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Effects of Button Width, Height, and Location on a Soft Keyboard: Task Completion Time, Error Rate, and Satisfaction in Two-Thumb Text Entry on Smartphone

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ABSTRACT This paper examined touch performance and satisfaction as a function of button width, height, and location in two-thumb interactions on a soft keyboard. Thirty-two college students with an experience of smartphone-use were recruited for testing. Task completion time (s), error rate, and subjective satisfaction were measured for different combinations of button widths (4.0, 5.3, 6.7, and 8.0 mm), heights (4.0, 5.3, 6.7, and 8.0 mm), and locations (LT: left-top, LC: left-center, LB: left-bottom, RT: right-top, RC: right-center, and RB: right-bottom). Task completion times (0.83 s) at LC and RC were significantly shorter than the peripheral button locations (0.91 s). Satisfaction scores (1: highly dissatisfied ∼ 7: highly satisfied) at LB and RB (4.1) were significantly worse than the other buttons (4.8). The linear regression analyses with button widths and heights for button locations revealed that increasing button height had a relatively larger impact in improving task completion times and error rates at LT and RT than increasing button width. However, increasing button height or width rate at the other button locations had similar impacts on one another in improving the task completion times and errors.

INDEX TERMS Button location, button size, soft keyboard, touch screen.

I. INTRODUCTION

Text entry on smartphones with a soft keyboard (or graphical keyboard) has been increasing with the active use of messaging and social network applications worldwide. Statista [1] reported that 2.46 billion people were using social network applications with smartphones in 2017 and MediaKix [2] found that 64% of smartphone users were communicating via messaging applications worldwide in 2017. In addition, it is well-known that approximately half of smartphone users have been utilizing email services on smartphones [3]. These recent statistics imply that the text entry with a soft keyboard on the touch-screen of a smartphone is becoming an important communication tool in everyday life [4]–[6].

Determining the optimal button size for a soft QWERTY keyboard has been regarded as an important challenge, since a large number of graphical buttons need to be displayed in the limited space of a touch-screen. In general, soft QWERTY keyboards employed in smartphones are inherited from QWERTY keyboards used for personal computers [7]. Thus, smartphone users feel familiar with these keyboard layouts because their prior experience might be transferred from personal computers to smartphones. However, the button size of the soft keyboards is relatively becoming smaller, since more than 30 graphical buttons should be placed in the small size of touch-screens corresponding to the handy size of smartphones. Therefore, a soft keyboard on a smartphone is usually prone to more touch errors, which has a potential to degrade touch performance and user satisfaction [8].

To improve usability and user experience of graphical buttons, some researchers have tried to investigate the effects of button size in text entry using a touch-screen. Parhi *et al.* [9] examined the effect of the size of square-shaped buttons on a personal digital assistant (PDA) and showed that

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larger buttons improved touch performance and user satisfaction, in terms of accuracy and task completion time. Park and Han [10], [11] also conducted similar studies, and their results confirmed that users experienced better accuracy and shorter task completion time with larger buttons on a PDA. Despite these significant effects of button size on a touch screen, however, the results cannot be directly applied to design of soft keyboards on a smartphone. Specifically, button shapes of the soft keyboards are generally rectangular (i.e., vertically long on a portrait mode) instead of square shaped due to the spatial limit of a handy size touch-screen. For example, Apple's iPhone (screen size = 4.7 inch) and Samsung's Galaxy (5 inch) have 5 mm (width) × 7 mm (height) and 5 mm × 6 mm buttons on their QWERTY keyboards, respectively. Likewise, the soft keyboards are usually displayed on the lower part of a smartphone (lower than the halfway point). The lower location of the keyboards often induces a user to grasp the lower part of a smartphone, which could lead to different pattern and performance of thumb motions from grasping the middle part of a smartphone [8].

A few studies have investigated the locational effects of graphical buttons on a soft keyboard. Parhi et al. [9] partially examined the locational effects of buttons on a PDA for one-thumb text entry. Meanwhile, Park and Han [10], [11] investigated the effects of button locations across the entire touch-screen of a PDA for one-thumb text entry. In addition, Chang et al. [8] examined the locational effects of graphical buttons displayed on the lower half of a smartphone in two-thumb interactions. Nevertheless, the locational effects of different sized buttons on a smartphone haven't been fully examined yet.

Research on the interaction effects between button size and location on a soft keyboard is still warranted in order to provide the appropriate design guidelines for smartphone user interface designs in two-thumb text entry. This study examined touch performance and user satisfaction as a function of button width, height, and location for two-thumb text entry and investigated if button sizes (combination of width and height) can improve touch performance and user satisfaction for each button location. An experimental software was developed to display graphical buttons with different sizes and locations on a given touch-screen and was programmed to automatically record participant's task completion time. Testing was conducted to measure touch performance and user satisfaction scores as a function of (1) four button widths, (2) four button heights, and (3) six button locations. Lastly, the effects of button width and height at different button locations were statistically tested, and design advice for the graphical buttons of a soft keyboard was discussed based on the analysis results.

II. METHOD

A. PARTICIPANTS

Thirty-two college students (male: 14, female: 18) were recruited for the experiment. They had 5.8 year (SD: 1.3) of experience in smartphone-use and had been using a soft keyboard on smartphones for text entry. Their average age was 23.3 years (SD: 1.5) and they were all right handers. Their hand length and width were 176.8 mm (SD: 11.8) and 82.6 mm (SD: 16.8), respectively. All the participants had normal vision and their average acuity was 1.1 (SD: 0.4). No musculoskeletal pain or discomfort on the upper limbs and thumbs was reported on the day of the experiments. All the participants signed an informed consent form and were given a description of the experimental procedures.

