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Investigation into Touch Performance on a QWERTY Soft Keyboard on a Smartphone: Touch Time, Accuracy, and Satisfaction in Two-Thumb Key Entry

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Abstract: This research aims to examine touch performance and user-satisfaction depending on key location in a QWERTY soft keyboard during two-thumb key entry on a smartphone. Thirty-three college students who were smartphone users were recruited, and an experimental program was implemented to measure their task completion time, the number of touch errors, and user-satisfaction during key entry. The QWERTY layout was split into 15 zones to assign absolute positions for reliable statistical analysis. The results showed that the zones with significantly longer task completion times were observed more prevalently in the zones in the periphery ($p < 0.0001$). In addition, relatively higher subjective satisfaction ratings were found in the zones in the center area of the QWERTY layout ($p < 0.0001$). It seemed that both of the results were improved in the zones that participants could immediately see without moving the thumbs, before touch interaction. Meanwhile, touch error frequencies failed to show statistical significance among the zones ($p = 0.3195$).

Keywords: QWERTY soft keyboard; two-thumb key entry; touch performance

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1. Introduction

Despite rapid changes in smartphone technologies, a QWERTY layout is still considered to be an important method of text entry on smartphones. A QWERTY soft keyboard is the most fundamental tool for text entry provided by most smartphones available in the global market [1,2], and simultaneously, it is regarded as the most popular layout of soft keyboards among smartphone users [3,4]. In general, smartphone users may prefer the QWERTY layout, as their previous experience with a personal computer can be applied to texting on a smartphone [5,6]. In sum, although a variety of new soft keyboard layouts have been introduced and attempted, a QWERTY layout has continued to be favored for text entry on smartphones in the market.

The use of a QWERTY soft keyboard on a smartphone could face a couple of chronic user-experience issues due to the characteristics that are inherent in the design, although it has shown high popularity as a way of text entry. In particular, for instance, the limited small area (usually the lower portion of a touch screen) of a smartphone must accommodate more than 26 keys consisting of letters and functions, and thus the key sizes are generally small, which could be considered a factor in performance degradation (e.g., speed and accuracy) during key entry [6]. Next, since the keys are widely spread out on the touch screen, the motion and travel distance of the fingers (usually the thumbs) required for key entry significantly change as functions of key positions [7–10]. In addition, depending on the hand postures or locations for grasping a smartphone, some keys (especially those located in the periphery of a QWERTY layout) could be often occluded by the fingers employed for touch interactions [8,10,11]. In short, these issues could degrade the texting speed and accuracy on a smartphone and furthermore have a negative impact on user-discomfort and user-satisfaction when using a smartphone.

A variety of studies with respect to soft keyboards have been conducted to improve the usability and performance of key entry on a smartphone. For example, Chang and Jung [9], Parhi et al. [12], and Park and Han [11] investigated the relationship between key sizes on a soft keyboard and touch performance. They reported that touch speed, touch accuracy, and user-satisfaction improved as the size of the keys increased. In addition, Chang et al. [8] and Park and Han [7] examined how the positions of keys on a soft keyboard affected touch performance. They confirmed that the keys that were located farther from the thumbs' initial positions required more cognitive effort as well as elongated the travel time of the thumbs to reach the keys, resulting in greater user-discomfort. On the other hand, Ashaduzzaman et al. [13] and Pritom et al. [3] analyzed the variation in touch performance as a function of different shapes and layouts of keys on a soft keyboard. They showed some evidence that the speed and accuracy of text entry could be improved when the shapes and layouts of keys on a soft keyboard were modified.

From a practical point of view, however, existing studies of soft keyboards on a smartphone might have a couple of limitations in the application of the results directly in design improvement in a QWERTY soft keyboard on a smartphone. Above all, a majority of these studies employed only part of the keyboard or a few of the keys that were placed far apart from one another, in order to clearly observe the positional effects of the keys. As is well known, however, a QWERTY soft keyboard consists of more than 26 keys with different alphabet letters and functions and the keys are stuck closely together in terms of distance. This indicates that a user would require greater cognitive and physical efforts for their decision making as well as need to secure more clear vision to locate one target key among a large number of keys on a QWERTY layout, as compared to the case of locating a target key from a small number of keys [14,15]. In addition, most of these studies guided participants' grip postures of holding a smartphone and placed the initial positions of their thumbs near the predetermined spots on its screen, so as to help clearly obtain the times taken until touches were made on target keys in different locations. However, users usually hold a smartphone in various preferred ways in everyday life, and it is certain that the initial positions of their thumbs are not predetermined during texting as well. Accordingly, users might face different use-cases with a QWERTY soft keyboard in real life from the existing studies, in terms of touch performance and user-experience. All things considered, more studies focusing on a QWERTY soft keyboard itself (i.e., its original layout) are warranted to help to improve its user-experience. In particular, the fundamental usability characteristics of a QWERTY layout on a smartphone should be investigated first.

This research aimed to investigate touch performance and user-satisfaction as functions of the key locations on a QWERTY soft keyboard for two-thumb key entry on a smartphone. Thus, the following research hypothesis was tested in order to discuss the significance of Fitts' law, securing vision on keys, and physical effort to reach keys in key entry using a QWERTY soft keyboard: users' task completion time, touch error frequency, and subjective satisfaction are significantly affected by the locations of target keys on a QWERTY layout. To verify this, a smartphone application was developed to display a QWERTY soft keyboard. Testing was performed to measure the task completion time, touch error frequency, and subjective satisfaction as functions of 26 alphabet letter keys on the QWERTY layout. In addition, the effects of the key locations were statistically tested against the results of the measurements. Lastly, the findings of the present study are discussed as compared with the existing studies on soft keyboards, and design recommendations to improve the usability of a QWERTY soft keyboard are suggested based on them.

