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The Effect of the Geometric Layout of Mobile-phone Keypads on Thumb-pressing Movement Time

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ABSTRACT

In this study, we investigate the effect of geometric layout features of mobile-phone keypads, such as the column-row location, the key width, the key-center distance, and so on, on key-pressing time when a mobile phone is held in one hand and the thumb is used to press the keys. During this study, six participants in the experiments used their dominant right hand to operate keys of three different widths, viz., 2, 6, and 12 mm. In the keypads, as in the standard mobile-phone-keypad layout, there are three vertical columns and four horizontal rows in the keypad; the distances from the center of one key to the next in the vertical/column direction are 12, 24, and 36 mm, while in the horizontal/row direction, they are 15 and 30 mm. The key-pressing performance was measured by the key-pressing movement time; the results indicate that the 6-mm key width leads to the best key-pressing performance. The movement time increases with increases in the distance between key centers. For the columns, the optimal location is 25.07 mm away from the right edge of the mobile-phone panel; for the rows, the optimal location is 40.73 mm away from the bottom of the mobile-phone panel. The basic model of Fitts' Law is not suitable for determining the relationship between the geometric layout of the keypad and the key-pressing time; the Welford model, although possessing better explanatory power, still needs further revision. This study adopts the basic concepts of the Welford model and introduces a key-location effect to establish a model for thumb-pressing in mobile phones. The analysis result indicates that the explanatory power of the thumb-pressing model is superior to that of the basic Fitts' Law model and that of the Welford model.

KEYWORDS;-*Mobile phone, keypad, Fitts' Law*

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I. INTRODUCTION

In recent years, mobile phones (cell phones) have attracted increasing attention from more and more consumers as their functions have expanded, becoming one of the most popular forms of portable equipment. Since mobile phones emphasize portability, the entry keypad's layout space is greatly compressed, due to the demand for a light, thin, short, and small phone as well as a large screen with high picture quality. However, overly small keys cause key-pressing difficulties and affect usage comfort (Oyama et al., 2003), so their input-interface design is much more complex than that of regular information products, such as computers.

Mobile phones are limited by the front panel area and possess a limited number of keys (12 in general), and hence cannot use the key-pressing style used in traditional computer keyboards for text entry. Most studies in this area have thus focused on text-entry techniques or text menu design. Some have explored current text-entry techniques; e.g., James and Reischel (2001) compared the effects on performance (key-pressing accuracy, speed, and so on) of two text-entry techniques, viz., T9 text input and multi-tap. Butts and Cockburn (2002) compared and analyzed three kinds of mobile-phone text-entry techniques, viz., multi-press input with timeout, multi-press input with a next button, and two-key entry. Some researchers have proposed methods to resolve the common confusion between each key's needed three-letter and four-letter encodings; for example, MacKenzie et al. (2001) used the probabilities of word bank-to-alphabetical sequence matches to predict the user's next intended alphabet entry. Wigdor and Balakrishnan (2003) adopted a mobile phone's tilt direction to choose from candidate letters to resolve the encoding problem of using a single key to represent many letters. Some have proceeded with the design and structure construction, focusing on text-entry techniques; for example, Curran et al. (2006), in dealing with various users and mobile equipment that are often used, established a mobile-phone text-entry technique suitable for specifically targeted user groups. Sörensen (2007) established the most suitable mobile-phone short-message text-entry technique using a multiple-target optimal layout for mobile-phone keypads.

