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Which Thumb, the Left or Right, Touches the Letter Keys on a Smartphone QWERTY Soft Keyboard during Two-Thumb Key Entry?

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Abstract: This study aims to observe which thumb, the left or right, is used for keystrokes and examine the patterns during two-thumb key entry on a smartphone QWERTY soft keyboard. A total of 36 college students, including 18 left-handed and 18 right-handed, were recruited for testing, and they had 9.7 years of smartphone use experience on average. A smartphone application was implemented, and whether the left or right thumb was used for touch interactions was recorded for each of the 26 letter keys. As a result, it was found that there were slightly more letter keys that were statistically more often tapped by the left thumb during the two-thumb key entry on the QWERTY soft keyboard, regardless of the participant's handedness. In addition, all the letter keys were touched statistically more often with the relatively closer one of both thumbs, except for the letter keys G and V in the center. It seemed that the distance between keys and thumbs was regarded as the most important factor influencing the thumb choice for keystrokes, followed by the habituated experience of using physical QWERTY keyboards.

Keywords: smartphone QWERTY soft keyboard; two-thumb key entry; thumb choice

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1. Introduction

As a built-in means of text input, a QWERTY soft keyboard has been responsible for most users' communication activities on smartphones. Palin et al. [1] reported that 87.0% of approximately 37,000 survey participants from 163 countries primarily used a QWERTY layout for text entry in 2018, and Statista [2] confirmed that more than 70.0% of smartphone users worldwide used chat, messaging, and email on their smartphones between July 2022 and June 2023. As such, a QWERTY soft keyboard has been popularly employed for text input on smartphones [1,3–5], and communication using text input is considered the most common activity among smartphone users [2,6]. In general, studies [7–9] have predicted that the primary reason for this popularity is that smartphone users are familiar with a QWERTY layout based on their previous experiences with personal computers, and thus, they prefer a QWERTY soft keyboard as a means of text input.

Although a smartphone QWERTY soft keyboard in the market has been implemented based on the layout of a physical QWERTY keyboard for personal computers and laptops, users can experience the following differences when using the QWERTY soft keyboard. First, multiple fingers are used to type keys on physical QWERTY keyboards, but users need to employ a limited number of fingers, such as one or two, for keystrokes on smartphone QWERTY soft keyboards [10]. Second, with the loss of some keys, including symbol and special purpose keys, the positions of some letter keys (e.g., B, G, and V) have been shifted slightly sideways on most smartphone QWERTY soft keyboards, and thus, this could require somewhat different typing patterns than using physical QWERTY keyboards. Third, for physical QWERTY keyboards, there has been a general consensus on which fingers should be employed for each key, but for smartphone QWERTY soft keyboards, some keystrokes (especially the keys in the middle) may require judgment based on personal habit and predisposition until they become familiar (i.e., until muscle memories are established) because there are no universal guidelines [11,12]. In sum, these differences are not only expected to result in a different user experience than using a physical QWERTY keyboard but could also be considered evidence that there may be somewhat unique keystroke patterns required for the use of a smartphone QWERTY soft keyboard.

While no consensus on keystrokes has been made for smartphone QWERTY soft keyboards, there have been a couple of studies that attempt to suggest keystroke guides to improve their typing performance. Negahban et al. [11] proposed key arrangements for each finger that can minimize the finger travel time between keys when typing on a QWERTY soft keyboard, based on Fitts' law. They developed the algorithm that determines which finger can minimize typing time for each key and applied it to provide optimal keystroke guidance as a function of the typing method (e.g., two-thumb entry, two-finger entry, and three-finger entry). Next, Alamdar Yazdi et al. [12] calculated the distance between keys when texting with two thumbs on a QWERTY soft keyboard and then assigned keys to the left and right thumbs in order to minimize the resulting typing time. The study developed an optimization model to identify the thumb that can minimize the travel time between keys and utilized it to improve the typing speed of a split QWERTY soft keyboard for a 7-inch Tablet PC. More recently, Xu et al. [13] proposed a new keystroke guide for the left and right thumbs that can help users utilize their muscle memory habituated from two-thumb text entry on a QWERTY soft keyboard and thereby improve typing speed. They developed a simulation model to derive the key arrangement for each thumb that can maximize eyes-free typing speed and exploited it in the design of a bimanual fingertip keyboard to advance typing performance and usability. To recap, although some keystroke guides to improve typing performance have been introduced, as mentioned above, there has been a clear lack of research that can help understand users' natural keystroke habits and characteristics in terms of user experience.

It is necessary to study users' keystroke habits and characteristics on a smartphone QWERTY soft keyboard and identify the reasons based on the analysis of the thumb choice patterns for keystrokes during two-thumb text entry with the keyboard. First, it can be utilized to improve the quality of interaction with a smartphone QWERTY soft keyboard in terms of user experience. Smartphone QWERTY soft keyboards typically have the inherent design challenge of placing a large number of keys in a small space, and thus, there has been a constant need to improve usability, especially in terms of typing speed and accuracy [14–18]. In this context, obviously, the study on the thumb choice patterns for keystrokes and their causes is expected to not only directly and indirectly help improve the design of the QWERTY soft keyboard for better usability but also increase user satisfaction. Second, it could contribute to identifying natural and fundamental behavioral tendencies of users for touch interaction with handheld touch-screen devices. Since there has been no consensus on keystroke guidelines for smartphone QWERTY soft keyboards [11,12], the keystroke style is likely to be determined by users' own judgment, preferences, habits, etc., without any particular restriction. Thus, studying such repetitive and regular keystroke patterns on a smartphone QWERTY soft keyboard could be useful in understanding users' preferred touch habits and natural decision-making tendencies when using such handheld touch-screen devices. Third, it may bridge the knowledge gap between the user experience of physical QWERTY keyboards and smartphone QWERTY soft keyboards. While user experience habituated from using a physical QWERTY keyboard has been shown to have a significant impact on the use of a smartphone QWERTY soft keyboard [19–21], almost no studies have explored the specific impacts. It is expected that a study examining the thumb choice patterns and keystroke tendencies could play a valuable role in confirming the specific relevance with a physical QWERTY keyboard in terms of user experience and satisfying scientific curiosity.