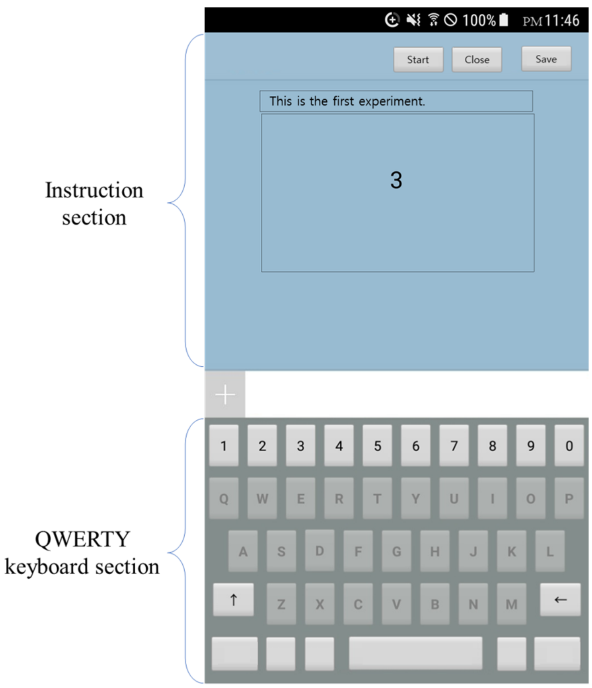
2. Methods

2.1. Participants

Thirty-three college students (males: 16, females: 17) voluntarily participated in this study. The participants ranged in age from 21 to 28 years (average age: 23.1 years; SD: 1.6), and owned smartphones for daily use (average smartphone experience: 5.7 years; SD: 1.6). They were all right-handed and their average hand length and width were 16.7 cm (SD: 1.5) and 6.6 cm (SD: 1.5), respectively. All of the participants had no history of visual impairment and were able to move their thumbs without musculoskeletal problems—in addition, wearing glasses or contact lenses were permitted to correct their vision during the experiments. The participants received a description of the experimental protocols, and their informed consent forms were then obtained. Note that this study had institutional review board approval from the Dongguk University, Seoul, Korea (DUIRB-202210-03).

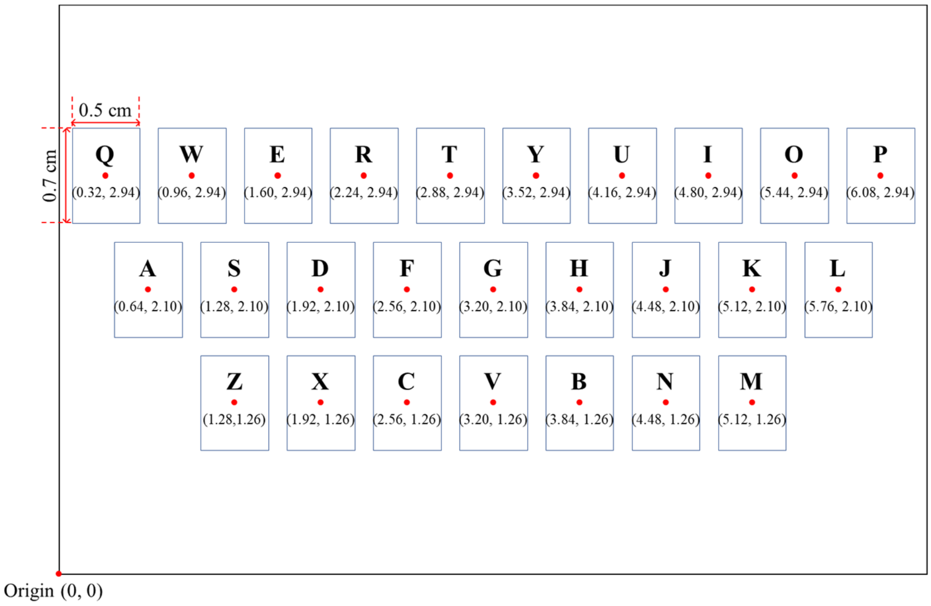
2.2. Equipment

Testing employed a smartphone with Android Oreo 8.1 (Google, Mountain View, CA, USA) commercially available on the market (Galaxy S6, Samsung, Gyeonggi Province, Korea). The smartphone had the dimensions of 7.1 cm × 14.3 cm × 0.7 cm (width × height × thickness), and its touch screen size and resolution were 6.4 cm × 11.3 cm (width × height) and 1440 × 2560 pixels, respectively. Two sections were created on the touch screen: (1) an instruction section (top) and (2) a QWERTY keyboard section (bottom) (Figure 1a). The instruction section (6.4 cm × 5.0 cm) was implemented to display experimental information such as a target letter and the number of trials that could help participants' progress in given tasks. On the other hand, the QWERTY soft keyboard (6.4 cm × 4.2 cm) of the application had a similar layout to a typical QWERTY keyboard that basically consisted of 26 alphabet letter keys—here, the size of the letter keys was maintained at 0.5 cm × 0.7 cm (width × height), and they were located in the predetermined positions on the keyboard, as illustrated in Figure 1b. Note that extra keys including ten numeric keys on the top row and a few additional keys near the bottom (assumed as functions) were also rendered on the QWERTY soft keyboard, but they did not actually work.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. Experimental application. (**a**) Experimental screen; (**b**) key positions in the QWERTY keyboard section (the dots indicate the geometric center of each key; unit: cm).