Although the design of text-entry techniques and text menus affects the accuracy and speed of mobile-phone text entry, the geometric layout of the keypad also affects mobile-phone text-entry performance. The relationship between the key size/dimension and the key-center distances and key-pressing performance has been interpreted in a few studies (Drury &Haffman, 1992) using Fitt's Law. Fitts (1954) pointed out that when the target width remains the same while the movement distance is increased, or when the movement distance remains the same while the target width is decreased, the movement time will increase logarithmically. The relationship is

$$MT = A + B\log_2\left(\frac{2D}{W}\right) \tag{1}$$

$$\text{ID} = \log_2\left(\frac{2D}{W}\right) \tag{2}$$

where, in the model, *MT* is the movement time, and *A* and *B* are constants derived from experimental results, which will differ with different experimental conditions; *D* is the distance between two target centers, *W* is the target width, and *ID* is the index of difficulty (in bits). MacKenzie et al. (1999) investigated text entry on a soft keyboard often used in mobile equipment and introduced Fitts' Law to predict the entry time when comparing and analyzing six kinds of keypad-layout models, viz., Qwerty, ABC, Dvorak, Fitaly, JustType, and Phone. Silfverberg et al. (2000) also used Fitts' Law to establish models to predict entry speed on a mobile phone using multi-press, two-key input, and T9 entry techniques. Li et al. (2006), taking movement-time minimization defined by Fitts' Law as the basis, adopted a heuristic method to explore the optimal layout for a mobile-phone keypad when the user keys with the index finger.

Although most studies have studied the use of one hand to hold a mobile phone, with the other hand pressing the entry using the index finger (Li et al.), mobile-phone users often hold other item(s) with one hand and use the other hand to both hold the mobile phone and enter text with the thumb. Under such circumstances, there is a significantly different key-pressing pattern, due to the restriction of the single-handed holding posture, as compared to the two-hand pressing mode with a freely pressing index finger. Hence, Silfverberg et al. (2000) established an entry model with a single-handed thumb and another model with a double-handed index finger simultaneously, when predicting the entry speed of mobile phones. Furthermore, most studies have focused on entry-time minimization (James &Reischel, 2001) when exploring numeric or alphabetical character-sequence key layout using current mobile-phone key dimensions as the basis. Less in-depth exploration has been done on the entry-time effects of the geometric keypad features, such as the key size, key-center distances, key layout, and so on. Li et al., although exploring a mobile-phone entry model based on Fitts' Law, mainly assumed that keying was done with the index finger and set the key width as a constant, without further discussions on the effects of key-width variation on the movement time. Silfverberg et al., although having taken key dimension into account in the index of difficulty computation in their Fitt's Law model, covered only two different sizes, viz., 6-mm height for numeric keys and 5-mm height for the #-key, a difference of merely 1 mm; hence, the model's index of difficulty only displays the movement-distance variation and cannot effectively respond to the effect of key-width variation on entry performance.

Since the mobile-phone entry process requires finger movements to press the keys, the keypad hardware design will significantly affect mobile-phone entry performance. The layout space of mobile-phone keypads is limited; hence, the distribution and arrangement of key dimensions and location is a very challenging problem. Due to the requirement of single-handed operation and restricted hand-holding gestures, the thumb-pressing range and angle are both restricted. The key layout will surely have an effect on the operation performance. This study intends to explore the effect of the keypad factors in a mobile-phone panel, such as the key layout location, the key size, the key-center distances, and so on, on entry performance when keying with the thumb.

II. METHOD

This experiment explores, in mobile-phone entry operation with the thumb, the effect of geometric distribution and arrangement factors, such as the keys' column-row locations, the key dimension, the key-center distances, and so forth, on key-pressing movement time. Our participants consist of six college students, ranging from 18 to 30 years old, using the right hand as the dominant hand, having used mobile phones for over a year, and having no eye or hand illnesses or obstacles. The experimental setup is self-installed, including key-activated switches, timers, and a related electric circuit layout, as shown in Fig. 1.

