

## Effect of touch coordinate display as a form of augmented, concurrent visual feedback on the accuracy of single-handed typing via smartphone virtual keyboards

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**Abstract:** This study assessed the effect of an easily perceived real-time visual feedback method on touchscreen typing accuracy. Thirty subjects were asked to hold a smartphone with a capacitive touchscreen in one hand and enter a text using the thumb of the same hand via a custom designed virtual keyboard. There were two types of text entry sessions: with or without visual feedback. The visual feedback consisted of a full-screen crosshair, representing the accurate coordinate of touch in real time. In each session, touch-down time on the virtual keyboard and touch coordinates were recorded for every touch action. Two types of typing errors were defined: 1) centering error (CE), which was calculated as the mm distance between the coordinate of the touch and the center of the key, and 2) incorrect entry (IE), which was the number of missed keys. Student *t*-tests and Wilcoxon tests were used for mean and mean-rank comparisons of CE and IE, respectively. The results showed that visual feedback decreased CE (mean  $\pm$  SD) significantly from  $1.34 \pm 0.38$  mm to  $0.85 \pm 0.24$  mm ( $P < 0.0005$ ), and decreased IE (median and range, # of incorrect entries) significantly from 5.50 and 32.00 to 1.00 and 7.00 ( $P < 0.005$ ). In conclusion, the accurate, easily perceived, and 2D real-time feedback decreases touch-typing error rates markedly and therefore can be of practical importance for increasing the productivity of smartphone users.

**Key words:** Concurrent visual feedback, capacitive touch screen, single-handed touch typing

### 1. Introduction

Smartphones are becoming increasingly important for daily life, as they serve various functions such as information retrieval, social networking, and communication. Furthermore, the number of smartphone users in the world is rising steeply: 8.6 million in 2007 [1] and more than a billion in 2012 [2; [www.strategyanalytics.com](http://www.strategyanalytics.com)], while the estimation for 2014 was 1.75 billion [3; [www.emarketer.com](http://www.emarketer.com)]. The most common means for text input in modern smartphones are virtual keyboards on touchscreens, which can be challenging compared to physical keyboards. In addition to being slow and uncomfortable, typing on virtual keyboards is inaccurate and difficult even for expert typists [4]. Although smartphones now have dictation features, typing remains the only suitable text entry mode in many situations and the accuracy of touch-typing is important for an effortless flow of text input.

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Acquiring on-screen targets upon touching is generally assumed to be prone to error and different models have been proposed to account for the discrepancy between the intended and detected touch points [5,6]. There has been considerable work to improve touch-screen interactions for the device or the user (or both). Even though advanced methods, such as registering personalized touch offsets to recompute the coordinates acquired by the sensors, have been described to improve touch accuracy [5], providing sensory feedback to users offers an easier way of exploiting the fact that motor learning is enhanced by feedback [7]. Currently, visual, auditory, and haptic virtual keyboard feedback in the form of key press pop-ups, clicks, or vibration is available for many smartphones. Upon touching a soft key, the user feels a vibration, hears a click sound, or sees the touched key's symbol in a pop-up window, depending on the feedback type chosen. Virtual keyboard design can also be an important factor that affects typing accuracy. Type and design of touch sensors, keyboard layout, spacing, and the size of virtual keys, as well as the type of alphabet and context, size of finger/hand, and dominant hand contribute to the accuracy of typing and user efficiency [8–11]. Whereas typing accuracy can be improved on the device end by newer designs, feedback implementation appears to be an easier way to improve user efficiency, as it is independent of brand and/or the type of device. Furthermore, there is still room for developing a feedback method that is easy to implement and use.

From a kinesiological point of view, the act of typing on touchscreens requires coordination and execution of specific hand and/or finger actions at certain areas of the screen. The touchscreen can be either resistive or capacitive, and the type of screen determines the nature of the typing action. Whereas resistive screens require a sufficient amount of pressure to translate the point of touch into screen coordinates, capacitive touchscreens can operate without exertion of pressure, as they rely on the conductive properties of fingers to activate the sensors inside the screen [12]. Although smartphone screens now are mostly capacitive [11], our knowledge of smartphone interactions is mainly based on resistive touchscreen technology [4,6,13–19].