B. EQUIPMENT

A smartphone available in the market (Galaxy S6, Samsung) was employed in the experiment. Its overall size and touch-screen size were 7.1 cm (width) × 14.3 cm (height) × 6.8 cm (thickness) and 6.4 cm (width) × 11.3 cm (height), respectively. The resolution was 2560 × 1140 pixels (1 pixel ≅ 0.13 mm). An experimental software was developed with M-BizMaker (Softpower, Korea). The experimental screen (portrait type) consisted of two sections: (1) experimental section (upper) and (2) soft keyboard section (lower). The experimental section (5.5 cm × 6.4 cm) was designed to inform experimental instructions (e.g., the number of trials and the target button), which helped participants proceed with the tasks given during the experiment. The soft keyboard section (4.5 cm × 6.4 cm) was composed of six buttons - six different locations were designated as the button locations on the soft keyboard section, as shown in Fig. 1: (1) left-top corner (LT); (2) left-bottom corner (LB); (3) left center (LC); (4) right-top corner (RT); (5) right-bottom corner (RB); and (6) right center (RC).

The experimental software was programmed to randomly provide one target button at a time among the six buttons. The target button information was simultaneously displayed on the experimental screen as well as the target button on the soft keyboard section. In addition, the experimental software automatically recorded task completion time (touch time) (unit: s). The beginning of the touch signal was given by a letter including L (left thumb) or R (right thumb), which informed the participant of which thumb to use, with a button location such as T (top), C (center), and B (bottom), after counting down numbers from 5 to 0 (pre-signal) seconds. Then, the software automatically detected the end moment when the thumb reached a target button. This procedure was repeated on every button trial.

C. EXPERIMENTAL DESIGN

A three-factor within-subject design was used in the experiment. Three within-subject factors (independent variables) were button width (4 levels: 30 pixel (4.0 mm), 40 (5.3), 50 (6.7), and 60 (8.0)), button height (4 levels: 30 pixel (4.0 mm), 40 (5.3), 50 (6.7), and 60 (8.0)), and button location (6 levels: LT, LB, LC, RT, RB, and RC).

Three dependent variables (task completion time, error rate, and subjective satisfaction) were measured for each button during the experiment. An interactive thumb for each button was designated: (1) the left thumb was only used for

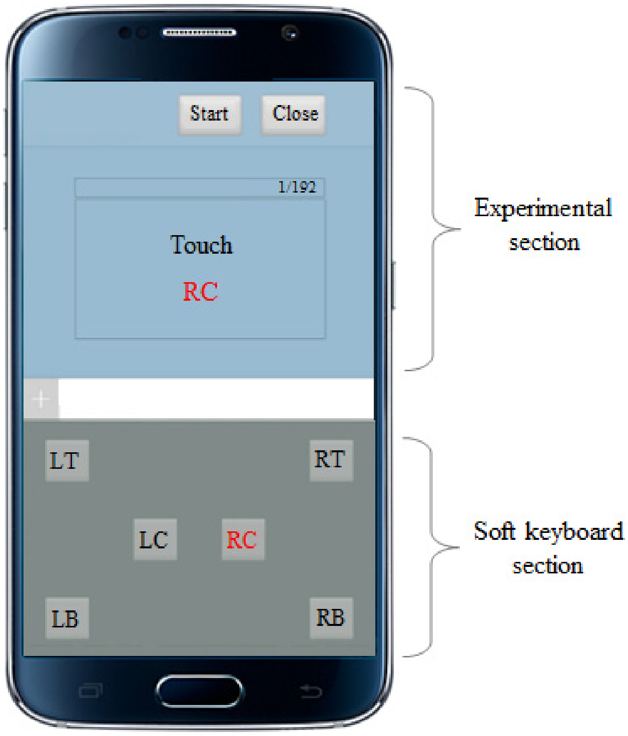

FIGURE 1. Experimental screen.

the left three buttons including LT, LB, and LC and (2) the right thumb was only used for right three buttons including RT, RB, and RC. In sum, the total number of possible button combinations was 96 (left thumb: 4 button heights × 4 button widths × 3 button locations; right thumb: 4 button heights × 4 button widths × 3 button locations).

Participants were allowed to sit on a chair and rest their elbows naturally on a desk (Fig. 2). They were asked to locate their thumbs near the initial positions (LC for the left thumb and RC for the right thumb), before every touching action. A target button was randomly provided every 10 sec and the participants were requested to tap the target button as fast and accurately as possible. Task completion time (unit: seconds) was recorded from the beginning of the touch signal to the moment that the designated thumb touched a target button. The measurement of each button condition was repeated until two successful touches were made by the designated thumb; i.e., each participant performed two trials on each button combination. An experimental instructor monitored touch errors and computed the error rate (unit: %) by dividing the number of errors by the total number of trials. A break of approximately one minute was given, and then each participant was asked to provide subjective satisfaction ratings for all the button sizes and locations using a 7-point scale [12] that varied between 1 (highly dissatisfied) and 7 (highly satisfied).

Testing consisted of 4 steps. First, the study objective and the experimental procedure were explained to the participants. Second, each participant was given a practice trial to help them become familiar with the use of the given

FIGURE 2. Experiment scene and participant's posture.

experimental procedure and system and to allow them to adjust their preferred grip position and posture. Third, the main experiment was conducted; task completion time, error rate, and subjective satisfaction rating were collected for all the button sizes and locations. Lastly, a debriefing session was conducted to discuss the testing results with the participants.

D. STATISTICAL ANALYSIS

This study conducted a MANOVA on the three dependent variables (task completion time, error rate, and satisfaction score) and found that the main effects for all dependent variables were significant at $\alpha = 0.05$. Thus, to examine the effects of the button width, button height, and button location on each dependent variable, three-factor within-subject ANOVAs were conducted on the results of each dependent variable with $\alpha = 0.05$. The ANOVAs were performed separately for the left thumb and the right thumb. As post-hoc analyses, the Tukey test and simple effects test were employed for significant variables and interactions, respectively. To test the effects of the hand, one-factor within-subjects ANOVAs on each pair of matched-locations (i.e., LT vs. RT, LC vs. RC, LB vs. RB) were performed at the same confidence level. Lastly, the linear regression analyses with the button widths and heights for each button location were employed to determine the impacts of the button width and height on task completion times, error rates, and satisfaction scores.