Taking the participants' individual differences into consideration, our experimental setup adopts a within-subject design, taking the keys' column-row locations, the key width, and the key-center distances as independent variables. Since the mobile-phone keypad layout has different numbers of keys in the column (four keys per column) and in the row (three keys per row), this experiment explores and divides the effects of the key layout into the effect in the column direction and the effect in the row direction, as shown in Figs. 1 and 2. In the column direction, there are three lines from left to right, with each column central line's distance being 39 mm (the first column), 24 mm (the second column), and 9 mm (the third column) away from the panel's right edge, respectively. Each column is arranged with four keys, so there are three distances among their centers, viz., 12, 24, and 36 mm, respectively. In the row direction, there are four rows from top to bottom, with each row's central line having a distance to the panel bottom of 56 mm (the first row), 44 mm (the second row), 32 mm (the third row), and 20 mm (the fourth row); each row is arranged with three keys, comprising two key-center distances, viz., 15 and 30 mm, respectively. The key widths in the columns and in the rows are all 2, 6, and 10 mm. The experiment comprises 27 types of scenarios in the column direction and 24 types of scenarios in the row direction. The dependent variable is the movement time (msec), denoting the time spent by the thumb in pressing two keys (Table 1).

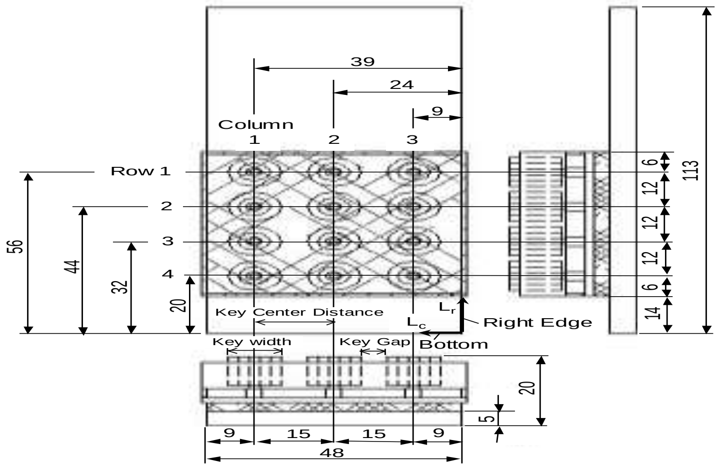
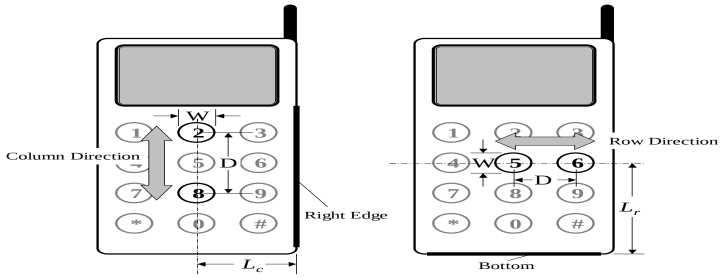


Figure 1. The mobile-phone test structure



(a) (b)

Figure 2. The geometric layout of the mobile-phone keypad

Table 1. The experimental variable values

	Column Direction	Row Direction
Independent Variable		
Column-row location	Column 1, 2, 3	Row 1, 2, 3, 4
Key width	2, 6, 10 mm	2, 6, 10 mm
Key-center distance	12, 24, 36 mm	15, 30 mm
Dependent Variable	Movement time (msec)	Movement time (msec)

During the execution of the experiments, after the test equipment is completely set according to the experimental variable values, the participant presses two keys with the thumb at the highest possible speed according to the instructed hand-holding gesture as one experiment (Figs. 2 and 3). After each experiment, we record the movement time and prepare for the next experiment. Before the experiments, the participant first carries out ten different experimental scenarios as an exercise to become familiar with the experimental scenarios and process steps and to eliminate the effect of learning. Each pair of experiments is separated by a two-minute interruption to eliminate tiredness. Each participant takes two trials in each of the experimental scenarios, which appear in a random order; all participants must complete all tests for all scenarios. Only successful experimental data are counted in the experimental record; if the participant cannot press two keys with the thumb solidly, that trial is considered a failure, and the experimental data for that trial will be abandoned and re-done until successful. In this study, we use the Statistical Package for Social Science (SPSS) for the statistical analysis on the data collected through the experiments.