As one-handed thumb text entry on a touchscreen is getting to be a significant task in our daily lives in the smartphone era, texting accuracy and its improvement is of importance for user efficiency. Previous work on facilitation of thumb interactions with touchscreens proposed different techniques such as Thumbspace [20–23]; however, those studies mainly focused on pointing tasks rather than text entry. Although different keyboard designs have also been reported for ease of text entry [8,18], the studied means of text entry was pointing devices or index fingers.

In this study, we devised a novel method of visual feedback for thumb touch-typing and investigated its effect on input accuracy on capacitive smartphone touchscreens. We evaluated our feedback method, which consists of continuous display of touch coordinates in real time with a full-screen 2D crosshair during screen interaction, by analyzing the accuracy of single-thumb text entry on a capacitive smartphone touchscreen.

The practical results of this research are twofold: first, we define a novel visual feedback method for screen interactions, and second, we provide data on touch-typing errors during text input on capacitive touchscreens.

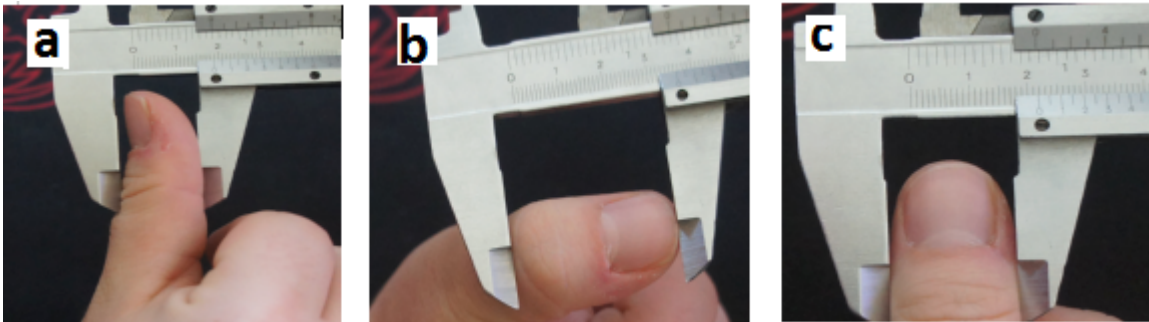
## 2. Methods

Thirty right-handed subjects (including 14 females) participated in the study. The subjects were volunteers recruited from among university students and faculties. Demographic information (age, body mass, and height), smartphone usage details (past smartphone experience duration (PSED), single-handed text input experience duration (SHTIED)), and thumb measurements of the subjects were collected (Table 1). For thumb measurements, distal phalanx length (from joint to tip), maximum width, and height of distal interphalangeal joint were measured (Figure 1A–1C). We assumed the thumb as a rectangular prism for our study and calculated

thumb area ( $thL \times thW$ ,  $thL \times thH$ ,  $thH \times thW$ , mean  $\pm$  SD) and volume ( $thL \times thW \times thH$ , mean  $\pm$  SD).

**Table 1.** Characteristics of the subjects. Normally distributed variables are shown as mean  $\pm$  SD. A non-Gaussian variable (\*) is shown as median (range).

