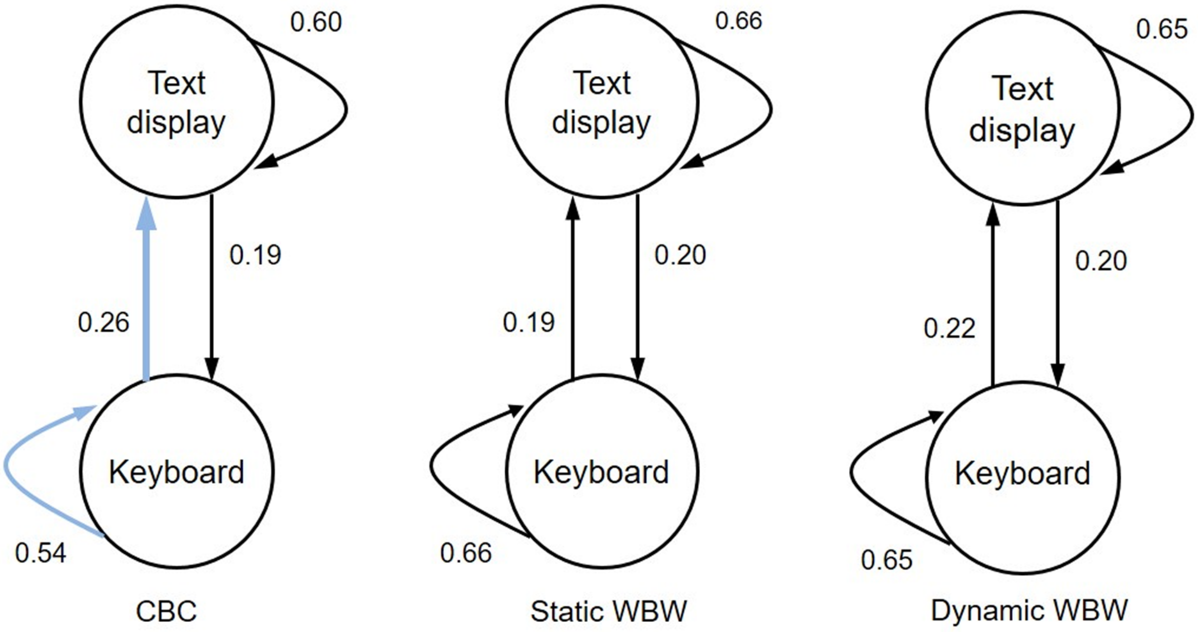


Fig. 13. Keyboard- text display areas transition probabilities in three feedback display conditions.

According to Nicolau and Jorge [45], omission errors are the most common error type made by elderly individuals when typing on virtual keyboards, which suggests that the static WBW can be more useful for elderly users.

Eye-tracking data analysis results showed that there was no significant difference in the eye fixation count and total dwell time across the three conditions. However, with the static and dynamic WBW displays, the participants focused more frequently on the keyboard area than the text display area while typing. This behavioral tendency was more obvious among participants with slower typing speeds because their unfamiliarity with QWERTY layouts would have increased dependency on the virtual keyboard. Feit et al. [7] also observed that unskilled typists used 40% of their time looking at the keyboard, but skilled typists spent only 20%. Heat maps comparison showed that the participants viewed the keyboard area more than the text display area when in either WBW conditions than the CBC condition. Moreover, the probability of switching from the keyboard to the text display was lower in both WBW displays than in CBC. We can interpret that the WBW feature allows users to feel more comfortable typing without looking at the text display as much.

The findings of this study indicate that the WBW feedback displays help users who are less familiar with virtual keyboards perform typing tasks significantly better. Novice typists read each letter, finding the corresponding key on the keyboard, then move a finger to the key, and press it. This is a serial processing. By contrast, skilled typists read each word, activating its constituent keystrokes in parallel, and execute them. This processes letters or keystrokes in parallel. Such parallel processing depends on hierarchical control where multiple characters and keystrokes are treated as a single unit or chunk [32,33]. The WBW displays proposed in this study seem to better guide novice typists with word-based parallel processing.