III. RESULTS

A. TASK COMPLETION TIME

The task completion times at the center buttons (LC and RC) were significantly shorter than those at the peripheral locations (LT, LB, RT, and RB), as shown in Fig. 3 (left thumb: $F(2, 62) = 46.86$, $p < 0.001$, partial $\eta^2 = 0.60$; right thumb: $F(2, 62) = 4.48$, $p = 0.015$, partial $\eta^2 = 0.13$). The Tukey tests for the left thumb grouped LB (0.94 ± 0.007) into a

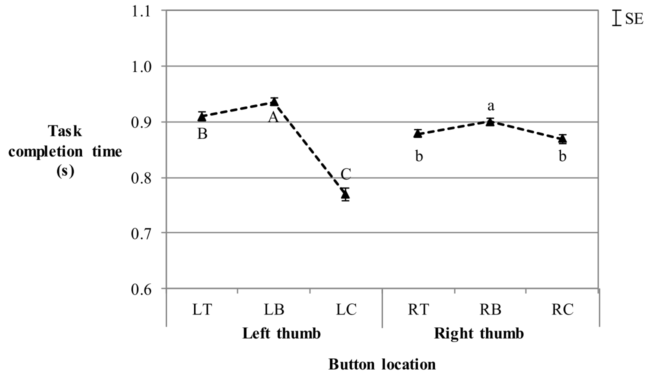

FIGURE 3. Task completion times as a function of button location (LT: Left-top corner, LB: Left-bottom corner, LC: Left center, RT: Right-top corner, RB: Right-bottom corner, RC: Right center; letters indicate significant differences at $\alpha = 0.05$).

higher group, LT (0.91 ± 0.008) into a middle group, and LC (0.77 ± 0.011) into a lower group, respectively. Similarly, the Tukey tests for the right thumb classified RB (0.90 ± 0.007) into a higher group and categorized RT (0.88 ± 0.007) and RC (0.87 ± 0.007) in a lower group.

Task completion times significantly decreased as the button width and height increased, as shown in Fig. 4. As the button width was extended, task completion times of both the left and right thumbs were gradually reduced, across all button locations (LT: F(3, 93) = 3.32, p = 0.02, partial η^2 = 0.11; LB: F(3, 93) = 6.62, p < 0.001, partial η^2 = 0.18; LC: F(3, 93) = 9.88, p < 0.001, partial η^2 = 0.24; RT: F(3, 93) = 2.15, p = 0.10, partial η^2 = 0.06; RB: F(3, 93) = 5.90, p < 0.001, partial η^2 = 0.16; RC: F(3, 93) = 8.43, p < 0.001, partial η^2 = 0.21). Overall, for both thumbs, the Tukey test classified 30-pt into a higher group and grouped 50-pt and 60-pt into a lower group, excluding RT. Similarly, as the button height increased, the task completion times of both the left and right thumbs were significantly decreased, across all button locations (LT: F(3, 93) = 15.45, p < 0.001, partial η^2 = 0.36; LB: F(3, 93) = 7.67, p < 0.001, partial η^2 = 0.19; LC: F(3, 93) = 8.31, p < 0.001, partial η^2 = 0.22; RT: F(3, 93) = 12.22, p < 0.001, partial η^2 = 0.28; RB: F(3, 93) = 14.47, p < 0.001, partial η^2 = 0.34; RC: F(3, 93) = 11.63, p < 0.001, partial η^2 = 0.27). The Tukey tests categorized 30-pt in a higher group and classified 40-pt, 50-pt and 60-pt into a lower group for both thumbs. On the other hand, there was no significant interaction found among the independent variables.

The linear regression analyses with the button widths and heights for each button location determined the impacts of the button width and height on task completion time, as shown in Table 1. For the top corner buttons (LT and RT), increasing the height of the button (LT: slope of height = − 0.0045; RT: slope of height = − 0.0034) was found to have a relatively larger impact in reducing the task completion times than increasing the width of the button (LT: slope of width = − 0.0028; RT: no significant effect of width). Meanwhile, increasing the width and height of the button shared similar

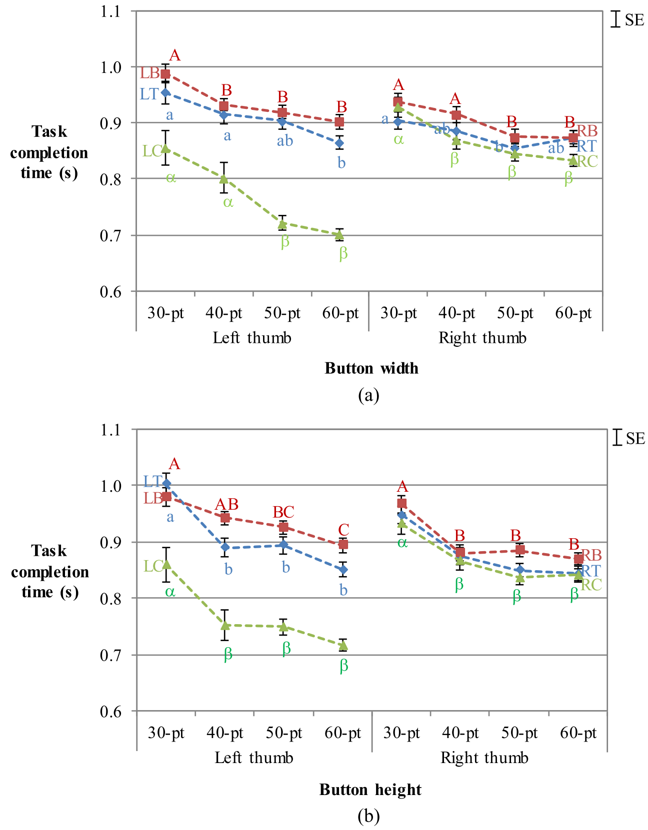

FIGURE 4. Task completion times as a function of button width and height (LT: Left-top corner, LB: Left-bottom corner, LC: Left center, RT: Right-top corner, RB: Right-bottom corner, RC: Right center; letters indicate significant differences at $\alpha = 0.05$). (a) Button width. (b) Button height.