An Android application for this study was implemented using M-BizMaker (Softpower, Seoul, Korea) based on the Samsung keyboard 3.2.10.22 (Samsung, Gyeonggi Province, Korea), as shown in Figure 1. The application was designed to provide one random target key from the 26 alphabet letters at a time; to be specific, the application was launched by pressing the start button on the top row of the screen. After a countdown of three seconds, the information for the first target key appeared in the center of the instruction section, and then the corresponding letter key on the QWERTY keyboard section was highlighted in light gray to help the participant to easily locate the key. After the target key was successfully touched, the application counted down three seconds again and provided its next target key—this was repeated until every alphabet letter appeared once in each experimental trial. On the other hand, the application had a feature that automatically recorded the task completion times (unit: msec) and touch error frequencies. The task completion time was defined to measure the duration from the moment when a target key was provided to the moment when the target key was successfully tapped. Meanwhile, the touch error frequency was counted for the touch errors occurring for each given key until a successful touch was made.

2.3. Experimental Design

A one-factor within-subject design was used for the current study. Fifteen zones that divided the QWERTY layout into equal-sized rectangles (1.28 cm $\times$ 0.84 cm) were employed as the independent variables for testing (Figure 2). In addition, three dependent variables were measured for each zone during the experiments: (1) task completion time, (2) touch error frequency (the number of touch errors), and (3) subjective satisfaction. In fact, testing was conducted for the 26 letter keys on the keyboard section, but the keys were rearranged into the zones due to the following reasons. First, since the large number of treatments (i.e., 26 letter keys) in the independent variables may disproportionally inflate the type I error amount in ANOVA, the number of treatments needed to be reduced to improve the reliability of the analysis. Second, the well-structured zones were assigned absolute positions on the QWERTY layout and thereby could not only help to clearly observe the positional effects of the keys but also allow us to compare them with similar studies regardless of device sizes, which could lead to better generalization. Therefore, the data (task completion time, touch error frequency, and subjective satisfaction) collected from the letter keys were assigned to the corresponding zone containing the key, and the values were averaged for each zone, respectively. Note that if a letter key was located across the boundary line between two zones (e.g., the letters B, C, F, H, K, M, S, and Z), the measured data of the letter key were assigned into both of the zones at the same time.

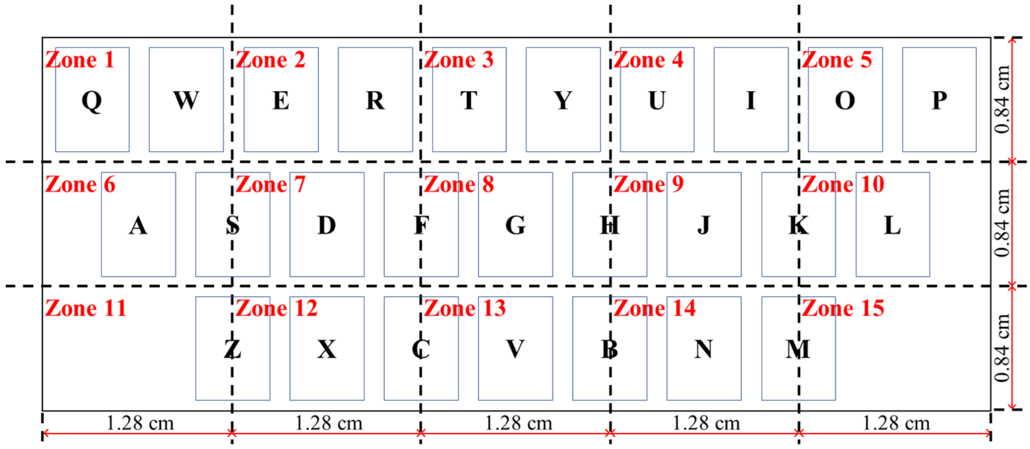


Figure 2. Fifteen zones.

Participants' postures were controlled during the experiments. The participants were required to sit in a given chair and had opportunities to set the seat pan height as needed. They were asked to keep their elbows in a relaxed position on a desk to minimize any extraneous body movements, and then permitted to hold a smartphone naturally using both their hands in portrait orientation as usual. Before each target key appeared, in addition, the participants were allowed to rest their thumbs wherever they preferred (assumed as the thumbs' initial positions before texting) over the QWERTY keyboard section.

The participants began the main experiments after having practice trials that were designed to familiarize them with the experimental application. During the main testing, the participants were instructed to tap the target keys as fast and accurately as possible. In addition, they were asked to move their thumbs back to the initial positions whenever target keys were successfully touched. Here, if the participants did not make a successful touch, they had to keep tapping the ongoing target key again until the key was successfully touched. Meanwhile, all of the letter keys were allowed to be tapped by the thumb of the favored hand (left or right) without any restriction—however, the participants showing extreme use-cases (e.g., the keys on the very right of the keyboard were tapped by the left thumb or most keys were tapped by only one thumb) were excluded. One experimental trial was composed of 26 target keys (i.e., 26 alphabet letters) and this was repeated twice, i.e., a total of 52 target keys were displayed during one experiment (26 alphabet letters $\times$ 2 repetitions). Lastly, the participants were asked to rate the subjective satisfaction of each alphabet letter key, after all of the given trials were completed. For the deliberate assessment, they were allowed to manipulate the smartphone employed in the experiments again, and no time restriction was imposed. Each alphabet letter was comprehensively assessed once and a 7-point Likert scale that varied from one to seven was employed for the assessment—any categorical meaning was not assigned to each point on the scale except one (highly dissatisfied), zero (neutral), and seven (highly satisfied). Note that the 7-point Likert scale in the present study was practically used as a continuous measure like a visual analog scale, except that only integers were allowed as answers.