7. Conclusions

It is a natural behavior to look at the keyboard and what is being typed in the text display area while typing. When typing using a virtual keyboard on smartphones or small size tablets, the frequency of looking at each area substantially increases in part because users no longer benefit from long-term established typing motor skill, i.e., muscle memory. Additionally, the substantial reduced keyboard often allow only two thumbs for text inputting. The absence of tactile feedback can make screen typing challenging.

Mobile devices are increasingly smarter, faster and more affordable, encouraging even more people to engage in online activity through their mobile devices. Many tasks and applications that people used to use computers for have been quickly adapted for mobile devices. As a result, mobile-only users are quickly rising [46]. Despite numerous apps and gadgets introduced for improved typing experience on mobile devices, challenging virtual keyboards have hindered many people from switching from PCs and physical keyboards to mobile devices. Issues with virtual keyboards are more obvious with novice users than expert users. Users who are not familiar with the keyboard display need to make frequent eye movements between the keyboard and text display areas, thus their typing becomes slower and more fatigued with increased efforts.

This study proposed two visual feedback display strategies to reduce the effort from frequent shifts in the eye gaze and ultimately to improve user satisfaction and performance of virtual keyboards. Two prototypes, one with static word-by-word (WBW) and the other one with dynamic WBW feedback display, were developed to employ viable visual touch feedback strategies that differ from standard keyboards. Virtual keyboards usually present visual popup character-by-character (CBC) display when the user presses a key. With the static WBW display, the word being typed is displayed in a fixed area at the top of the keyboard, as well as the enlarged popup display of the character. With the dynamic WBW display, the word appears in a popup feedback display above the key/character typed. These WBW displays are to enable users to type with less eye gaze shifts because the word for the selected key/character is integrated in the virtual keyboard.

In order to test the proposed displays in comparison with the commonly used CBC system, we conducted a within subject design experiment where each participant used all three systems in a random order to type randomly assigned phrases using an iPad mini while wearing ASL mobile eye-tracking glasses. The analysis results show that both the static or the dynamic WBW feedback display benefits less experienced, slower typists by allowing them to remain focused on the virtual keyboard while typing, thereby reducing eye movements and enhancing their typing speed. Based on our findings, we recommend word-by-word touch feedback displays for virtual keyboards on smartphones and tablets as a variable strategy for improved functionality. If incorporated as an option for users to enable or disable, such WBW features will be able to boost overall user experience.

The current study only used the QWERTY keyboard layout for English. By replicating the study on different types of keyboard or different language systems or different typing modes with one or both thumbs, the viability of the WBW displays can be further investigated.

One limitation of this study is in using a palm tablet instead of a smartphone that is more broadly used screen size. Despite the advancement of eye-tracking technology, there was a technical challenge in detecting eye-movements when the target viewing area is as small as a smartphone screen. Although the findings are likely to transfer for smartphone experiences, it would be useful to confirm with a follow up study using a smartphone in the future. Another consideration is the decreasing font size in the WBW displays. Most of words used in the experiment were short, the average word length was 4.46 characters (12,095 characters/2,712 words); however, decreasing font size in the popup view with the dynamic WBW could affect its performance. This effect needs to be clarified in future research.

In this study, we systematically demonstrated how and to what extent the virtual keyboard display strategy plays a significant role in improving typing performance and subjective experience based on self-reports and eye-tracking measures. The approach and findings of this study should provide useful information and practical guidance to mobile application developers and designers who are interested in improving virtual keyboard performance and user satisfaction.

Conflicts of interest

None.

Acknowledgements

This study was supported by the Research Program funded by Seoul National University of Science and Technology, South Korea.

References

[1] A. Lipsman, A. Lella, The 2017 U.S. Cross-Platform Future in Focus, 2017.

[2] F. Wu, Y. Huang, M. Wu, New chording text entry methods combining physical and virtual buttons on a mobile phone, Appl. Ergon. 45 (2014) 825–832.

[3] J. Pavlus, Two Ways to Fix the Typing-on-Touch-Screens Problem, MIT Technol Rev (2013).

[4] C. Bonnington, In less than two year, a smartphone could be your only computer, Wired Mag (2015).