The present study observed which thumb, the left or right, was used for keystrokes and examined the patterns, during two-thumb key entry on a smartphone QWERTY soft keyboard. Four hypotheses were tested for each letter key: (1) there is one thumb, the left or right, that is statistically more often used for touch interaction; (2) handedness significantly affects the thumb choice for keystroke; (3) keystrokes were made statistically more often by the relatively closer one of both thumbs; and (4) the thumb choice for keystrokes was significantly influenced by the fact that which of both the thumbs was relatively longer or shorter. For testing, a smartphone application rendering a QWERTY soft keyboard was developed, and which of both the thumbs was employed for keystrokes was recorded per letter key. In addition, statistical analyses were conducted to determine which thumb, the left or right, was used significantly more often for keystrokes per letter key, and then the factors that might influence the thumb choice for keystrokes were discussed.

2. Methods

2.1. Participants

Thirty-six college students, including 18 males and 18 females, were recruited on campus for testing. Their mean age was 22.4 years (SD: 3.1), and they have 9.7 years (SD: 2.0) experience on average in smartphone use. The ratio of left-handed and right-handed participants was maintained at one to one in each gender (i.e., nine left-handed and nine right-handed males; nine left-handed and nine right-handed females)—prior to recruiting; the participants were screened based on the questionnaire of Veale [22], which helped determine if they were strongly lateralized to left or right-handedness. All the participants did not report any musculoskeletal disorder of the upper extremities or disease of the eyes on the day of the experiments, and they were permitted to use spectacles or contact lenses to correct their vision during testing. Before testing, in addition, the participants were given a description of the experimental procedures and the length of their left/right thumbs was measured based on the landmarks in the anthropometric survey of US Army personnel [23], as shown in Table 1. Lastly, all the participants agreed with an informed consent form and were compensated for their participation. Note that the IRB (institutional review board) of the Dongguk University—Seoul (DUIRB-202210-03) approved the current study.

Table 1. Thumb length (unit: mm).

Handedness	N	Left Thumb		Right Thumb	
		Mean	SD	Mean	SD
Left-handed participants	18	56.3	6.3	56.8	6.9
Right-handed participants	18	57.1	7.6	58.0	7.9

2.2. Equipment

Galaxy S8 plus (Samsung, Gyeonggi-do, Republic of Korea) with Android Pie 9 (Google, Mountain View, CA, USA) was employed as a smartphone for the experiments. The smartphone had dimensions of 7.3 cm × 16.0 cm × 0.8 cm (width × height × thickness), and its touch-screen measured 7.0 cm × 14.2 cm (width × height) with a resolution of 2960 × 1440 pixels. The experimental touch-screen was designed to be the same as the design of Galaxy S8 plus, and thus, it was divided into two sections, as shown in Figure 1: namely (1) an instruction section and (2) a QWERTY keyboard section. The instruction section (7.0 cm × 8.4 cm) was intended to display experimental information (e.g., a target letter, a countdown for the next target letter appearance) and guide participants in performing tasks during testing. Meanwhile, the QWERTY keyboard section (7.0 cm × 4.6 cm) was designed according to the structure of a typical QWERTY soft keyboard, consisting of 26 alphabet letter keys (Figure 1)—the size (width × height: 0.55 cm × 0.77 cm) and location of the letter keys followed the way of the QWERTY soft keyboard in Galaxy S8 plus (Samsung keyboard 3.3.23.31). Note that the size of the letter keys was within the key width and height ranges measured on a number of popular brand smartphones, including Samsung Galaxy S21 and S22 Plus and Apple iPhone 12 and 13. In addition, extra keys, such as ten numeric keys on the top row and a couple of functional keys around the bottom, were implemented on the QWERTY soft keyboard, but they were all façades (i.e., not actually working).