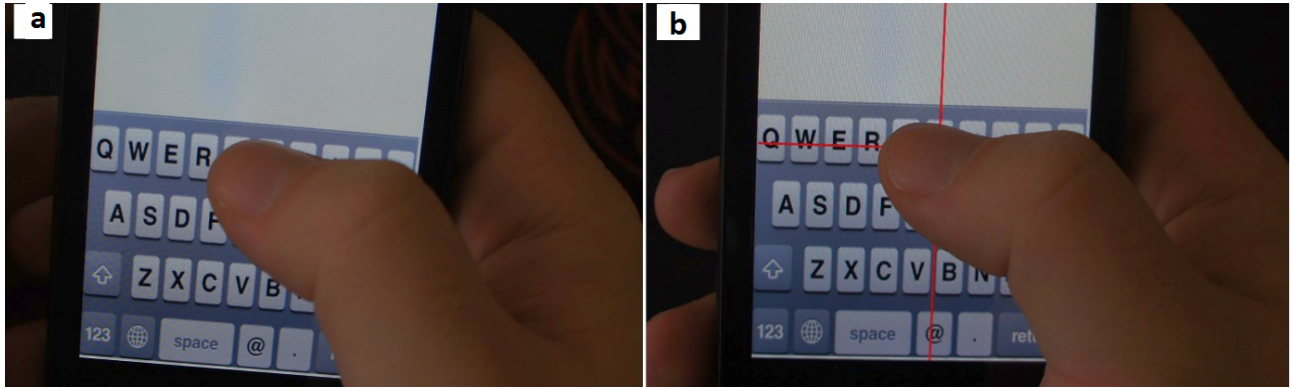
Variable	Mean $\pm$ SD
Age*	23.5 (R: 18-55) years
Body mass	68.6 $\pm$ 17.6 kg
Height	170.2 $\pm$ 9.1 cm
Past smartphone experience duration (PSED)	4.3 $\pm$ 2.8 years
Single handed text input experience duration (SHTIED)	2.7 $\pm$ 2.3 years
Average thumb length (thL)	34.3 $\pm$ 3.5 mm
Average thumb width (thW)	20.3 $\pm$ 3.5 mm
Average thumb height (thH)	16.9 $\pm$ 2.4 mm



**Figure 1.** Thumb height: a) length; b) width; c) measurement procedure.

A Motorola Droid X smartphone (Android OS version 2.3.4) was used in the study. The screen size was 4.3" and 480  $\times$  854 pixels. To assess the effect of 2D visual feedback, we developed an Android-based software that records users' touch-based interactions with the touchscreen. The software was displaying a keyboard image on the screen that mimicked the popular virtual keyboard with QWERTY layout from iPhone 5 iOS 6.1.3 (Figure 2A), allowed precise recording of touch coordinates (x, y) and number of touch occurrences (taps), and displayed a crosshair on the touch coordinate in real time on demand (visual feedback). The crosshair was augmented and appeared full-screen (Figure 2B).

Subjects were pseudorandomly assigned to two groups: A ( $n = 18$ ) and B ( $n = 12$ ). In Group A, the experimental procedure consisted of two sessions with at least 1-min intersession breaks for each subject. The subjects held the smartphone in their dominant hands and used the dominant hand's thumb for text entry. Subjects were asked to touch the center of areas that represent keys (26 alphabet and space keys) five times in a session with the following sequential order: 'qwertyuiopasdfghjklzxcvbnm' and 'space' (27 characters in total). We chose the sequential order as it is simple, context-free, and independent of language. Of the two consecutive sessions, one session (marked as  $n$ ) was without visual feedback, and the other was with visual feedback (marked as  $f$ ). The session order for each subject was either 'first  $n$ , then  $f$ ' or 'first  $f$ , then  $n$ '. Session orders were pseudorandomly assigned to the subjects. An adaptation session was carried out before the experiment. The subjects were asked to touch the virtual keys for 5 min in the order described previously,