Figure 3. The hand-holding position in the mobile-phone experiment

III. RESULTS AND DISCUSSION

Key Layout Variables And Thumb-Pressing Performance

Taking the movement time as a dependent variable and the key's column-row location, the key width, and the key-center distances as independent variables, we proceed with a variance analysis and a Duncan pairwise comparison test, with α equal to 0.05, to identify the statistically significant variables.

The variance-analysis result in the column direction indicates that the variables Column location ($F_{2,10}$=6.76, p=0.01), Key-center distance ($F_{2,10}$=44.53, p<0.01), and Interaction term ($F_{4,20}$=3.06, p=0.04) of the column location and key-center distances have a significant effect on the movement time (Table 2). As shown in Table 3, the mean movement time (36.69 msec) of the second-column keys is significantly shorter than that of the first- and third-column keys (38.81, 39.51 msec), indicating that the middle-column keys have a shorter movement time. This is because the thumb presses the first-column keys with an extended posture and the third-column keys with a bent posture; in short, a more unnatural operation posture reduces key-pressing performance.

Table 2. Variance analysis on the column-direction movement time

Source	Df	SS	MS	F	P-value
Column Location (L)	2	232.24	116.12	6.76	0.01[a]
L×Subject	10	171.88	17.19		
Key Width (W)	2	45.91	22.95	2.05	0.18
W×Subject	10	111.91	11.19		
Key-center Distance (D)	2	4536.38	2268.19	44.53	0.00[a]
D×Subject	10	509.31	50.93		
L×W	4	49.39	12.35	0.62	0.65
L×W×Subject	20	397.37	19.87		
L×D	4	102.15	25.54	3.06	0.04 [b]
L×D×Subject	20	167.06	8.35		
W×D	4	36.58	9.15	1.16	0.36
W×D×Subject	20	157.22	7.86		
L×W×D	8	87.46	10.93	0.99	0.46
L×W×D×Subject	40	443.92	11.10		

Note: 1. [a]: Significant at α=0.01 for testing the movement time.
2. [b]: Significant at α=0.05 for testing the movement time.

Table 3. Average movement time in the column direction

Variable	Mean Movement Time (msec)	Group
Column Location		
Column 2	36.69	A
Column 1	38.81	B
Column 3	39.51	B
Key-center Distance		
12 mm	31.82	A
24 mm	38.41	B
36 mm	44.78	C
Column Location × Key-center Distance		
Column 2, 12 mm	30.66	A
Column 3, 12 mm	32.34	A
Column 1, 12 mm	32.47	A
Column 2, 24 mm	37.56	B
Column 1, 24 mm	37.68	B
Column 3, 24 mm	39.99	C
Column 2, 36 mm	41.86	C
Column 3, 36 mm	46.21	D
Column 1, 36 mm	46.28	D

Note: Factors with the same letter across occupational groups indicate that their movement times are not significantly different.

Looking at the key-center distances, the mean movement time of 12 mm (31.82 msec) is the shortest, and that of 36 mm (44.78 msec) is the longest; the mean movement time increases with increasing key-center distance. In other words, with increased key-center distance, the thumb shift-movement time becomes longer. Looking at the interaction effect between the column location and the key-center distance, the movement time is mainly affected by the key-center distance; the effect of column location varies according to various key-center distances. When the key-center distances are 12 mm, the effect of the keys' column location is not significant; they all have the shortest mean movement time. When the movement distances increase to 24 mm, the mean movement time, affected by the increase, also increases; however, the third-column keys' mean movement time is noticeably longer than that of the second- and the first-column keys, caused by the thumb's unnatural bent posture. When the key-center distances are 36 mm, the mean movement time reaches the longest for the third and first column locations, since the thumb movement distance is the longest and the thumb operates with an over-extended or bent posture, while the second-column keys have a shorter mean movement time, since the thumb presses the keys with a more natural posture.