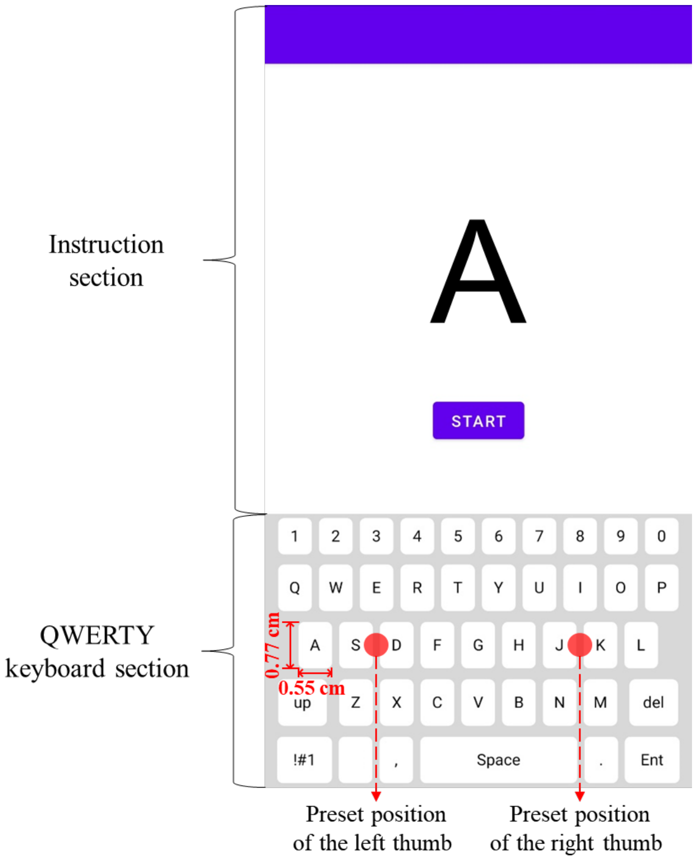

Figure 1. Experimental application.

For the current study, a smartphone application was programmed with the JAVA programming language (version 8, Oracle, Austin, TX, USA) and Android Studio Dolphin (Google, Mountain View, CA, USA). The application was launched by pressing a start button, and after a three-second countdown, it displayed one target letter (out of 26 alphabet letters) at a time in the instruction section—this was repeated until all the alphabet letters appeared once in a trial, and the orders of the letter appearance were fully randomized for each trial. In addition, the application counted down three seconds after a successful touch was sensed on an ongoing letter key and subsequently provided the next target letter. Note that since this application did not include the function that recorded whether the left or right thumb was used for touch interactions, the GoPro HERO 8 (GoPro, San Mateo, CA, USA) was prepared for the video analysis.

2.3. Experimental Design

Testing was conducted with a one-factor within-subject design. The independent variable was the soft keyboard consisting of 26 alphabet letter keys on the keyboard section, as shown in Figure 1. In addition, the dependent variable was defined as whether to use the left or right thumb for the touch interaction with each letter key.

The entire experiment consisted of three sessions: (1) preparatory; (2) main experimental; and (3) post-experimental sessions. Above all, in the preparatory session, two tasks were primarily conducted. First, the experimental postures of the participants were guided and controlled for testing. For instance, the participants were asked to take a seat in a chair and then had a chance to adequately set the height of the seat pan as preferred. They were also instructed to rest their elbows comfortably on a desk and to hold a given smartphone as naturally as possible in portrait mode with both hands as usual (Figure 2). However, in order to prevent the grip postures of both hands from being too unusual (e.g., too asymmetrical between the left and right hands), the participants were dictated to place their thumbs around the preset positions on the QWERTY keyboard section (i.e., around the letter keys S and D for the left thumb and around the letter keys J and K for the right thumb; Figure 1). Second, the participants had opportunities to directly manipulate the experimental application. No strict time limit was set, but it lasted approximately five minutes before the main experiments began. These practical trials were intended to reduce the learning effect by familiarizing the participants with the experimental application.

Figure 2. Experimental posture.

During the main experimental session, data were collected on whether the participants employed their left or right thumb for touch interaction with each letter key. The testing was conducted in a small chamber in which temperature and illumination were maintained at approximately 21 °C and 300 lux to avoid interfering with the performance of the experimental tasks. The participants were asked not only to touch a given target key with their preferred thumb (no regional restriction) but also to do so as quickly and accurately as possible when the target letter appeared on the instruction section after a three-second countdown. Here, if the target key was missed, they needed to tap the key repetitively until the application conceded its successful touch. After the successful touch, the participants were also instructed to replace their thumbs with the preset positions before the next target letter key was displayed in the instruction section. The participants were asked to remain focused on tapping given target letter keys until all 26 alphabet letter keys appeared one by one. Note that the orders of the letter key appearance were completely randomized between participants and trials within participants because the application was programmed to display a randomly selected letter key at a time in a trial, as aforementioned. Each participant conducted 26 key tapping (i.e., 26 alphabet letters) in one experimental trial, and seven trials were repeated—a two-minute rest was given between the trials. Therefore, a total of 182 target letter keys (26 alphabet letters $\times$ 7 repetitions) were processed by each participant. All the touch interactions during the experiments were video recorded under the consent of the participants, and the very first touch on each letter key was only investigated to identify whether the participants employed their left or right thumb for touch interaction via video analysis.

After all the experimental processes, a debriefing was conducted. A short interview was carried out with each participant to listen to their opinion on the experiments. The participants had opportunities to discuss the results of the experiments based on their daily basis experience with respect to the use of a smartphone QWERTY soft keyboard with two-thumb text entry.

2.4. Data Analysis

Binomial tests were performed at $\alpha = 0.05$ to determine which thumb, the left or right, was predominantly used for touch interaction on each alphabet letter key. The tests were conducted separately for left-handed and right-handed participants. Note that the measurements were not normally distributed, and thus, a non-parametric test (i.e., binomial test) was needed. The number of touches made by the left and right thumbs were counted, respectively, and the thumb usage rate (TU; unit: %) was computed for each letter key—the TU was defined as the ratio of the number of the left or right thumb touches to the total number of touches (i.e., left + right) made on a target letter key, and thus the abbreviations, TUL and TUR, were employed to represent the ratios of the left and right thumb touches, respectively. For each letter key, two binomial tests with different hypotheses were performed. The first binomial test was employed to determine if the TUL or TUR accounted for a significant majority of 50.0% or more on each letter key. This was done to see which thumb, the left or right, was particularly preferred for touch interaction per letter key. The second binomial test was conducted to determine whether the TUL or TUR had a significant superiority of 85.0% or more on each letter key. This was intended to see if one of both the left and right thumbs overwhelmingly dominated touch interaction on each letter key. Note that the criterion of 85.0% was a more conservative value as compared with the previous studies that an individual handedness was determined when 75.0% or more of a certain task was performed by either the left or right hand [24,25].