**Figure 2.** Screen images of the virtual keyboard: a) without and b) with visual feedback (red crosshair).

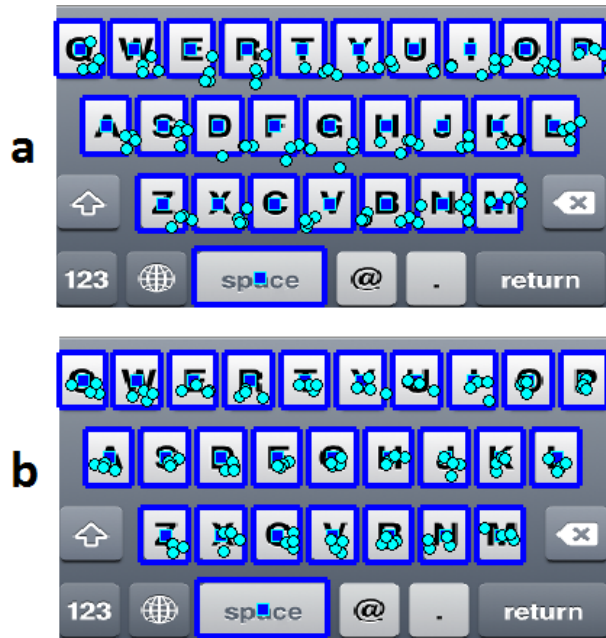
without visual feedback. The aim of this session was to accustom the subjects to the experimental device and ensure the stability of their self-selected tapping speed. In Group B, the experimental procedure was the same as in Group A, except a metronome with an audible sound beating at 60 ticks per minute was used during the sessions. The subjects were asked to synchronize their touch actions with the tick sounds. The metronome was used in both the adaptation and test sessions.

Every screen touch executed by the subjects was recorded in all sessions except the adaptation session. Figure 3 shows an example of a representative subject's touch coordinates for  $n$  (no feedback) (Figure 3A) and  $f$  (visual feedback) sessions (Figure 3B). Two error measures and intertouch intervals (ITIs, the interval between consecutive touches in ms) were calculated offline from the first 104 ( $26 \times 4$ ) touches. The first error measure, centering error (CE), was defined as the distance in mm between a touch coordinate and the corresponding key's center coordinate, and was calculated using the Pythagorean distance formula,  $d = \sqrt{\Delta x^2 + \Delta y^2}$  ( $\Delta x$  and  $\Delta y$  are the distance errors in x and y dimensions, respectively). The second error measure, incorrect entry (IE), was defined as the total number of the incorrectly pressed keys. A touch was counted as incorrect when its coordinate did not fall within the corresponding key's icon. The space key was not used in error measures because of its incompatible size. For the statistical analyses of CE, IE, and ITI measurements of the  $n$  and  $f$  sessions, we used the mean value of CE over all keys (except the space key), the sum of IE values, and the mean value of ITI for each subject.

Two-sided Student t-tests and Wilcoxon matched-pairs signed rank tests were used for Gaussian and non-Gaussian variables, respectively. The Kolmogorov–Smirnov test was used for a normality check prior to parametric tests. For each subject, the effect of visual feedback on mean error was calculated using the formula  $e_f/e_{nf}$ , where  $e_f$  and  $e_{nf}$  are errors of no-feedback ( $n$ ) and errors of feedback ( $f$ ) sessions, respectively. Spearman r correlation coefficients were calculated for  $e_f/e_{nf}$  versus user variables (age, weight, height, thL, thW, thH, thL  $\times$  thW, thL  $\times$  thH, thH  $\times$  thW, thL  $\times$  thW  $\times$  thH, PSED, and SHTIED). We used the Bonferroni correction for statistical tests and reported the corrected P-values.

### 3. Results

All variables other than IE were normally distributed according to the Kolmogorov–Smirnov test results. Figures 4A–4F show the individual data, mean/median of the error measures, and ITI values for the two experimental groups. The descriptive analysis of the error measures and ITI values are given in Table 2.