TABLE 1. The linear regression analysis between task completion times and button width and height.

Button	Equation	R^2	Predictor	p
LT	1.24 − 0.0028 Width − 0.0045 Height	0.71	Intercept	0.000
			Width	0.011
			Height	0.000
LB	1.18 − 0.0027 Width − 0.0028 Height	0.91	Intercept	0.000
			Width	0.000
			Height	0.000
LC	1.21 − 0.0054 Width − 0.0043 Height	0.67	Intercept	0.000
			Width	0.002
			Height	0.007
RT	1.09 − 0.0012 Width − 0.0034 Height	0.64	Intercept	0.000
			Width	0.118
			Height	0.001
RB	1.13 0.0023 Width 0.0029 Height	0.70	Intercept	0.000
			Width	0.004
			Height	0.001
RC	1.14 − 0.0031 Width − 0.0030 Height	0.77	Intercept	0.000
			Width	0.000
			Height	0.001

impacts in reducing the task completion times at the bottom corner (LB and RB) and center (LC and RC) buttons (Table 1). However, relatively larger negative slopes were observed at LC (slope of width = − 0.0054 and slope of height = − 0.0043) and RC (slope of width = − 0.0031 and slope of height = − 0.0030), as compared to the slopes of LB (slope of width = − 0.0027 and slope of height = − 0.0028)

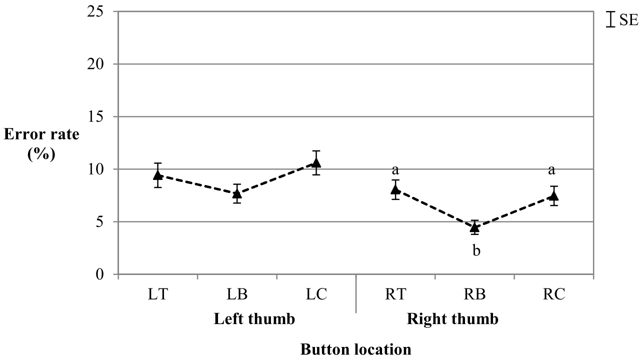

FIGURE 5. Error rates as a function of button location (LT: Left-top corner, LB: Left-bottom corner, LC: Left center, RT: Right-top corner, RB: Right-bottom corner, RC: Right center; letters indicate significant differences at $\alpha = 0.05$).

and RB (slope of width = – 0.0023 and slope of height = – 0.0029). Note that the interaction between the button width and height was disregarded in the regression models because it was not statistically significant in the ANOVA analysis.

The task completion times of the right thumb were significantly faster than those of the left thumb, except for the center buttons (LC and RC) (top corners: F(1, 31) = 9.92, p = 0.004, partial η^2 = 0.23; bottom corners: F(1, 31) = 7.46, p = 0.010, partial η^2 = 0.19), as shown in Fig. 3. At the peripheral button locations (LT, LB, RT, and RB), the task completion times of the right thumb (RT: 0.88 ± 0.007; RB: 0.90 ± 0.007) were quicker than those of the left thumb (LT: 0.91 ± 0.008, LB: 0.94 ± 0.008). However, the task completion times at the center locations showed an inverse pattern. The task completion times at RC (0.87 ± 0.007) were slower than those at LC (0.77 ± 0.011) (F(1, 31) = 28.62, p < 0.001, partial η^2 = 0.49). The results of the linear regression analyses showed that the task completion times of the left thumb were more rapidly reduced (larger negative slopes) than those for the right thumb, as the button width and height increased (Table 1).

B. ERROR RATE

The error rates at LB and RB were smaller than those at the other locations, as shown in Fig. 5 (left thumb: F(2, 62) = 1.03, p = 0.364, partial η^2 = 0.03, right thumb: F(2, 62) = 3.93, p = 0.025, partial η^2 = 0.11). The error rates at LB ranged between 7.7% ± 0.89. This was 22.8% and 38.2% smaller than those at LT (9.4% ± 1.16) and LC (10.6% ± 1.14), respectively; however, these results failed to show statistical significance. Meanwhile, the error rates at RB were found to occur between 4.5% ± 0.66, which was significantly smaller than those at RT (8.0% ± 0.93) and RC (7.5% ± 0.91) (smaller by 80.4% and 67.0%, respectively). The Tukey tests for the right thumb grouped RT and RC into a higher group and categorized RB in a lower group (Fig. 5).