2.4. Statistical Analysis

The data of the dependent variables failed to show their normality. However, no outliers were found (three sigma rule) and the data had good equal variances among the differences between all possible pairs of within-subject conditions—the *p*-values of Mauchly's sphericity test were 0.116, 0.323, and 0.233 for the task completion time, touch error frequency, and subjective satisfaction, respectively. ANOVA was finally selected as the analysis method for the study, because it is well known that the results of the F-test in ANOVA are statistically robust, regardless of whether the data are sampled from a normally distributed population or not [16–21].

In the present study, therefore, to investigate the variations in the task completion time, touch error frequency, and subjective satisfaction as functions of the 15 zones, one-factor within-subject ANOVA was conducted for each dependent variable at $\alpha = 0.05$. In addition, the partial eta^2 was simultaneously computed to confirm the reliability of the ANOVAs. Lastly, a post hoc analysis was conducted using the Tukey test at the same significance level.

3. Results

3.1. Task Completion Time

The task completion times varied significantly by the zones in the QWERTY soft keyboard ($F(14, 448) = 4.84$, $p < 0.0001$, partial eta$^2 = 0.13$) (Table 1). As shown in Figure 3, the Tukey test determined that zones 1, 3, 4, 6, 7, 9, 11, 12, 14, and 15 showed statistically longer task completion times than the other zones—in particular, the longest task completion times were found in zone 11. Meanwhile, zones 2, 3, 4, 5, 7, 8, 9, 10, 13, and 14 were classified into the shortest group of the task completion times.

Table 1. Task completion time, touch error frequency, and subjective satisfaction as functions of zones.

Zone	Task Completion Time (s)	Touch Error Frequency	Subjective Satisfaction
1	$1.04^{\alpha,\beta}$ (SE: 0.05)	0.05 (0.05)	$4.59^{\delta-\zeta}$ (0.27)
2	$0.92^{\gamma,\delta}$ (0.04)	0.02 (0.02)	$5.29^{\alpha-\gamma}$ (0.21)
3	$0.98^{\alpha-\delta}$ (0.04)	0.03 (0.03)	$5.35^{\alpha-\gamma}$ (0.22)
4	$0.96^{\alpha-\delta}$ (0.05)	0.02 (0.03)	$5.35^{\alpha-\gamma}$ (0.20)
5	$0.94^{\beta-\delta}$ (0.05)	0.01 (0.02)	$4.61^{\delta-\zeta}$ (0.25)
6	$1.04^{\alpha,\beta}$ (0.09)	0.02 (0.02)	$4.68^{\gamma-\zeta}$ (0.24)
7	$0.96^{\alpha-\delta}$ (0.08)	0.01 (0.02)	$5.42^{\alpha,\beta}$ (0.21)
8	$0.95^{\beta-\delta}$ (0.03)	0.01 (0.01)	5.67^{α} (0.21)
9	$0.95^{\alpha-\delta}$ (0.03)	0.02 (0.02)	$5.55^{\alpha,\beta}$ (0.21)
10	0.90^{δ} (0.03)	0.00 (0.00)	$4.98^{\beta-\varepsilon}$ (0.25)
11	1.08^{α} (0.05)	0.03 (0.03)	3.88^{ζ} (0.28)
12	$1.00^{\alpha-\gamma}$ (0.05)	0.03 (0.03)	$4.43^{\varepsilon,\zeta}$ (0.26)
13	$0.92^{\gamma,\delta}$ (0.04)	0.03 (0.03)	$5.03^{\beta-\delta}$ (0.22)
14	$1.00^{\alpha-\delta}$ (0.04)	0.01 (0.02)	$4.76^{\gamma-\varepsilon}$ (0.23)
15	$1.07^{\alpha,\beta}$ (0.04)	0.00 (0.00)	$4.36^{\varepsilon,\zeta}$ (0.22)

The Greek letters indicate statistically different groups at a 95% confidence level ($\alpha > \beta > \gamma > \delta > \varepsilon > \zeta$); the superscripts indicate the statistical groups to which the values belong (e.g., α–γ indicates that the value belongs to three groups: α, β, and γ).

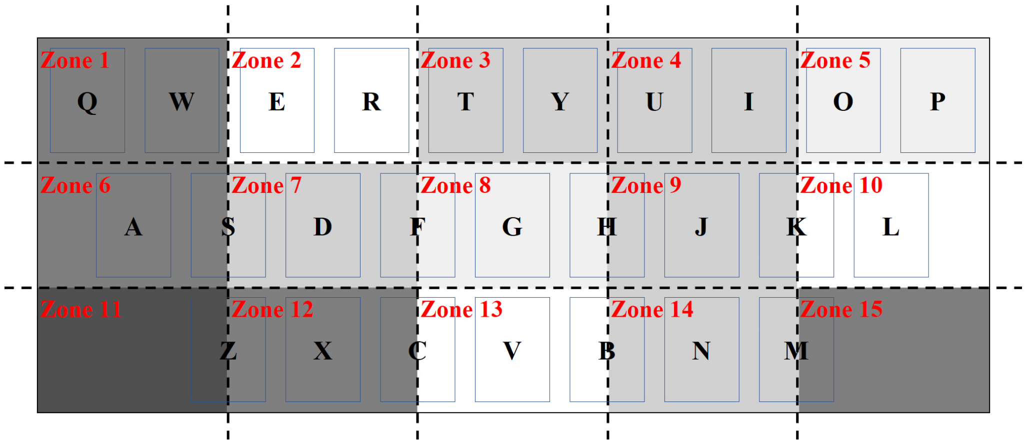


Figure 3. Task completion times in fifteen zones (the darker colors represent longer task completion times).