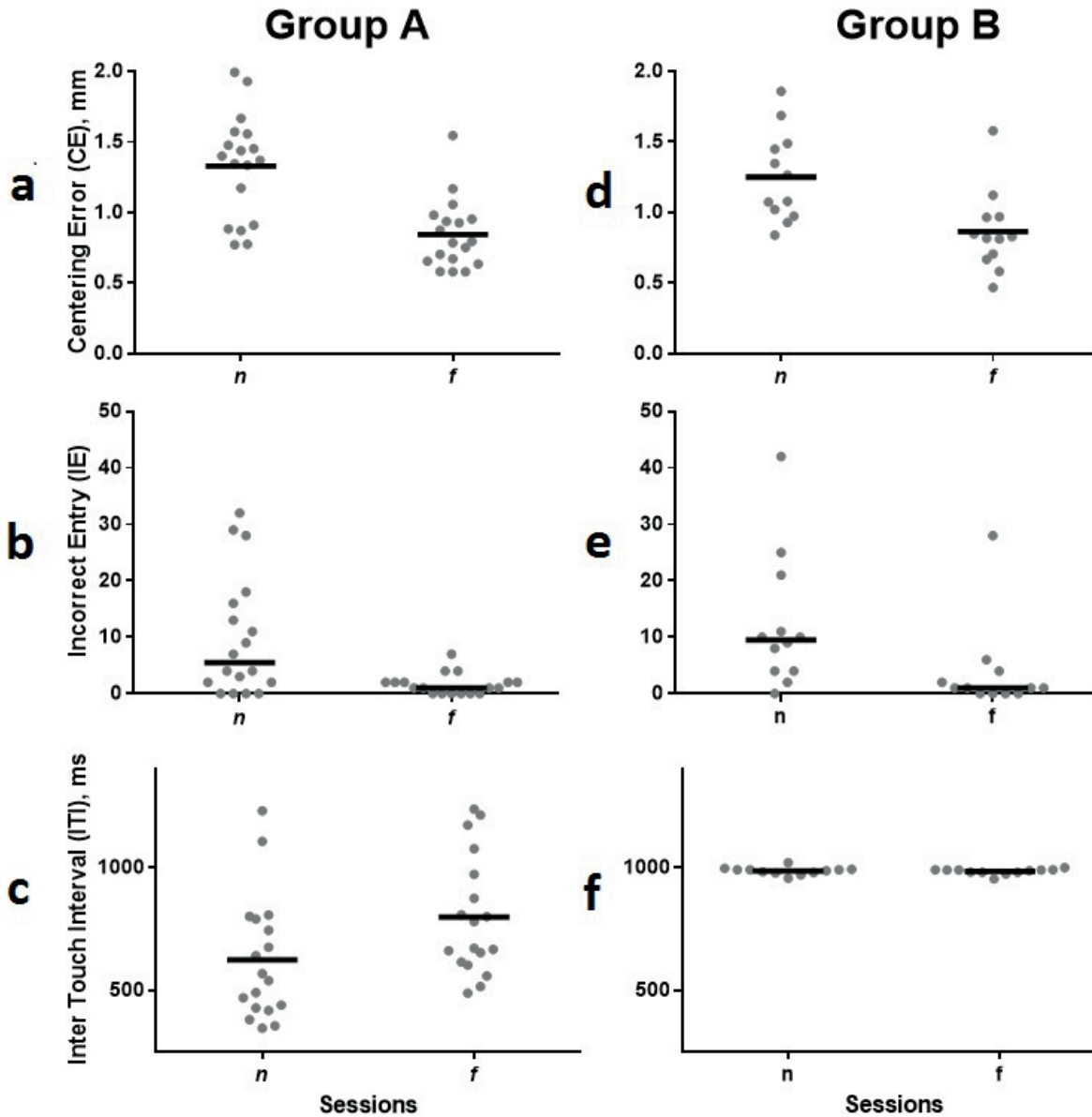
**Figure 3.** Touch coordinates of a representative subject from Group A in a)  $n$ , and b)  $f$  sessions. Touch coordinates and centers of key icons are shown with filled circles and filled small squares, respectively. Key icons were framed with blue lines for visualization purposes.

**Table 2.** Analysis results. Mean  $\pm$  SD and median (range) values of the variables used for comparison of the test groups are given along with Bonferroni corrected P-values. Gaussian and non-Gaussian variables were compared using two-tailed paired Student t-tests and two-tailed Wilcoxon matched-pairs tests, respectively. Detailed results of the statistical analysis are given in the text.