[5] I.S.M.W. Soukoreff, Theoretical upper and lower bounds on typing speeds using a stylus and keyboard, Behav. Info. Tech. 14 (1995) 379 379.

[6] L.J. West, The Standard and Dvorak Keyboards Revisited: Direct Measures of Speed, Res. Econ. (1998) 98–05–041e.

[7] A.M. Feit, D. Weir, A. Oulasvirta, How we type: Movement strategies and performance in everyday typing, Proc. 2016 Chi Conf. Hum. Factors Comput. Syst. ACM, 2016, pp. 4262–4273.

[8] J. Clawson, On-the-go text entry: Evaluating and improving mobile text input on mini-qwerty keyboards, Georgia Institute of Technology (2012).

[9] A. Sears, D.J. Revis, R. Swatski, Investigating touchscreen typing: The effect of keyboard size on typing speed, Behav. Info. Tech. 12 (1993) 17–22.

[10] M. Silfverberg, S. MacKenzie, Prediction text entry speeds on mobile phones, Hum.

Factors. 9–16 (2000).

[11] M.D. Fleetwood, M.D. Byrne, P. Centgraf, K.Q. Dudziak, B. Lin, D. Mogilev, An evaluation of text-entry in Palm OS – Graffiti and the virtual keyboard, Proc. Hum. Factors Ergon. Soc. 46th Annu. Meet. Human Factors Society, Santa Monica, CA, 2002, pp. 617–621.

[12] M. Dunlop, J. Levine, Multidimensional pareto optimization of touchscreen keyboards for speed familiarity and improved spell checking, Proc. SIGCHI Conf. Hum. Factors Comput. Syst. ACM, 2012, pp. 2669–2678.

[13] A.S.L.A. Leiva, A. Sahami, A. Catalá, N. Henze, Text Entry on Tiny QWERTY Soft Keyboards, Proc. 33rd Annu. ACM Conf. Hum. Factors Comput. Syst. ACM, 2015, pp. 669–678.

[14] S. Reyal, S. Zhai, P.O. Kristensson, Performance and User Experience of Touchscreen and Gesture Keyboards in a Lab Setting and in the Wild, Proc. 33rd Annu. ACM Conf. Hum. Factors Comput. Syst. ACM, 2015, pp. 679–688.

[15] É. Rodrigues, M. Carreira, D. Gonçalves, Enhancing typing performance of older adults on tablets, Univers. Access Inf. Soc. 15 (2016) 393–418.

[16] A.L. Smith, B.S. Chaparro, Smartphone text input method performance, usability, and preference with younger and older adults, Hum. Factors. 56 (2015) 1015–1028.

[17] M.D. Dunlop, A. Crossan, Predictive text entry methods for mobile phones, Pers. Technol. 4 (2000) 134–143.

[18] S. Kwon, D. Lee, M.K. Chung, Effect of key size and activation area on the performance of a regional error correction method in a touch-screen QWERTY keyboard, Int. J. Ind. Erg. (2009) 888–893.

[19] S. Zhai, P.O. Kristensson, Introduction to Shape Writing, 2007.

[20] A. Gunawardana, T. Paek, C. Meek, Usability guided key-target resizing for soft keyboards, Proc. IUI 10 (2010:) 111–118.

[21] H. Nicolau, T. Guerreiro, D. Lucas, J. Jorge, Mobile text-entry and visual demands: reusing and optimizing current solutions, Univers, Access Inf. Soc. 13 (214AD) 291–301.

[22] Y. Park, H. Heo, K. Lee, Enhanced auditory feedback for Korean touch screen keyboards, Int. J. Hum. Comput. Stud. 73 (2015) 1–11.

[23] E. Hoggan, S.A. Brewster, J. Johnston, Investigating the effectiveness of tactile feedback for mobile touchscreens, CHI 2008, ACM, Florence, Italy, 2008, pp. 1–10.

[24] A.B. Smith, S. Zhai, Optimised virtual keyboards with and without alphabetical ordering – a novice user study, in: Proc. INTERACT ‘2001, Tokyo, Japan, 2001: pp. 92–99.