3.2. Touch Error Frequency

No statistical significance was found in touch error frequencies among the zones of the QWERTY soft keyboard ($F(14, 448) = 1.14$, $p = 0.3195$, partial eta$^2 = 0.03$), as shown in Table 1. Although the touch error frequencies failed to show statistical significance, a couple of remarkable patterns were observed. For example, touch errors were more likely to occur in the peripheral area (especially zones 1, 3, 11, and 12) on the left side of the QWERTY keyboard. Overall, in addition, the right side of the QWERTY keyboard (e.g., zones 4, 5, 9, 10, 14, and 15) showed a relatively small number of touch errors.

3.3. Subjective Satisfaction

Subjective satisfaction ratings significantly changed depending on the zones of the QWERTY soft keyboard ($F(14, 448) = 13.17$, $p < 0.0001$, partial eta$^2 = 0.29$), as illustrated in Table 1. The Tukey test revealed that relatively higher subjective satisfaction ratings were observed in zones 2, 3, 4, 7, 8, and 9 (Figure 4). Simultaneously, the lowest subjective satisfaction rating was found in zone 11, followed by zones 1, 5, 6, 11, 12, and 15.

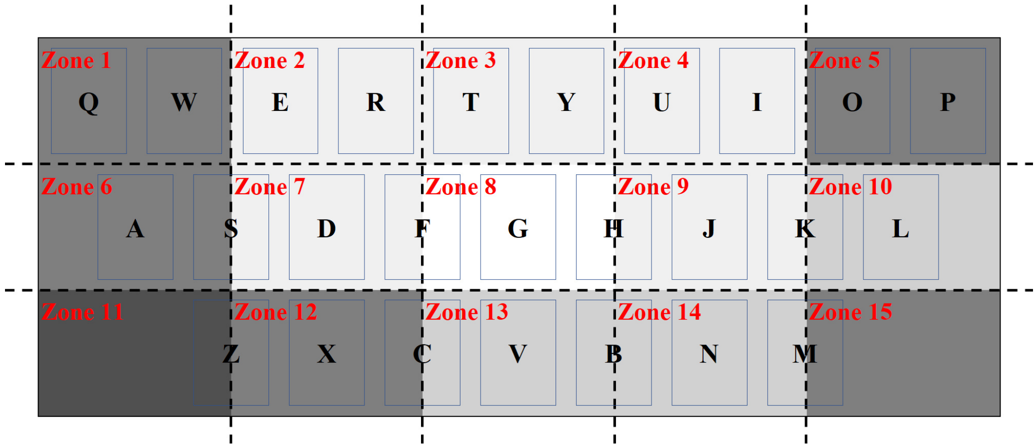


Figure 4. Subjective satisfactions in fifteen zones (the darker colors represent lower subjective satisfaction ratings).

4. Discussion

4.1. Task Completion Time, Touch Error Frequency, and Subjective Satisfaction

As expected, the task completion times varied significantly by zones on the QWERTY soft keyboard. The results showed a couple of unique patterns that were somewhat different from the previous studies, which showed two findings for key entry using the thumbs [8,9,11,22]: (1) the shortest task completion times were found near the center area of the keyboard (i.e., approximately around zone 7 for the left thumb and zone 9 for the right thumb in this study), where the thumbs were designated to stay before every movement for touch interaction (i.e., called the initial positions of the thumbs) for testing, and (2) the farther away from the initial positions of the thumbs the target keys were, the longer the task completion times became. First of all, the shortest task completion times were observed in zones 2, 10, and 13 in the present study. When considering the finding of the previous studies that the shortest touch times were observed around the thumbs' initial positions according to Fitts' law, this can be interpreted as the fact that the initial positions of the thumbs in the present study were likely to be located near those zones. That is, in this study, the initial positions of the thumbs were placed asymmetrically around zones 2 and 13 for the left thumb and zones 10 and 13 for the right thumb. It was unclear why the initial positions of the thumbs were found in these zones in the present study. However, we estimated that the habits of grasping a smartphone with the hands would influence this phenomenon, because participants were allowed to grasp the given smartphone in their preferred ways as usual in the present study. To give a plausible example, for two-thumb text entry using a QWERTY soft keyboard, users tend to grasp a smartphone (in particular, its lower part) with their dominant hand first and then wrap it using the other hand. Naturally, this could help the tip of the dominant thumb (i.e., the thumb-tip of the right hand in this study) to be located near the right border of the QWERTY keyboard section (approximately near zones 5 and 10 in the present study) because the back of the phone is likely to rest on the palm of the dominant hand—in particular, the deeper the smartphone is held in the palm of the dominant hand, the clearer this tendency could become. In addition, the tip of the non-dominant thumb (i.e., the thumb-tip of the left hand) may be located toward the center area of the keyboard (approximately near zones 2, 7, 8, 12, and 13 in the present study), since the non-dominant hand needs to grasp the smartphone over the dominant hand. However, this mechanism is one assumption based on the participants' debriefing session of the present study, and thus further study is warranted to verify this habitual way to grasp a smartphone and its relationship with the thumbs' initial positions for text entry.