Group	Variable	No-feedback group	Feedback group	P value (no-FB vs. FB)
A (self-paced, $n = 18$ )	Centering error (CE), mm	$1.33 \pm 0.37$	$0.84 \pm 0.25$	$P < 0.0006$
	Incorrect entry (IE)	5.50 (R: 32.00)	1.00 (R: 7.00)	$P < 0.0020$
	Inter touch interval (ITI), ms	$624.47 \pm 253.00$	$798.76 \pm 242.55$	$P < 0.0006$
B (metronome-paced, $n = 12$ )	Centering error (CE), mm	$1.25 \pm 0.32$	$0.86 \pm 0.29$	$P < 0.0006$
	Incorrect entry (IE)	9.50 (R: 42.00)	1.00 (R: 28)	$P < 0.0070$
	Inter touch interval (ITI), ms	$986.63 \pm 15.48$	$984.27 \pm 11.73$	NS

For Group A ( $n = 18$ ), Student t-tests showed that there was a statistically significant effect of visual feedback on CE, as the mean value of CE in the  $f$  session was significantly smaller than that of  $n$  session ( $t(17) = 7.48$ ,  $P < 0.0006$ ). Wilcoxon tests showed that there was a statistically significant effect of visual feedback on IE, as the difference between the mean (rank) of the IE was significantly smaller for the  $f$  session compared to the  $n$  session ( $P < 0.0020$ ). Student t-tests showed that there was also a statistically significant effect of visual feedback on ITI values, as there was a significant difference between the mean ITI values of  $n$  and  $f$  sessions ( $t(17) = 7.90$ ,  $P < 0.0006$ ).

For Group B ( $n = 12$ ), Student t-tests showed that there was a statistically significant effect of visual feedback on CE, as the mean value of CE in the  $f$  session was significantly smaller than that of the  $n$  session ( $t(11) = 9.05$ ,  $P < 0.0006$ ). Wilcoxon tests showed that there was a statistically significant effect of visual



**Figure 4.** The results for Group A (4a, 4b, 4c) and Group B (4d, 4e, 4f). The horizontal line superimposed on individual values show the mean (CE, ITI) or median (IE) values of all the subjects. Each individual data point in 4a, 4c, 4d, and 4f shows the mean value of the respective measure over a total of 104 ( $26 \times 4$ ) touch actions. Each individual data point in 4b and 4e shows the total number of missed keys (IE) in a session. Units for IE and ITI are mm and ms, respectively. In Group A, the subjects touched the virtual keys at a self-selected tapping speed; in Group B, the subjects touched virtual keys at each tick sound of a metronome (60 ticks/min). See Section 2 for the details of the sessions.

feedback on IE, as the difference between the mean (rank) of the IE was significantly smaller for the *f* session compared to the *n* session ( $P < 0.007$ ). There was no statistically significant difference between the ITI values of the *n* and *f* sessions ( $t(11) = 0.53$ ,  $P > 0.05$ ).

In summation, for Group A, visual feedback caused a significant improvement in accuracy, as there was a 37% decrease in the mean CE value and an 82% decrease in the median IE value. Visual feedback also caused

a 28% increase in the mean ITI value (from  $624 \pm 253$  ms to  $799 \pm 242$  ms). For Group B, visual feedback also caused a significant improvement in accuracy, as there was a 31% decrease in the mean CE value and an 89% decrease in the median IE value. No significant difference was observed when the error measures were compared between the two groups ('CE, Group A vs. B' and 'IE, Group A vs. B'). The results show that there is no statistically significant ITI effect on the CE and IE error measures.

We performed microanalyses of our data by calculating separate Student t-tests of error measures for each key (except the space key) by pooling all the subjects into a single group ( $n = 30$ ). Student t-tests showed that, for each key, the CE was significantly lower in the visual feedback (**f**) session than in the no-feedback (**n**) session. The result confirms that no key-related bias was created in our experimental setup. We did not perform microanalyses for the IE error measure, as the missed key count in our experiments was not sufficient for statistical analysis.

Measurements of thumb areas and volume were  $thL \times thW = 7.0 \pm 1.8$ ,  $thL \times thH = 5.8 \pm 1.3$ ,  $thH \times thW = 3.5 \pm 1.1$  cm<sup>2</sup>, and  $thL \times thW \times thH = 12.2 \pm 4.9$  cm<sup>3</sup>, respectively. Spearman r correlation analyses did not show any significant correlation between the error rate values and thumb parameters. Similarly, there was no significant correlation between the error rate values and user experience parameters (PSED, SHTIED).