Further analyses were conducted to examine the factors that influenced the decision of the left or right thumb use (i.e., thumb choice) in the touch interaction with the letter keys. First, the effect of the distances between the preset thumb positions and the centers of the letter keys was investigated. The 26 alphabet letter keys were grouped according to the distances and were divided into three areas (Figure 3): (1) the left area that was relatively close to the preset positions of the left thumb; (2) the middle area that had the same distances from the preset positions of both the thumbs; and (3) the right area that was relatively close to the preset positions of the right thumb. Then, the TU values of the letter keys were examined as a function of these areas.

Second, the Mann–Whitney U test was conducted to explore the effect of the difference in length between the left and right thumbs on the choice of which thumb to use to tap letter keys—that is, the thumb lengths of both hands were compared, and the difference in TU values between the longer and shorter thumbs was statistically examined. Note that since the measured data were not normally distributed, the Mann–Whitney U test was conducted instead of the *t*-test. However, this was investigated for only (1) the keys that were not unilaterally tapped by the relatively closer one of both the thumbs (i.e., TU $<$ 85.0%) and (2) the keys that were located in the middle area (i.e., the keys G and V). For this analysis, both the left-handed and right-handed participants were categorized according to whether their left thumb was longer than their right thumb and vice versa, and thereby the following four groups were made: (1) the group of the left-handed participants with the relatively longer left thumb; (2) the group of the left-handed participants with the relatively longer right thumb; (3) the group of the right-handed participants with the relatively longer left thumb; and (4) the group of the right-handed participants with the relatively longer right thumb. In addition, the participants' TUL and TUR values were assigned to the corresponding groups. Note that the participants with the same thumb length on the left and right hands were excluded from the analysis. On each designated letter key, the

Mann–Whitney U test was conducted separately for each group of the participants with $\alpha = 0.05$ and verified if there was a significant difference between the TUL and TUR values.

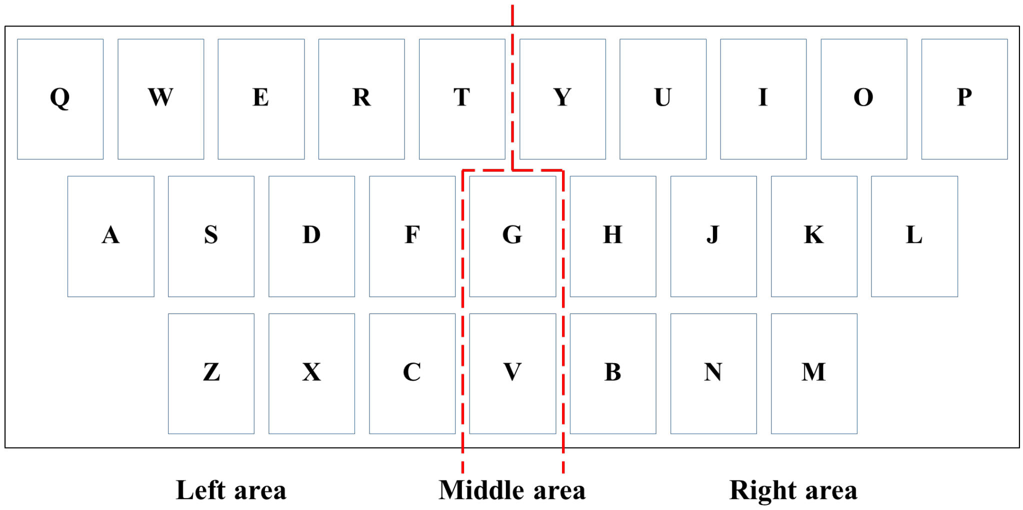

Figure 3. Three areas on the QWERTY keyboard section. The dotted line divides the keyboard section into the three areas (left, middle, and right).

3. Results

3.1. Use of the Left or Right Thumb

For the left-handed participants, the number of the letter keys that were touched statistically more often by the left thumb was relatively higher than that of the letter keys that were touched statistically more often by the right thumb. The binomial tests determined that the letter keys with TUL values of 50.0% or more were A, C, D, E, F, G, Q, R, S, T, V, W, X, and Z (14 letter keys in total) and the letter keys with the TUR values of 50.0% or more were B, H, I, J, K, L, M, N, O, P, U, and Y (12 letter keys in total), as illustrated in Figure 4a. In addition, the binomial tests showed that the letter keys with TUL values of 85.0% or more were A, C, D, E, F, G, Q, R, S, T, W, X, and Z (13 letter keys in total) and the letter keys with the TUR values of 85.0% or more were H, I, J, K, L, M, N, O, P, and U (10 letter keys in total) (Figure 4a). Meanwhile, although the letter keys B, V, and Y were found to be touched relatively more often by one of either the left or right thumb (i.e., TUL or TUR $>$ 50.0%), they were classified into the keys that were not unilaterally dominated by one of either the left or right thumb during touch interaction because their TU values failed to exceed 85.0%—the TUL value on the key V was 66.7%, and the TUR values for the keys B and Y were 62.7% and 65.9%, respectively.