The results of the variance analysis in the row direction indicate that the variables Row location ($F_{3,15}$=3.24, p=0.05), Key width ($F_{2,10}$=4.85, p=0.03), and Key-center distance ($F_{1,5}$=22.96, p<0.01) have significant effects on the movement time (Table 4). As shown in Table 5, the second, third, and first rows (33.63, 33.72, 34.83 msec) belong to the low movement time group, and the first and fourth rows (34.83, 36.19 msec) constitute the high movement time group, indicating that the keys with middle-row locations have a shorter row direction movement time. In other words, the thumb operating in a more natural posture will have better key-pressing performance. When the thumb is in an over-extended or bent posture, its key-pressing performance will decrease accordingly; thumb-bending is even lower than thumb-extending in terms of operation performance.

Table 4. Variance analysis on the row-direction movement time

Source	Df	SS	MS	F	P-value
Column Location (L)	3	154.73	51.58	3.24	0.05[b]
L×Subject	15	239.11	15.94		
Key Width (W)	2	81.72	40.86	4.85	0.03[b]
W×Subject	10	84.24	8.42		
Key-center Distance (D)	1	2003.49	2003.49	22.96	0.00[a]
D×Subject	5	436.38	87.28		
L×W	6	95.45	15.91	2.14	0.08
L×W×Subject	30	222.92	7.43		
L×D	3	109.03	36.34	2.86	0.07
L×D×Subject	15	190.82	12.72		
W×D	2	17.38	8.69	0.42	0.67
W×D×Subject	10	204.60	20.46		
L×W×D	6	92.36	15.39	2.02	0.09
L×W×D×Subject	30	228.31	7.61		

Note: 1. [a]: Significant at α=0.01 for testing the movement time.
2. [b]: Significant at α=0.05 for testing the movement time.

Table 5. Average movement time in the row direction

Variable	Mean Movement Time (msec)	Group
Row Location		
Row 2	33.63	A
Row 3	33.72	A
Row 1	34.83	AB
Row 4	36.19	B
Key Width		
6 mm	33.53	A
2 mm	35.03	B
10 mm	35.21	B
Key-center Distance		
15 mm	30.86	A
30 mm	38.32	B

Note: Factors with the same letter across occupational groups indicate that their movement times are not significantly different.

Thumb-Pressing Movement-Time Prediction Model

To assure a functional relationship between the column-row geometric parameters and the thumb-pressing movement time, we construct a basic Fitts' Law model with regression analysis on the experimental data (Table 6).

In the column direction,

$$MT = 30.78 + 2.40 \log_2\left(\frac{2D}{W}\right) \tag{3}$$

In the row direction,

$$MT = 29.50 + 1.64 \log_2\left(\frac{2D}{W}\right) \tag{4}$$

The regression analysis result indicates that the coefficients of determination, whether in the column or row direction, in the basic Fitts' Law model, tend to be lower (0.2513 and 0.1801), in contrast to the high coefficient of determination value (R^2=0.970) obtained from the Shannon model adopted by Silfverberg et al. when holding a mobile phone single-handedly and keying with the thumb. Responding to the different phenomena in Fitts' Law prediction results from various studies, Whisenand and Emurian (1999) believed that, unless the experimental conditions of the studies are identical, the R^2value is applicable only to within-study comparisons, not across-study comparisons. In this study, we proceed with single discrete movements between two keys with a self-made mobile-phone emulator, while Silfverberg et al. proceeded with reciprocal movements between two keys of existing mobile phones as their experimental device. Being limited by the study purpose, the two studies differ greatly in key dimension, geometric layout, and text-entry model. That is the main reason for the difference in R^2-valuesbetween the two studies. Since the basic Fitts' Law model's coefficient of determination (R^2) tends to be lower in this study, a further modification of the model seems needed.