In addition, the zones with significantly longer task completion times were more prevalently observed in the bottom row and the very left column of the zones—this was also a little different from the aforementioned studies that showed the regular pattern that task completion times gradually increased as a target key moved from the center (i.e., the thumbs' initial positions) to the periphery areas on the QWERTY keyboard. We estimated that this propensity was strongly associated with the thumbs' initial positions that were asymmetrically found in the present study. A couple of pieces of evidence support this assumption. First, the zones with relatively longer task completion times were roughly matched with the keys on the keyboard that could be visually occluded due to the thumbs' initial positions. For instance, zones 1, 6, 11, and 12, with relatively slow task completion times, were likely to be screened by the left thumb when the thumb-tip was located in zones 2 or 13 (i.e., the left thumbs' initial positions in the current study). Simultaneously, zone 15 could be potentially obscured by the right thumb because the thumb-tip was probably placed in zones 10 or 13 (i.e., the right thumbs' initial positions in the current study) before touch interaction. Likewise, the zones (mostly in the center area of the keyboard) that were not likely to be visually occluded due to the thumbs' initial positions showed relatively shorter task completion times. Chang and Jung [9] explained these phenomena that visually occluded keys could delay touch interaction during key entry on a smartphone by the fact that users might need to unnecessarily do one more step called searching a target with the eyes before moving their fingers. Second, the zones that had to be reached by flexing the interphalangeal and metacarpophalangeal joints of the thumbs were well-matched with the zones with relatively longer task completion times in the present study. For example, zones 6, 11, and 12 that could be reached by flexing the left thumb from the initial position were roughly accorded with the zones that showed relatively slow task completion times on the left side of the keyboard (zones 1, 6, 11, and 12). In the same manner, zone 15, which could be reached by flexing the right thumb, was completely consistent with the zones that showed relatively slow task completion times on the right side of the keyboard (zone 15). In fact, this was expected because the flexion of the thumbs typically requires a great deal of perceived effort as well as a large amount of joint displacement [8,9,22–25]. Therefore, we believed that it was natural that touch interactions were delayed in zones 6, 11, 12, and 15 during key entry. All things considered, to recap, these findings could be regarded as evidence enough to support the notion that the patterns in the task completion times were strongly affected by the thumbs' initial positions in the present study.

On the other hand, overall, the task completion times on the left side of the keyboard were longer than those on the right side. We estimated that this was related to the fact that all of the participants recruited for the present study were right-handers, since it is well known that the dominant hands typically outperform the non-dominant hands in most motor tasks, especially in speed and accuracy [26–28], i.e., this is just a guess but this might indicate that the thumb of the dominant hand still showed more superior touch performance than that of the non-dominant hand in key entry, even using a QWERTY soft keyboard. However, this should be verified via experimental methods.

Touch error frequencies failed to show statistical significance among the zones. In other words, this indicated that touch errors may have occurred, regardless of the locations of keys on the QWERTY soft keyboard in the present study. However, we assumed that this might be a premature judgement, in considering the fact that each experimental trial was only repeated twice during testing. Note that, indeed, the number of touch errors was too small in the present study as well, perhaps because the size of the keys (0.5 cm $\times$ 0.7 cm) employed in the present study was used in a large number of smartphones often enough that the participants could feel familiarity with them. This was because the lack of experimental trials could have an adverse effect on the statistical significance of the touch error frequencies among the zones, i.e., an adequate number of touch errors to have statistical power may not have been acquired in this study. As evidence, although not statistically significant, faint but reasonable patterns in the touch error frequencies were observed as a function of the zones in this study. For example, touch errors were more prevalent on the left side of the keyboard—as aforementioned, this might have been affected by the fact that the dominant hand usually has better motor performance than the non-dominant hand in speed and accuracy [26–28]. In addition, relatively more touch errors were found, especially in the zones located in the periphery area of the keyboard—this was natural because the keys in these zones typically inflated the index of difficulty according to Fitts' law and thus more conscious muscle control and perceived effort could be required for reaching such keys [9,10,29,30]. We estimated that these phenomena would have become apparent enough to be statistically significant if the number of touch errors was sufficiently acquired in the present study. That is, in conclusion, further research is needed to identify the significant relationships between the touch error frequencies and the locations of keys on the QWERTY soft keyboard. In particular, increasing the number of experimental trials could be useful for clarifying this issue.

Relatively higher subjective satisfaction ratings were found in the center area of the QWERTY layout, including zones 2, 3, 4, 7, 8, and 9. It looked like the subjective satisfaction ratings were roughly tied up with the task completion times, as previous studies have claimed [8,9,11], although there were differences in zones 5, 10, and 13. However, simultaneously, the pattern of subjective satisfaction ratings found in this study was somewhat different from the finding of the studies that the keys near the thumbs' initial positions (with the shortest task completion times) showed the highest subjective satisfaction ratings for key entry. We estimated that these could be induced by the differences in the soft keyboard layouts employed for testing—that is, the present study employed a typical QWERTY soft keyboard consisting of 26 alphabet letter keys that were stuck together next to one another in the keyboard section (i.e., a small space), while those studies used only part of the keyboard, or a few of the keys were placed far apart from one another. In sum, relatively more cognitive and physical efforts could be required during key entry while using a soft keyboard with more than 26 keys, since users need to locate targets out of many alternatives [14,15]. In fact, since muscle memory (from familiarity with a QWERTY layout) could help the thumbs to move close to the target keys, the number of alternatives that users' thumbs face is probably reduced to three to six keys, including the surrounding and target keys. Nevertheless, it is inferred that eyes-free finger-based touch attributed to muscle memory is regarded as conceivably inaccurate on small keys (4 to 6 mm) [31–33], and thus users still need to make more efforts to avoid typos. Naturally, this might be interpreted as the fact that securing vision on target keys would have a relatively greater impact than usual in key entry while using a QWERTY soft keyboard, and furthermore it could significantly affect users' subjective satisfaction—this mechanism was similar to the reason why the zones with less opportunities of being visually occluded by the thumbs showed relatively shorter task completion times in this study. To recap, this might be a plausible reason to explain the high satisfaction ratings of zones 2, 3, 4, 7, 8, and 9 during key entry—this was also supported by the opinions of the participants in the debriefing session of the present study. On the other hand, it was still unclear why zones 5, 10, and 13 showed relatively lower subjective satisfaction ratings despite their relatively shorter task completion times. However, we assumed that this phenomenon was strongly relevant to the fact that zones 5, 10, and 13 were located in the areas that could be relatively easily occluded due to the thumbs in the field of view, as well as the fact that they needed to be reached by using relatively difficult thumb motions such as abduction/adduction and flexion/extension.