For the right-handed participants, the number of the letter keys tapped statistically more by the left thumb was equal to or somewhat more than the number of the letter keys tapped statistically more by the right thumb. The binomial tests revealed that the letter keys with TUL values of 50.0% or more were A, C, D, E, F, G, Q, R, S, T, W, X, and Z (13 letter keys in total) and the letter keys with the TUR values of 50.0% or more were B, H, I, J, K, L, M, N, O, P, U, and Y (12 letter keys in total) (Figure 4b). Simultaneously, the tests determined that the letter keys that had TUL values of 85.0% or more were A, C, D, E, F, Q, R, S, W, X, and Z (11 letter keys in total) and the letter key that had the TUR values of 85.0% or more were H, I, J, K, L, M, N, O, P, U, and Y (11 letter keys in total), as illustrated in Figure 4b. On the other hand, even for the right-handed participants, there were the letter keys of which TUL or TUR values failed to exceed 85.0%, although these keys were touched statistically more often by one of either the left or right thumb (i.e., TUL or TUR $>$ 50.0%). For example, the keys G and T had 63.5% and 65.9% of the TUL values, respectively, and the keys B had 77.0% of the TUR value.

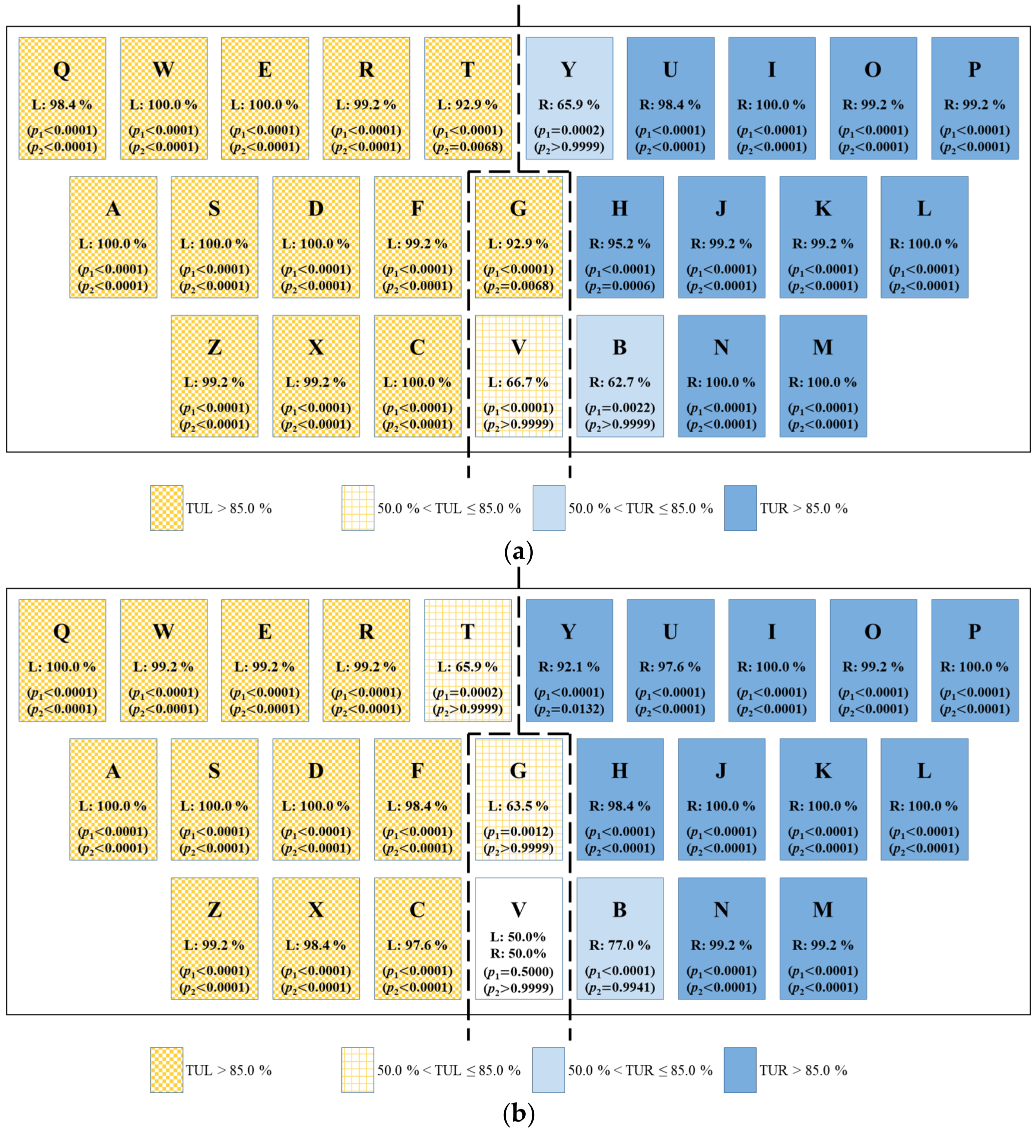

Figure 4. TUL and TUR values for letter keys. TUL (L): the ratio of the number of the left thumb touches to the total number of touches made on a letter key, TUR (R): the ratio of the number of the right thumb touches to the total number of touches made on a letter key, p_1: the *p*-value of the binomial test that verified if the TUL or TUR accounted for 50.0% or more at α = 0.05, p_2: the *p*-value of the binomial test that verified if the TUL or TUR accounted for 85.0% or more at α = 0.05. The dotted line divides the keyboard section into the three areas (left, middle, and right). (**a**) Left-handed participants; (**b**) right-handed participants.