[25] J. Kim, S. Hong, R. Myung, A study on the eye-hand coordination for Korean text entry interface development, J. Ergon. Soc. Korea. 26 (2007) 149–155.

[26] M. Yamaguchi, M.J. Crump, G.D. Logan, Speed–accuracy trade-off in skilled typewriting: decomposing the contributions of hierarchical control loops, J. Exp. Psychol. Hum. Percept. Perform. 39 (2013) 678–699.

[27] T.A. Salthouse, Anticipatory processing in transcription typing, J. Appl. Psychol. 70 (1985) 264–271.

[28] T.A. Salthouse, Effects of age and skill in typing, J. Exp. Psychol. Gen. 113 (1984) 264–271.

[29] H. Oh, Soft keyboard interface design for mobile device, J. Korean Contents. 7 (2007) 79–88.

[30] V.V. Bochkarev, A.V. Shevlyakova, V.D. Solovyev, Average word length dynamics as indicator of cultural changes in society, Soc. Evol. Hist. 14 (2015) 153–175.

[31] T.A. Salthouse, Perceptual, cognitive, and motoric aspects of transcription typing, Psychol. Bull. 99 (1986) 303–319.

[32] G.D. Logan, M.J. Crump, Hierarchical control of cognitive processes: the case for skilled typewriting, Psychol. Learn. Motiv. 54 (2011) 1–27.

[33] M. Yamaguchi, G.D. Logan, Pushing typists back on the learning curve: Revealing chunking in skilled typewriting, J. Exp. Psychol. Hum. Percept. Perform. 40 (2014) 591–612.

[34] I.S. MacKenzie, R.W. Soukoreff, Phrase sets for evaluating text entry techniques, Ext. Abstr. ACM Symp. Hum. Factors Comput. Syst. ACM, 2003, pp. 745–755.

[35] A.L. Smith, Smartphone input method performance, satisfaction, workload and preference with younger and older novice adults, Wichita State University, 2013.

[36] J.E. Gold, J.B. Driban, N. Thomas, T. Chakravarty, V. Channell, E. Komaroff, Postures, typing strategies, and gender differences in mobile device usage: an observational study, Appl. Ergon. 43 (2012) 408–412.

[37] A. Karlson, B. Bederson, J. Contreras-Vidal, Understanding single-handed mobile device interaction, in: Handb. Res. User Interface Des. Eval. Mob. Technol., 2006: pp. 86–101.

[38] D.M. Kietrysf, M.J. Gerg, J. Dropkin, J.E. Gold, Mobile input device type, texting style and screen size influence upper extremity and trapezius muscle activity, and cervical posture while texting, Appl. Ergon. 50 (2015) 98–104.

[39] I.S. Mackenzie, A note on calculating text entry speed, 2015. http://www.yorku.ca/mack/RN-TextEntrySpeed.html.

[40] J.T. Grudin, Error patterns in novice and skilled transcription typing, in: W.E. Cooper (Ed.), Cogn, Asp. Ski. Typewriting, Springer, New York, 1983, pp. 121–143.

[41] K. Curran, D. Woods, B.O. Riordan, Investigating text input methods for mobile phones, Telemat. Informatics. 23 (2006) 1–21.

[42] R.W. Soukoreff, I.S. MacKenzie, Measuring errors in text entry tasks: An application of the Levenshtein string distance statistic, Ext. Abstr. ACM Conf. Hum. Factors Comput. Syst. ACM, Seattle, 2001, pp. 319–320.

[43] L.A. Granka, T. Joachims, G. Gay, Eye-tracking analysis of user behavior in WWW search, Proc. 27th Annu. Int. ACM SIGIR Conf. Res. Dev. Inf. Retr. ACM, 2004, pp. 478–479.

[44] R.J. Jacob, S.K. Keith, Eye tracking in human-computer interaction and usability research: ready to deliver the promises, Mind’s Eye. (2003) 573–605.

[45] H. Nicolau, J. Jorge, Elderly text-entry performance on touchscreens, in: ASSETS’12, Colorado, 2012: pp. 127–134.

[46] K. McGrane, The rise of the mobile-only user, Harv. Bus Rev. (2013).