Error rates decreased across all button locations as the button width and height increased, as shown in Fig. 6. The button width significantly affected the error rates (LT: F(3, 93) = 2.88, p = 0.040, partial η^2 = 0.08; LB: F(3, 93) = 6.36, p = 0.001, partial η^2 = 0.17; LC: F(3, 93) = 9.64,

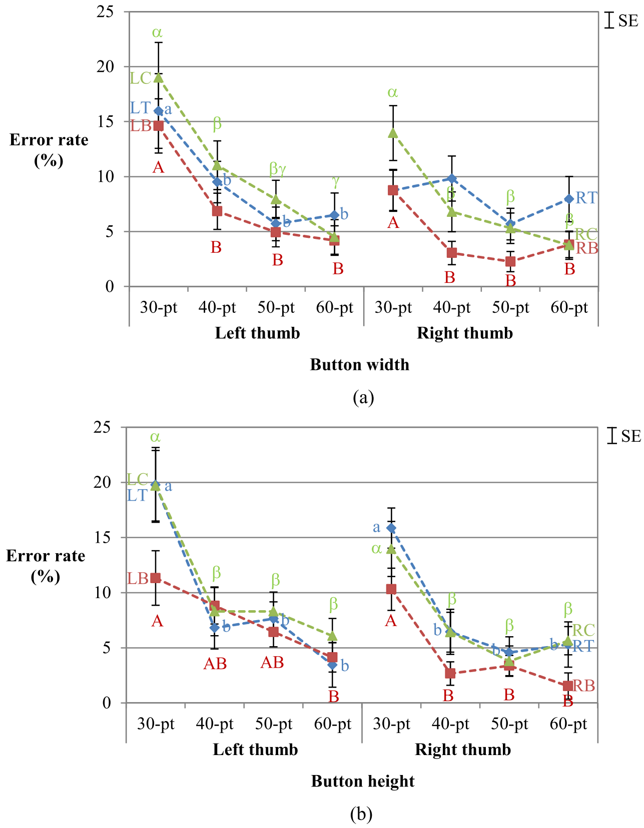

FIGURE 6. Error rates as a function of button width and height (LT: Left-top corner, LB: Left-bottom corner, LC: Left center, RT: Right-top corner, RB: Right-bottom corner, RC: Right center; letters indicate significant differences at $\alpha = 0.05$). (a) Button width. (b) Button height.

p < 0.001, partial η^2 = 0.24; RT: F(3, 93) = 1.03, p = 0.384, partial η^2 = 0.03; RB: F(3, 93) = 5.56, p = 0.001, partial η^2 = 0.15; RC: F(3, 93) = 5.16, p = 0.002, partial η^2 = 0.14), with the exclusion of RT. Across all the significant button locations, the Tukey tests for both the left and right thumbs classified 30-pt into a higher group and categorized 50-pt and 60-pt in a lower group. Similarly, the error rates decreased significantly as the button height increased (LT: F(3, 93) = 6.33, p = 0.001, partial η^2 = 0.18; LB: F(3, 93) = 3.14, p = 0.029, partial η^2 = 0.09; LC: F(3, 93) = 6.01, p = 0.001, partial η^2 = 0.16; RT: F(3, 93) = 7.31, p < 0.001, partial η^2 = 0.19; RB: F(3, 93) = 7.68, p < 0.001, partial η^2 = 0.21; RC: F(3, 93) = 9.54, p < 0.001, partial η^2 = 0.23). Overall, the Tukey tests classified 30-pt into a higher group and grouped 50-pt and 60-pt into a lower group for both thumbs. On the other hand, no significant interactions were observed among the independent variables.

The impacts of the button widths and heights on error rates were determined by linear regression analyses for each button location, as shown in Table 2. Increasing the height of the top corner buttons (LT: slope of height = – 0.0048; RT: slope of height = – 0.0034) had a relatively larger impact in improving the error rates than increasing their width (LT: slope of width = – 0.0032; RT: no significant effect of width). Meanwhile, at the bottom corner (LB and RB)

TABLE 2. The linear regression analysis between error rates and button width and height.

Button	Equation	R^2	Predictor	p
LT	0.46 − 0.0032 Width − 0.0048 Height	0.61	Intercept	0.000
			Width	0.025
			Height	0.002
LB	0.34 − 0.0032 Width − 0.0025 Height	0.78	Intercept	0.000
			Width	0.000
			Height	0.001
LC	0.50 − 0.0047 Width − 0.0041 Height	0.51	Intercept	0.000
			Width	0.016
			Height	0.030
RT	0.26 − 0.0007 Width − 0.0034 Height	0.43	Intercept	0.003
			Width	0.555
			Height	0.009
RB	0.23 0.0015 Width 0.0026 Height	0.44	Intercept	0.002
			Width	0.129
			Height	0.018
RC	0.34 − 0.0032 Width − 0.0028 Height	0.64	Intercept	0.000
			Width	0.003
			Height	0.008

and center (LC and RC) buttons, no remarkable differences between the slopes of the button width and height were found. However, increasing the width or height of the center buttons (LC: slope of width = − 0.0047 and slope of height = − 0.0041; RC: slope of width = − 0.0032 and slope of height = − 0.0028) had a relatively larger impact in reducing the error rates, in comparison with increasing the width or height of the bottom buttons (LB: slope of width = − 0.0032 and slope of height = − 0.0025; RB: slope of height = − 0.0026).

The error rates of the left thumb (9.2% ± 0.6) were greater than those of the right thumb (6.7% ± 0.5); however, the difference at the bottom corners (LB vs. RB) was only significant (top corners: F(1, 31) = 1.05, p = 0.314, partial η^2 = 0.03; bottom corners: F(1, 31) = 5.66, p = 0.024, partial η^2 = 0.15; centers: F(1, 31) = 2.28, p = 0.141, partial η^2 = 0.07) (Fig. 5). In addition, the linear regression analyses showed that the error rates of the left thumb decreased more rapidly (larger negative slopes) than those for the right thumb as the button width and height increased (Table 2).