3.2. The Effect of the Distance between Keys and Thumb Positions

All the letter keys on the QWERTY soft keyboard were tapped statistically more often with the relatively closer one of both thumbs, regardless of the participant's handedness (Figure 4). For example, almost all the letter keys in the left area were touched unilaterally by the left thumb (i.e., TUL > 85.0%) for both the left-handed and right-handed participants—exceptionally, the TUL value of the key T for the right-handed participants only failed to exceed 85.0% but was 65.9%, still above 50.0%. In the right area, similarly, most of the letter keys were pressed unilaterally by the right thumb (i.e., TUR > 85.0%). Only the TUR values of keys B and Y (62.7% and 65.9%, respectively) for the left-handed participants and key B (77.0%) for the right-handed participants did not exceed 85.0%, but they were still above 50.0%, as shown in Figure 4.

The touches of the letter keys in the middle area (i.e., the keys G and V) that was equidistant from the preset positions of both the left and right thumbs were statistically more often made by the left thumb, except for the key V for the right-handed participants. The TUL values of these keys were above 50.0%—to be specific, the keys G and V for the left-handed participants had 92.9% and 66.7% of the TUL values, respectively, and the key G for the right-handed participants had 63.5% of the TUL value, as shown in Figure 4. Meanwhile, the key V of the right-handed participants had equal TU values between the left and right thumb touches; thus, the binomial tests failed to verify that its TUL or TUR value was statistically above 50.0% and 85.0%.

3.3. The Effect of Thumb Length

The Mann–Whitney U tests were conducted on the letter keys B, G, V, and Y for the left-handed participants and for the letter keys B, G, T, and V of the right-handed participants (eight letter keys in total)—this was because (1) the keys B and Y for the left-handed participants and the keys B and T for the right-handed participants were not unilaterally tapped (TU < 85.0%) by the relatively closer thumbs and (2) the keys G and V for both the left-handed and right-handed participants were located in the middle area. As a result, for the left-handed participants, statistically significant differences between TUL and TUR values were found on the key G in the group with relatively longer left thumbs and on the keys G, V, and Y in the group with relatively longer right thumbs (Table 2). For key G, the TUL values were significantly greater in both groups, while the TUL values of key V and the TUR values of key Y were found to be significantly greater in the group with relatively longer right thumbs. Meanwhile, for the right-handed participants, there were significant differences between the TUL and TUR values on the keys B and G for the group with relatively longer left thumbs and on the keys B and T for the group with relatively longer right thumbs (Table 2). In key B, the TUR values were statistically greater in both groups and simultaneously, the TUL values were significantly greater on the key G for the group with relatively longer left thumbs and on the key T for the group with relatively longer right thumbs.

Table 2. A significant difference between the TUL and TUR values of the designated letter keys for each participant group.

Group	N	Letter Key	Comparison between TUL and TUR	*p*-Value
Left-handed participants with the relatively longer left thumb	7	B	TUL < TUR	0.3347
		G	TUL > TUR	**0.0010**
		V	TUL > TUR	0.1739
		Y	TUL < TUR	0.2197
Left-handed participants with the relatively longer right thumb	11	B	TUL < TUR	0.0777
		G	TUL > TUR	**<0.0001**
		V	TUL > TUR	**0.0216**
		Y	TUL < TUR	**0.0256**
Right-handed participants with the relatively longer left thumb	9	B	TUL < TUR	**0.0178**
		G	TUL > TUR	**0.0089**
		T	TUL > TUR	0.1644
		V	TUL > TUR	0.9643
Right-handed participants with the relatively longer right thumb.	8	B	TUL < TUR	**0.0034**
		G	TUL > TUR	0.1671
		T	TUL > TUR	**0.0015**
		V	TUL > TUR	0.5946

TUL: the ratio of the number of the left thumb touches to the total number of touches made on a letter key; TUR: the ratio of the number of the right thumb touches to the total number of touches made on a letter key. The bold texts in the *p*-values indicate statistical significance at $\alpha = 0.05$.

4. Discussion

This study found that there were slightly more letter keys that were statistically more often touched by the left thumb (i.e., TUL > 50.0%) during two-thumb key entry on the QWERTY soft keyboard, regardless of the participant's handedness. For both the left-handed and right-handed participants, the number of letter keys with TUL values exceeding 50.0% was greater than the number of keys with TUR values exceeding 50.0%. In addition, the number of keys with TUL values greater than 85.0% was equal to or more than the number of keys with TUR values greater than 85.0%. To recap, this can be interpreted as that keystrokes on the QWERTY soft keyboard were made by the left thumb relatively more than the right thumb, regardless of handedness. In fact, this propensity was expected because the habits developed from using a physical QWERTY keyboard were likely to have influenced the use of a smartphone QWERTY soft keyboard—this has often been noted in existing studies [19–21]. In general, a physical QWERTY keyboard tended to be designed to use the left hand relatively more for typing letter keys to compensate for the technical defects of mechanical typewriters [26–29]. Thus, users have naturally been trained and accustomed to using their left hand relatively more often for typing letter keys on the physical QWERTY keyboard, as illustrated in Figure 5. In considering that QWERTY keyboard layouts of mechanical typewriters were passed down to QWERTY keyboard layouts of computers and furthermore smartphones [21,30,31], it was not surprising to see this finding in the present study—the keys that were relatively more often touched by the left thumb in the present study were almost identical to the keys that were specified to be pressed by the left hand in Figure 5, except the key B.