4.2. Comparison with Previous Studies

In comparison with the findings of existing studies of soft keyboards on a smartphone (e.g., [8–11,22]), the following commonalities were still shared with the present study. First, task completion times significantly varied as a function of key locations. As shown in the previous studies, task completion times tended to be delayed for the keys in the periphery of the QWERTY layout in this study. It looked like touch interaction with the keys, which were likely to be visually occluded due to the thumbs or needed to be reached by using difficult thumb motions (e.g., abduction, adduction, flexion, and extension), was still a challenge in terms of speed, even for two-thumb key entry using a QWERTY soft keyboard. Second, subjective ratings were tied up with the results of task completion times. Relatively higher subjective satisfaction ratings were primarily found in the zones of the QWERTY soft keyboard where relatively faster task completion times were observed, although they did not match perfectly. It seemed that task completion times for keys still played an important role in determining user-satisfaction for key entry even using a QWERTY soft keyboard, as Chang et al. [8] and Chang and Jung [9] claimed. Lastly, this is just conjecture but the thumbs of the dominant hands might show better touch performance than those of the non-dominant hands, especially in terms of speed. This is because relatively shorter task completion times were primarily observed for the keys on the right side of the QWERTY layout that were likely to be touched by the right thumb in this study. Given that all of the participants were right-handers in this study, we could assume that the better motor skill of the dominant hand still appeared to contribute to the improvement in touch performance in key entry even using a QWERTY soft keyboard. As aforementioned, however, this should be proven via further experiments.

Simultaneously, the following unique findings were also identified from the present study. First, this study showed that the initial positions of the thumbs of both of the hands could be asymmetrically located on the left and right during two-thumb key entry. Indeed, this was expected because the present study allowed participants to hold the given smartphone in their preferred manners as usual without any guidance—this was different from the fact that the initial positions of the thumbs have been symmetrically controlled on the left and right in a large number of studies into soft keyboards on a smartphone, in order to clarify the effects of design elements in soft keyboards. We reckon that this finding suggests three meanings: (1) users may not hold a smartphone symmetrically on the left and right during texting with two thumbs on a smartphone in real life; (2) naturally, the thumbs' initial positions are likely to be asymmetrically located corresponding to the ways to hold a smartphone; and (3) touch performance during key entry could be significantly affected by these asymmetric initial positions of the thumbs.

Second, the present study suggested that securing vision during key entry with a QWERTY soft keyboard might be relatively more critical than usual, in order to help improve touch performance. The study showed that task completion times and user-satisfaction were dramatically improved in the zones on the QWERTY soft keyboard (i.e., zones 2, 3, 4, 7, 8, and 9) that the participants were able to immediately see without certain effort such as moving the thumbs or changing the hand grip postures, before touch interactions—this was inconsistent with the previous studies that showed that the closer a target key is to the initial positions of the thumbs, the greater its benefit becomes in terms of touch performance (e.g., touch time, touch error, and user-satisfaction) during key entry [8,9,11,22]. As aforementioned, we estimated that the reason for this inconsistency was from the fact that a large number of small keys are stuck together in a QWERTY layout. This is because users not only had to face more options despite the benefit of muscle memory from the familiarity with a QWERTY layout but also made greater cognitive and physical efforts to accurately locate a small target among these options. Naturally, it was assumed that securing vision would become relatively more useful than usual for improving task completion time and user-satisfaction during key entry using the QWERTY soft keyboard.

Lastly, it seemed that Fitts' law worked subordinately during key entry in this study. This was because if Fitts' law played a primary role in key entry, task completion times should have been gradually increased as the target keys moved away from the thumbs' initial positions. Of course, these propensities were essentially observed near the zones that were considered to be the thumbs' initial positions in this study. Simultaneously, however, several zones (e.g., zones 1, 6, 12, and 15) tended to show disproportional delay in their task completion times even though they were located right next to the zones that were regarded as the initial positions of the thumbs. We expected that this would suggest two meanings. First, the distances between keys and the initial positions of the thumbs would not be a primary factor to determine task completion times in key entry using a QWERTY soft keyboard. Note that we assumed that the index of difficulty only depended on the distances in Fitts' law, because all of the keys employed in this study shared the same size. Second, it looked like Fitts' law still worked fundamentally in determining task completion times for keys during key entry using a QWERTY soft keyboard, but task completion times for keys might have been more significantly affected by other factors. In fact, as aforementioned, we assume that securing vision on keys and physical effort to reach keys might be regarded as the potential candidates of those other facts that have more impacts on key entry using a QWERTY soft keyboard. In sum, these suggestions should be cautiously made. When considering that each zone employed in the present study was composed of two or three keys, the patterns in task completion times would be different in the level of the keys. Therefore, further study is needed for verifying this. Note that, in fact, we already found similar propensities even from the key level after the raw data on the keys in this study were reviewed.