#### 4. Discussion

From messaging to getting directions, text entry is a part of various smartphone interactions. As touchscreen smartphones are gaining popularity, soft keyboards are becoming the major means of text input. Touch-typing on virtual keyboards of smartphones, as an action, is a small target acquisition task [24], which requires precise motor control and benefits from external sensory feedback [18].

In this study, we evaluated the effect of a novel visual feedback method on the accuracy of text entry on a smartphone touchscreen. The display of touch coordinates in real time during single-handed thumb-typing on the virtual keyboard significantly reduced the deviation of touches from the center of the soft keys and decreased the number of mistypes. Moreover, the crosshair style does not limit the visibility of the screen or virtual keyboard.

As we observed a statistically significant increase in the ITI values of visual feedback (**f**) sessions compared to no-feedback (**n**) sessions, we examined the effect of ITI on the error measures, i.e. IE and CE error differences that could arise from ITI differences. For this purpose, we performed a metronome-paced touch experiment (i.e. Group B), which would also serve as a control for Group A (self-paced session). As some of the Group A subjects expressed their subjective feeling that their performances were spontaneously improved after the visual feedback session, we recruited a separate group of subjects (selected pseudorandomly from thirty subjects) for the metronome-paced measurements to eliminate a possible effect of attention or adaptation. We used a 1-s period for the metronome rather than the mean ITI of Group A's **f** session (799 ms), because some of the subjects expressed that the period was fast and irritating. No further complaints were received upon increasing the period to 1 s. Although ITI values were statistically different between the **n** and **f** sessions within Group A, the comparison of error measures of Group A and B ('**n** of Group A vs. **n** of Group B' and '**f** of Group A vs. **f** of Group B') did not show any statistically significant ITI effect. The results indicated that the observed increase in touch-typing accuracy upon touch coordinate feedback was not biased by ITI. We also examined whether our results had been affected by the order of **f** and **n** sessions despite pseudorandom assignment. Comparison of the error measures of the two groups of subjects that performed the sessions in the order of **f** – **n** ( $n = 9$ ) and **n** – **f** ( $n = 9$ ) did not show a significant effect of session order. Detailed statistical analysis



of our data indicate that coordinate display provides an effective method of external visual feedback.

Touch acquisition errors have been explained with the ‘fat finger’ problem, which defines the fingertip softness and occlusion of small targets as the cause of error [6]. Recently, an alternate explanation, which indicates the touchscreen device as the origin of touch errors, has been published [5]. Our data, where no correlation between the error rates and thumb properties was found, appear to support this view. In effect, if touch-typing errors are due to sensor properties, concurrent display of touch coordinates as detected by the sensors can improve typing accuracy regardless of device/model. Considering that we found no correlation between the subject experience and error rates, the prominent decrease in errors upon coordinate feedback suggests that the method can be beneficial for a wide variety of user profiles.

Although the cross-air feedback method significantly decreased the text input error rates, it did not completely eliminate them. It is possible that the limited range of thumb motion [25] can complicate thumb-typing while holding the device in one hand. This limitation can be seen as a drift from the visual center of soft keys [5,19]. The cross-hair method was effective in decreasing the DC shift from the button center (Figure 3). A real-time touch coordinate display provides an easily perceived and accurate visual feedback method, which might be beneficial in increasing productivity in a considerable percentage of over one billion smartphone users, who thumb-type while holding their smartphones with one hand.

The method might also be valuable for patients that have motor control disorders during their interactions with touchscreens. As sequential order text entry is context-free and independent of any language-specific keyboard layout, this method can be used universally in quantifying motor control during touch-typing on smartphones. However, there are certain limitations to this study: the results are valid only for the screen size of the selected test device, and the education level of the subjects and the memory effect of the visual feedback might have affected the results. Further research is necessary for the comparison of the cross-hair method to existing feedback methods and for establishing its use under disease conditions.

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The ethics committee approval label of the study is GO 13/231.

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