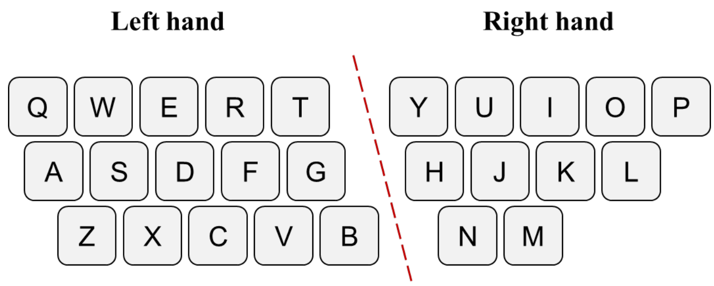

Figure 5. The recommended key assignment to the left and right hands on a physical QWERTY keyboard. The key assignment was adapted from [26]. The dotted line indicates the key assignment to the left and right hands.

Most keys were touched statistically more often using the thumbs that were relatively closer to the keys in the distance, excluding the keys G and V in the middle area. This tendency seemed to weaken the more centrally the keys were on the QWERTY soft keyboard. Namely, the closer a thumb was to a target key, the more likely it was that the thumb could tap the target key. We estimated that this phenomenon was associated with the following human behavioral predispositions. First, this could be affected by the human tendency to choose the most economical trajectory or sequence of movements in terms of energy cost [32–34]. This was because the participants in the present study may have intended to shorten the travel distance to target keys by choosing a relatively closer one of the left and right thumbs in order to reduce the energy that was required for keystrokes and increase the efficiency of the touch tasks. Second, this finding could be seen as a result of another human tendency to prefer easier ways to complete tasks [35]. This was because the finding can be interpreted as a behavior to lower the index of difficulty to locate the key—considering all the letter keys had the same size in this study, the most effective way to decrease the index of difficulty was to reduce the thumb excursion, according to Fitts' law [36–38], i.e., this could be considered a behavior that attempted to make the given task easier by choosing the thumb that was relatively closer to the target key.

Interestingly, for the letter keys G and V (i.e., in the middle area) that were equidistant from the preset positions of both the left and right thumbs, overall, their touches were observed to be made relatively more often with the left thumb—these keys shared the TUL values more than 50.0%, except for the key V for the right-handed (the same TUL and TUR values of 50.0%). Above all, we predicted that this was because the keystroke habits developed from using a physical QWERTY keyboard affected the use of a smartphone QWERTY soft keyboard, as discussed earlier. The rationale was that the keys G and V were located in the region that typically encourages typing with the left hand when typing on a physical QWERTY keyboard, as shown in Figure 5. I.e., this means that such a habitual experience may have led the participants to involuntarily touch the keys G and V with their left thumb in the current study. Meanwhile, simultaneously, we estimated that the reason why all the keys in the middle area were not unilaterally tapped by the left thumb would be related to the layout difference between a physical QWERTY keyboard and a smartphone QWERTY soft keyboard. To be specific, the keys G and V of physical QWERTY keyboards are located slightly left from the center (Figure 5), while the keys G and V of typical smartphone QWERTY soft keyboards are positioned at the very center column (Figure 1). That is, as compared with typing on physical QWERTY keyboards, users could likely feel less distance penalty for using the right thumb to touch the keys G and V on a smartphone QWERTY soft keyboard because the keys were moved closer to the right thumb than before. Thus, we determined that this would be a plausible cause of the noticeable increase in the use of the right thumb for tapping the keys G and V in this study.

TUL or TUR values between 50.0% and 85.0% were also observed on the keys B and Y for the left-handed participants and on the keys B and T for the right-handed participants—these keys were touched statistically more often by the thumbs that were relatively closer to the keys in the distance. As shown in their TU values (i.e., 50.0% $\leq$ TUL or TUR $<$ 85.0%), we should note that the touches on these keys were not made unilaterally with the relatively closer thumbs. That is, this indicated that a noticeable percentage of touches occurred with the thumb that was relatively more distant from the keys as well. We reviewed the possible reasons for this phenomenon. First, in the case of key B, we predicted that such an increase in its TUL values was associated with the trained experience of using a physical QWERTY keyboard, as described above. This was because the key B was originally included in the region on a physical QWERTY keyboard, typically recommended to press it with the fingers of the left hand, as illustrated in Figure 5. Namely, this means that these trained experiences from using a physical QWERTY keyboard may have caused the participants (regardless of handedness) to occasionally press the key B on the QWERTY soft keyboard with their left thumb even though the key B was located slightly off-center to the right, in the present study. Next, for the key Y for the left-handed and the key T for the right-handed, it was unclear why there was such an increase in the number of touches made by the relatively distant thumbs from the keys. Simply, given the scope of this study, it was inevitable to assume that this was vaguely due to the participants' handedness. We just estimated that the participants may have instinctively touched those keys often with their dominant thumb because the keys T and Y were located in the very center column of the QWERTY soft keyboard, which was likely fuzzy in distance perception. However, this is a conjecture, and thus, further study is needed to clarify this.