4.3. Implementation and Limitations of the Present Study

When considering the findings and their practicality of the current study, design guidelines can be advised to help improve the usability of key input with two thumbs on a QWERTY soft keyboard. Note that, here, the design advice is restrained as well as cautiously made, as far as a typical layout of QWERTY soft keyboards on a smartphone is maintained. First, the key size needs to be maximized as much as the technology allows, in order to minimize the index of difficulty of a QWERTY layout and provide better vison on keys. Second, the size of the keys, especially that show relatively low touch performance and user-satisfaction (e.g., the keys that are often occluded due to the thumb have to be reached using difficult thumb motions, or need to interact with the non-dominant thumb) need to be enlarged in comparison with the other keys, in order to improve the overall user-experience in two-thumb key entry using a QWERTY soft keyboard. Chang and Jung [9] reported that the sizes of the keys that achieved the same goals in touch performance and user-satisfaction were different depending on the key locations in two-thumb key entry—they found that the closer the keys were located toward the periphery, the larger the sizes of the keys should become to achieve the touch performance similar to the keys near the thumbs' initial positions, and vice versa. This finding would be employed as evidence to resize the keys on a QWERTY soft keyboard. Lastly, more keys need to be assigned in the region (or close to this region) of a QWERTY layout that is supposed to interact with the dominant thumb—this is because the dominant thumb with better motor skills would be utilized as much as possible for two-thumb key entry.

The present study was still in the early stage of the long research plan, and thus the research theme was narrowed down in order to ascertain the significance and validity of the study as clearly as possible. Therefore, the applicability of the study's findings and countermeasures may be tied up only with the following restricted smartphone-use contexts: (1) two-thumb key entry with a QWERTY soft keyboard was examined using a single size of a smartphone; and (2) a single key input at once was only regarded as a text entry task. In everyday life, however, users typically send text messages with a variety of ways such as one-thumb, two-thumb, or one index finger interaction, and even use various sized smartphones. Moreover, it is certain that texting generally consists of continuous activities in which a series of letters are typed, rather than typing a single keystroke. To recap, this may be evidence enough that the findings of the present study might significantly vary depending on different smartphone-use contexts. Therefore, we strongly recommend that the findings and countermeasures of this study need to first be interpreted and applied within the smartphone-use contexts designed in the study—applications beyond the scope of this research should be implemented with caution.

In addition, this study has the following weak points in the experimental protocol, and thus the findings should be cautiously interpreted and adapted. First, the thumbs' initial positions suggested in the present study were estimated using Fitts' law, and not actually measured. Although it is well known that Fitts' law is considered to be a scientifically proven tool, we need to be aware that this often leads to the invalid interpretation of the findings based on "ground truth" unless the initial positions are recorded via experiments. Second, the effect of the individual thumb was not investigated (i.e., which thumb predominantly taps which zone). It is certain that the findings were well matched with those of the related existing studies, but some interpretation of the results relied on conjecture based on the findings of previous mobile HCI studies. Third, the participants may have had difficulty differentiating the 26 letter keys when rating the subjective satisfaction in the present study. Although they were allowed to freely manipulate the smartphone with no time limit for the deliberate evaluation, it might have been challenging for them to logically compare the touches of 26 similar items. Lastly, more participants needed to be recruited for testing, and organized debriefing sessions for the participants were necessary. The study showed some evidence that more participants were required. For example, if a sufficient number of touch errors had been acquired, the patterns in touch errors would have become apparent enough to be statistically significant. In addition, since the debriefing sessions were conducted only with the volunteers among the participants, their opinions were not collected systematically enough to suggest specific ideas.

Further research is warranted for addressing the knowledge gap in the present study and helping to generalize the findings. First, studies involving different age groups are needed. The current study only employed college students in their 20s as participants, since they were considered to be major smartphone users [34,35]. However, the researchers emphasize that tactile performance varies significantly with age [36,37]. Therefore, research including different age groups could be useful in helping to generalize the findings of this study. Second, left-handed people should be included in testing to examine the effect of handedness during two-thumb key entry. In the current study, only right-handers were recruited in order to minimize unwanted factors in the experiments and clearly observe the effects of independent variables. However, as is well known, handedness is regarded as a significant factor affecting hand motor skills, especially in motion speed and accuracy [26–28]. We believe that further studies including left-handers could help to not only investigate the effects of the non-dominant hand during two-thumb key entry but also to generalize the findings of this study. Third, increasing the number of experimental trials could be helpful in clarifying touch error patterns that occur during key entry using a QWERTY soft keyboard. Although not statistically significant, the present study found some faint but reasonable patterns in touch errors. It looked like these patterns could become apparent enough to be statistically significant if the number of touch errors was sufficiently acquired, i.e., increasing the repetition of experimental trials may be helpful in compensating for the lack of statistical power in the touch errors and furthermore contribute to clarifying this issue. Lastly, obtaining the positions of touch errors would be useful for understanding the patterns in touch errors while using a QWERTY soft keyboard. Since the present study only focused on the number of targets missed, there was a restrictive approach to interpreting the patterns in touch errors and identifying their causes. It is well known that touch error coordinates typically provide more insight in terms of user-experience (e.g., which zone has a small or large touch offset of touch errors), because they include geographic information such as the distance and direction from targets [10]. Thus, obtaining touch error coordinates is recommended in order to obtain more valuable and scientific hints for improving the user-experience of a QWERTY soft keyboard on a smartphone.

5. Conclusions

This study investigated task completion time, touch error frequency, and user-satisfaction as functions of the location of keys on a QWERTY soft keyboard, for two-thumb key entry on a smartphone. The current study can be summarized in three ways. First, the thumbs' initial positions may not be symmetrically located on the left and right during two-thumb key entry on a QWERTY soft keyboard of a smartphone, and this could significantly affect the touch performance as well. Second, it was assumed that securing vision during key entry with a QWERTY soft keyboard might be relatively more critical than usual, in order to help to improve user-experience. Lastly, it looked like Fitts' law still plays an important role in determining touch performance and user-satisfaction even in key entry using a QWERTY soft keyboard, but it seems to work subordinately.

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