C. SATISFACTION SCORE

For both thumbs, the bottom buttons (LB and RB) showed worse satisfaction scores than the other button locations (LT, LC, RT, and TC), as illustrated in Fig. 7 (left thumb: F(2, 62) = 12.65, p < 0.001, partial η^2 = 0.29, right thumb: F(2, 62) = 16.67, p < 0.001, partial η^2 = 0.35). The satisfaction scores at LB ranged between 3.9 ± 0.08, which was 15.4% and 26.6% lower than those at LT (4.5 ± 0.07) and LC (4.9 ± 0.07). Similarly, the satisfaction scores at RB ranged between 4.2 ± 0.07. This was 11.9% and 16.7% lower than those of RT (4.7 ± 0.07) and RC (4.9 ± 0.07). The Tukey tests grouped LT, LC, RT, and RC into a higher group and classified LB and RB into a lower group. On the other hand, the satisfaction scores for the right thumb (4.6 ± 0.04) were significantly greater (0.2) than those of the left thumb (4.4 ± 0.04) (F(1, 31) = 12.36, p = 0.001, partial η^2 = 0.29).

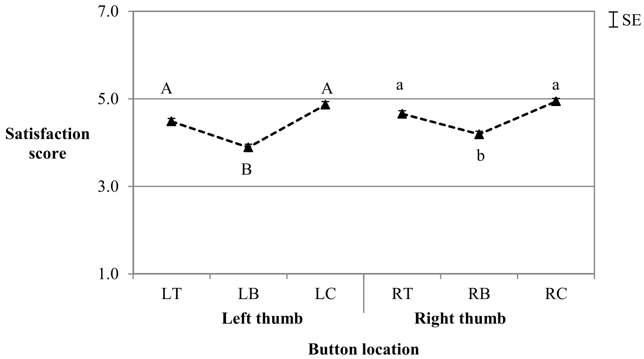

FIGURE 7. Satisfaction score as a function of button location (LT: Left-top corner, LB: Left-bottom corner, LC: Left center, RT: Right-top corner, RB: Right-bottom corner, RC: Right center; letters indicate significant differences at $\alpha = 0.05$).

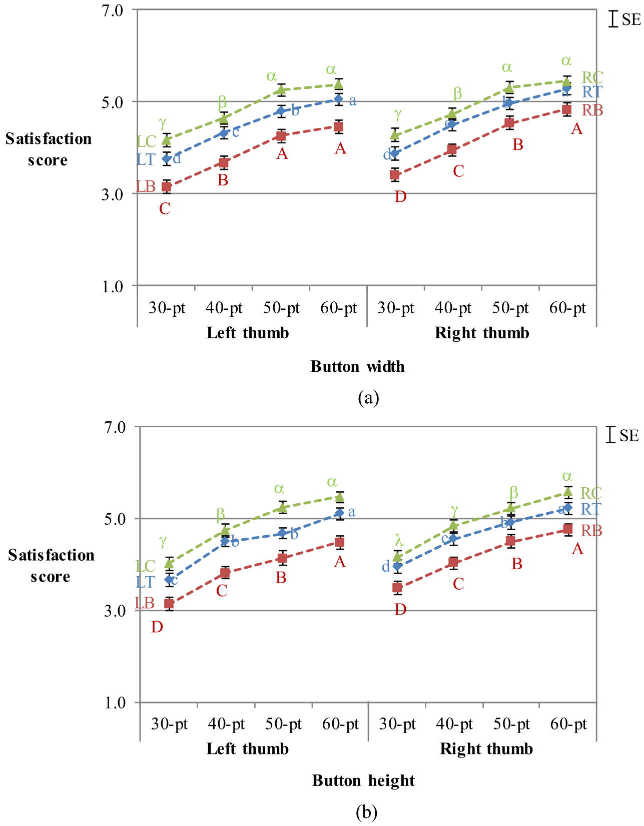

FIGURE 8. Satisfaction scores as a function of button width and height (LT: Left-top corner, LB: Left-bottom corner, LC: Left center, RT: Right-top corner, RB: Right-bottom corner, RC: Right center; letters indicate significant differences at $\alpha = 0.05$). (b) Button width. (b) Button height.

Subjective satisfaction scores were significantly improved as the button width and height increased, across all button locations (Fig. 8). The satisfaction scores for the both thumbs (LT: F(3, 93) = 27.10, p < 0.001, partial η^2 = 0.45; LB: F(3, 93) = 27.17, p < 0.001, partial η^2 = 0.45; LC: F(3, 93) = 38.58, p < 0.001, partial η^2 = 0.54; RT: F(3, 93) = 22.98, p < 0.001, partial η^2 = 0.41; RB: F(3, 93) = 31.54, p < 0.001, partial η^2 = 0.49; RC: F(3, 93) = 41.66, p < 0.001, partial η^2 = 0.56) increased gradually as the button width was extended. Overall, the Tukey tests for both the thumbs

TABLE 3. The linear regression analysis between satisfaction scores and button width and height.

Button	Equation	R^2	Predictor	p
LT	0.48 + 0.0454 Width + 0.0435 Height	0.89	Intercept	0.248
			Width	0.000
			Height	0.000
LB	− 0.10 + 0.0434 Width + 0.0454 Height	0.88	Intercept	0.803
			Width	0.000
			Height	0.000
LC	0.78 + 0.0484 Width + 0.0423 Height	0.87	Intercept	0.110
			Width	0.000
			Height	0.000
RT	0.67 + 0.0417 Width + 0.0469 Height	0.92	Intercept	0.063
			Width	0.000
			Height	0.000
RB	0.06 + 0.0429 Width + 0.0488 Height	0.93	Intercept	0.850
			Width	0.000
			Height	0.000
RC	1.02 + 0.0462 Width + 0.0409 Height	0.92	Intercept	0.008
			Width	0.000
			Height	0.000

classified 60-pt of the button into the highest group and 30-pt into the lowest group. In the same manner, the satisfaction scores for both thumbs (LT: $F(3, 93) = 20.99$, $p < 0.001$, partial $\eta^2 = 0.39$; LB: $F(3, 93) = 22.69$, $p = 0.001$, partial $\eta^2 = 0.41$; LC: $F(3, 93) = 20.91$, $p < 0.001$, partial $\eta^2 = 0.39$; RT: $F(3, 93) = 24.43$, $p < 0.001$, partial $\eta^2 = 0.43$; RB: $F(3, 93) = 25.78$, $p < 0.001$, partial $\eta^2 = 0.44$; RC: $F(3, 93) = 22.44$, $p < 0.001$, partial $\eta^2 = 0.41$) also increased, as the button height increased. For both thumbs, the Tukey tests generally classified 60-pt into the highest group and 30-pt into the lowest group. However, no significant interaction effect was found.