Although significant differences between the TU values of the longer and shorter thumbs in both hands were observed in some cases, as shown in Table 2, there was insufficient evidence to conclude that this finding would have a significant impact on the choice of the thumb to be used for keystroke for the following reasons. First, no consistent pattern was found among those significant differences. The Mann–Whitney U tests showed that for the left-handed participants, the group with the relatively longer left thumbs statistically more often used their left thumbs to tap the key G, and the group with the relatively longer right thumbs statistically more often employed their relatively shorter left thumbs to tap the keys G and V and their right thumbs to tap the key Y. Simultaneously, for the right-handed participants, the group with the relatively longer left thumbs statistically more frequently used their left thumbs and relatively shorter right thumbs to touch the keys G and B, respectively, and the group with the relatively longer right thumbs statistically more frequently employed their shorter left thumbs and longer right thumbs to touch the keys T and B, respectively. In other words, it was difficult to find repetitive and clear patterns between the thumb choice (used to touch the keys) and the fact that the left or right thumb was relatively longer. Second, this finding might not be driven by the fact that which thumb, the left or right, was relatively longer. Regardless of whether the left or right thumb was relatively longer, the left thumb was statistically more often used for keystrokes on the key T in the left area, the keys G and V in the middle area of the QWERTY soft keyboard, and the right thumb statistically more often touched the keys B and Y in the right area of the keyboard. Interestingly, this was completely consistent with the aforementioned results that were induced by the tendencies to (1) employ the relatively closer one of both the thumbs for keystrokes and (2) use primarily the left thumb to tap the keys G and V due to the habitual experience from using a physical QWERTY keyboard. I.e., this means that this finding may not be due to the fact that which thumb, the left or right, was relatively longer or shorter but rather to the tendencies described above. In sum, from these contexts, it was not clear enough to conclude that this finding was purely the result of whether the left or right thumb was relatively longer.

All things considered, the results of the present study can be summarized as follows. First, overall, the left thumb was used slightly more for keystrokes during two-thumb key entry on the QWERTY soft keyboard—in particular, the keys in the middle area were tapped preferentially by the left thumb, regardless of handedness. Second, most keys on the QWERTY soft keyboard were touched statistically more often by the relatively closer one of both the left and right thumbs, excluding the keys in the middle area. Third, noticeable differences were not found between the touch patterns of the left-handed and right-handed participants. Lastly, there was no clear evidence that the thumb choice for keystrokes on the QWERTY soft keyboard was significantly influenced by the fact that which thumb, the left or right, was relatively longer. Based upon these findings, in sum, for two-thumb key entry on a QWERTY soft keyboard, the distance between keys and thumbs was predicted to be the most important factor influencing the thumb choice for keystrokes, followed by the habits from using a physical QWERTY keyboard.

This study can be extended in the following ways to address the knowledge gap and limitation and to achieve a better generalization of the results. First, a larger number of participants should be recruited for further study. The current study only included 36 participants due to the difficulty of recruiting left-handed participants. The number of participants may not be considered a small number, but they had to be divided into two groups (i.e., 18 left-handed and 18 right-handed) and examined separately in most analyses. Although this study showed statistically reliable results, we might have missed some noticeable thumb choice patterns for keystrokes or possible alternative conclusions, which could emerge if more participants were involved. Thus, we expected that recruiting more participants would help increase the confidence in the results and also find novel patterns regarding the thumb choice for keystrokes. Second, the future study needs to involve a series of letter keystrokes as an experimental task. This is because, in everyday life, texting on a smartphone is typically done by typing serial letters rather than typing a single letter employed in this study. More importantly, however, during a series of letter keystrokes with two thumbs, the thumb choice patterns for keystrokes are not likely consistent with those for a single letter keystroke because the thumb action of touching the previous letter key might significantly affect the thumb action of touching the next letter key. Therefore, it is worth clarifying this in further study in order to improve the generalizability of the results. Third, participants from various age groups should be included in the future study. The present study recruited only users in their 20s as its participants because they were considered major users of smartphones [39,40]. However, age generations with different levels of familiarity with smartphones and physical QWERTY keyboards are likely to show different thumb choice patterns for keystrokes when using a smartphone QWERTY soft keyboard. Thus, further study including a variety of different age groups would be valuable to strengthen the generalizability of the current study as well as to understand how familiarity with smartphones and physical QWERTY keyboards affects the thumb choice patterns for keystrokes. Lastly, it would be valuable to study the thumb choice patterns for keystrokes on a QWERTY soft keyboard, depending on different languages and cultures. This is because, for users who do not come from an alphabetic culture, common sense suggests that the thumb choice patterns for keystrokes on a QWERTY soft keyboard may be influenced by the linguistic peculiarities of native languages or habits created by the key arrangements within native language keyboard layouts. Although the current study employed engineering students who were familiar with coding using a QWERTY layout as its participants, this problem is still inherent in this study. Accordingly, we believe that a comparative study of these differences would be helpful for understanding the inherent thumb choice patterns and habits for keystrokes during two-thumb key entry on a QWERTY soft keyboard.

5. Conclusions

The current study observed which thumb, the left or right, was used for keystrokes and examined the patterns during two-thumb key entries on a smartphone QWERTY soft keyboard. This research can be summarized in three ways. First, overall, the left thumb was employed slightly more for the keystrokes—especially, this was even more pronounced in the middle area of the QWERTY soft keyboard, regardless of handedness. Second, most letter keys were primarily tapped by the relatively closer one of both the left and right thumbs, except the letter keys in the middle area that was equidistant from the preset positions of both the left and right thumbs. Lastly, handedness was not a key factor in significantly differentiating thumb choice patterns for keystrokes during two-thumb key entries on the QWERTY soft keyboard. This study is expected to be utilized in the following ways. As a fundamental knowledge, first of all, the findings of this study could help address the reasons for various phenomena (e.g., variation of touch performance and satisfaction) caused by thumb choice for keystrokes, which have been raised in various studies on smartphone key entry. In addition, the knowledge gained from the present study would be useful not only to improve the layouts of QWERTY soft keyboards but also to refine the arrangement of soft buttons on a smartphone touch-screen in terms of usability. Note that these findings may be tied up with the context of smartphone use established in the current study, and thus, their application and interpretation that might exceed the scope of this study are recommended to be implemented with caution.

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