The linear regression analyses determined the impacts of the button width and height on user satisfaction scores for each button location, as shown in Table 3. Overall, increasing the width and height of the buttons had similar impacts in improving satisfaction scores, across all the button locations. In addition, no remarkable differences between the slopes of the button width and height were found between the left and right thumbs.

IV. DISCUSSION

Despite varying button width and height, button location showed strong impacts on touch performance and user satisfaction. The task completion times (mean = 0.82 s) for the center buttons (LC and RC) were shorter than those (mean = 0.91 s) of the peripheral buttons (LT, LB, RT, and RB). These results were expected because the peripheral buttons were placed away from the initial positions (near LC and RC) of both the thumbs, which increased the index of difficulty (ID) and thus increased the thumb's transition time for reaching the buttons according to Fitts's law [13]. In addition, pressing the peripheral buttons required a larger amount of thumb joint displacement as well as the corresponding conscious muscle control, in comparison with the center buttons that were located near the initial positions [8], [14]. Previous studies have confirmed the positive relationships between touch times and the movement distances of the thumbs [8], [10], [11], [15].

The task completion times (mean = 0.89 s) at the top corner buttons (LT and RT) were slightly shorter than those (mean = 0.92 s) for the bottom corner buttons (LB and RB). The primary reason for this is that the bottom corner buttons are often visually occluded by the thumbs, particularly when the thumbs are in the initial positions. This could require users to unnecessarily take one more step in searching for the button locations with their eyes before moving their thumb, which could slow their task completion times. Alternatively, the result can be explained from a biomechanical point of view. A thumb's inward motion (flexion of the thumb) for pressing the inner corner buttons, such as LB and RB, requires a larger amount of thumb joint displacement than the outward motion (adduction of the thumb) for pressing the upper corner buttons [8], [16]. In addition, the inward motion of the thumbs requires a greater perceived effort than their outward motion [17].

The center buttons showed the fastest task completion times, despite also having the highest error rates. On the other hand, the bottom corner buttons showed the slowest task completion times, although the lowest error rates were found at these button locations. This indicated that thumb motions for pressing the center buttons were inherently quicker than those for pressing the bottom corner buttons, regardless of whether errors occur or not. Thus, we could predict that task completion times without any error also had similar propensities to the task completion times with errors that were shown in the present testing.

The error rates (mean = 6.1%) at the bottom corner buttons (LB and RB) were smaller than those (mean = 8.9%) for the other buttons. This finding is inconsistent with the results of previous studies for one thumb text entry; Parhi et al. [9] reported that button locations did not significantly affect the error rates and Park and Han [10], [11] found that the right bottom corner buttons, in the case of the right thumb text entry, showed relatively poor error rates. The reason for these differences is unclear. However, we can estimate two reasons from the unique features of two-thumb text entry. First, we observed that a user during two-thumb text entry maintained a more upright posture of her/his thumb (i.e., the thumb stood vertically from the screen) and frequently used the top area (tip) of the thumbs to press the buttons, as compared to one-thumb text entry where a user often used the upper-lateral area (ulnar aspect) of her/his thumb due to thumb's adduction and supination. The contact areas between the thumbs and buttons could be reduced when the tip of the thumb is employed with the upright posture of the thumb, and thus this would positively affect the motion accuracy of thumbs for two-thumb text entry [18]. Second, as aforementioned, the bottom corner buttons are more often visually occluded by the thumbs for two-thumb text entry because a user usually holds a cell-phone body using its bottom corners with two hands. This requires a user to take an additional action of searching and confirming the button locations before moving the thumbs, which may cause a user to more cautiously control her/his thumbs. In fact, this assumption is consistent with the participant's opinions from the debriefing session; some participants more consciously pressed the bottom corner buttons during the testing because the buttons were visually occluded and required more physically difficult thumb motions and a greater perceived effort. Parhi et al. [9] also described this trend, where a user traded time for accuracy. Furthermore, this observation could account for the reason why the relatively higher error rates were found at LC and RC where participants did not need to search for the button locations but just tap the buttons almost unconsciously.

As expected, task completion times and error rates were reduced as the button width or height increased. The results agree with the findings of previous studies examining the effects of square button sizes on a soft keyboard in one-thumb text entry [9]–[11]. Parhi *et al.* [9] previously explained this result using Fitts's law (i.e., the larger the tolerance of target buttons, the lower the index of difficulty). The regression slopes of the button width and height on task completion time and error rate showed that increasing the height of the button (LT: time = −0.0045, error = −0.0048; RT: time = −0.0034, error = −0.0034) had a relatively larger impact in reducing the task completion times and error rates than increasing width of the buttons (LT: time = −0.0028, error = −0.0032; RT: time = no significant, error = no significant) for the top corner buttons (LT and RT). We estimated that this result could be associated with thumb postures, such that when the thumbs pressed LT and RT, they were usually adducted and supinated. These thumb postures often enable the thumbs to tap the buttons using the lateral side (ulnar aspect) of the thumbs, which could make a long-shaped contact from the top to the bottom of the buttons. This could further explain the reason why the task completion times and error rates for the top corner buttons were more sensitive to the variations in the button height than that for the button width.

Increasing the button width and height shared similar impacts in reducing the task completion times and error rates at the bottom corner (LB and RB) and center (LC and RC) buttons. However, the regression analysis showed that the bottom corner buttons (−0.0024 on average) had relatively smaller negative slopes than the center buttons (− 0.0035 on average). This implied that the performance of the bottom corner buttons were less sensitive to the variations in the button width and height. We assumed that this could be associated with the sizes of the contact areas between the thumbs and the buttons. As aforementioned, the sizes of the contact areas while pressing the bottom corner buttons are usually smaller than those for the other buttons due to thumb's vertical posture. Meanwhile, the thumb needs to be extended (the interphalangeal joint) to reach the center buttons, and thus the pad of the thumb is naturally involved to press the buttons, which makes for a larger area of contact between the thumb and the button [10]. This result could explain the improved task completion times and error rates of the center buttons as the button width or height increased.

Regardless of button size and location, the right thumb showed better performance in terms of task completion time and error rate than the left thumb, with the exclusion of the task completion times at the center buttons (LC and RC). In particular, the shorter the width or height of the buttons was, the worse the performance of the left thumb was, although the performance was more rapidly improved than the right thumb while increasing the button width and height. It is likely that this finding is strongly associated with the experimental protocol in the present study, where all the participants were right handed and are expected to have asymmetrically better motor skills in their right hands. Previous studies support this result by showing that the dominant or preferred hand clearly outperforms the non-dominant or non-preferred hand for most motor tasks, particularly in terms of motion accuracy and speed [19]–[21]. Surprisingly, at the center buttons (LC and RC), the left thumb showed faster task completion times than the right thumb. The reason for this result is unclear, but we estimate that this could be related to a ballistic mode of performance: after long-term practice, the predetermined finger movement of the non-preferred hand is automatically triggered without any form of feedback monitoring (i.e., conscious control), leading to higher speed than that of the preferred hand [22]. Pressing LC with the left thumb in the present study satisfied most conditions of the ballistic mode of performance. For example, all the participants were not only right handed but they were also already familiar with smartphone-use (average 5.8 years). In addition, LC was located near the initial position of the left thumb and thus almost unconscious thumb control (i.e., not necessary for searching buttons and locating buttons) was required to press the predetermined button. Nevertheless, it is cautious to conclude that the ballistic mode of performance completely occurred at LC during the testing, because pressing LC was not completely triggered off unconsciously in this experiment; visual cues were given to inform the participants of a target button before each button pressing task was performed.

Across all button sizes and locations, subjective satisfaction scores showed strong relationships (left $r = -0.21$, $p = 0.041$; right $r = -0.18$, $p = 0.074$) with task completion times. However, the scores did not appear to be strongly associated with the error rates, since the center buttons had the highest satisfaction scores despite also having the highest error rates. These results suggest that satisfaction scores in the present study were more affected by task completion times than error rates. In other words, the participants preferred pressing buttons that required less physical and perceived efforts. This result is consistent with the results of Chang et al. [8] who measured muscle activities and subjective discomfort as a function of button locations on a soft keyboard for two-thumb text entry. In addition, this can account for the results where the satisfaction scores of the right thumb were higher than those for the left thumb, because right handed users may feel more comfortable in the use of their right thumb [19], [23]. On the other hand, satisfaction scores were significantly improved as the button width and height increased. However, increasing the width and height of the buttons shared similar impacts (average slope: 0.0447 ± 0.003) in improving satisfaction scores regardless of button locations and use of the left or right thumbs.

Considering the results of the present study and its practicality, the following advices can be recommended for the design of soft keyboards for two-thumb text entry. First, increasing the button height would help improve user's task completion times and error rates at the top corner buttons. Second, increasing both button width and height is recommended to reduce the task completion times and error rates of the center buttons. Third, increasing the width or height of the bottom corner buttons had relatively less of an impact in improving the task completion times and error rates. Instead, reducing the duration of time spent searching for visually occluded buttons located at the bottom corners could be more beneficial to reduce the task completion times and error rates. Fourth, considering the motor skills of the non-dominant or non-preferred hand, relatively larger sized buttons are needed for the thumb of the non-dominant or non-preferred hand. In sum, if a certain target performance value (e.g., task completion time, error rate, satisfaction) is given, different button size could be assigned for each button location, which could help improve the overall touch performance as well as minimize the reduction of a viewing area due to enlarged buttons.

Further research is warranted for better generalization of the results presented in this study. First, the present study only focused on the top corner, center, and bottom corner buttons. Further studies should be done for the remaining button locations to complete design advice on soft keyboards for two-thumb text entry. In particular, the top center and bottom center button locations which require thumb extension and abduction should be investigated, because these button locations are usually considered challenging for users due to their intrinsic motion difficulty [5], [8], [16], [17]. Second, the testing was conducted with only one size of smartphone (7.1 cm $\times$ 14.3 cm) in portrait mode. However, sizes and holding orientations of smartphones could affect user's task completion times, error rates, and discomfort during text entry [8], [16], [24]. Further experiments to clarify how such sizes and holding orientations of smartphones have impacts on the performance for two-thumb text entry would be useful for improving the results of the present study. Third, biomechanical measurements were not examined during the experiments conducted herein. It is well-known that thumb's kinetic and kinematic features are strongly associated with its joint displacement, movement speed, motion accuracy, and discomfort [8], [16]. In particular, muscle activity or motion analysis would be useful for interpreting the results of the present study, because thumb's different touch motions were observed as a function of button locations and sizes (widths and heights) during the testing. Thus, electromyography (EMG) measurement or quantitative motion capturing is recommended for future studies. Lastly, the error rates in the experiments should have been automatically detected by the program developed for the present study, because the instructor's observation might have errors. Thus, the function of error detection should be embedded in the program to improve the accuracy of the experimental deliverables in the future research.

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