Table 6. Thumb-pressing movement-time prediction model

Model	R^2
Column Direction	
Fitts' Law basic model	
$MT = 30.78 + 2.40 \log_2(2D/W)$	0.2513
Welford model	
$MT = 2.38 + 8.01 \log_2 D – 0.15 \log_2(1/W)$	0.8744
Thumb-pressing model	
$MT = 1.08 + 0.0110 (L_c – 25.07)2 + 8.01 \log_2 D$	0.9194
Row Direction	
Fitts' Law basic model	
$MT = 29.50 + 1.64 \log_2(2D/W)$	0.1801
Welford model	
$MT = 1.92 + 7.46 \log_2 D + 0.09 \log_2(1/W)$	0.7848
Thumb-pressing model	
$MT = 0.52 + 0.0064 (L_r – 40.73)^2 + 7.46 \log_2 D$	0.8442

Note: 1. MT: Movement time.
2. D: Key-center distance.
3. W: Key width.
4. Lc: Distance from the column central line to the right edge.
5. Lr: Distance from the row central line to the bottom.

Welford (1968) believed that an aiming movement can be divided into two stages: a rapid and non-aiming trajectory movement process followed by a slow vision-controlled target-aiming process. The former is related to movement distance; the latter is affected by target width. Hence, the index of difficulty is comprised of two portions:

$$ID = b_1 \log_2 D + b_2 \log_2\left(\frac{1}{W}\right) \tag{5}$$

In the model, *ID* denotes the index of difficulty, *b1* and *b2*are constants derived from experimental results, *D*is the distance between the two target centers, and *W*is the target width. Chi and Lin (1997) observed, from experiments in eye-gaze-pointing operations, that when carrying out aiming movements, the effects of distance and target width on time are different; hence, the index of difficulty should be decomposed from one combined term into two individual terms. In this study, we adopt Welford's concept and construct a Welford model with regression analysis on our experimental data:

In the column direction,

$$MT = 2.38 + 8.01 \log_2 D - 0.15 \log_2\left(\frac{1}{W}\right) \tag{6}$$

In the row direction,

$$MT = 1.92 + 7.46 \log_2 D + 0.09 \log_2\left(\frac{1}{W}\right) \tag{7}$$

After the regression analysis, we obtain a coefficient of determination of 0.8744 for the Welford model in the column direction and 0.7848 in the row direction; both are noticeably increased,and thus,this model has a better explanatory effect.

However, in the Welford model, the slopes of the key-width-related explanatory variable, $\log_2(1/W)$, in both the column direction (p=0.73) and the row direction (p=0.87), are not significantly different from zero, indicating that the key width makes no obvious contribution to the model's index of difficulty. The reason is that the participants' thumb widths are all greater than the key width; the effects of key width should have been cancelled by the effect of the thumb-tip width. The same outcome was also observed in the experiments conducted by Silfverberg et al.

The experimental results indicate that, whether in the column or row direction, keys located in the middle of the panel have the shortest movement time; the movement time and the column-row locations of the keys should exhibit a second-order hyperbolic relationship. Hence, we modify the Welford model by discarding the key-width term and introducing the key location as an explanatory variable and construct a mobile-phone thumb-pressing model via regression analysis on the experimental data:
In the column direction,

$$MT = 7.96 - 0.55L_c + 0.0110L_c^2 + 8.01\log_2 D \qquad (8)$$

In the row direction,

$$MT = 11.09 - 0.52L_r + 0.0064\,L_r^2 + 7.46\log_2 D \qquad (9)$$

where L_c and L_r are the key's column-row locations in millimeters, taking the mobile phone's bottom right corner as the reference point;L_c is the distance from the column central line to the mobile phone's right edge, and $L_r$is the distance from the row central line to the bottom (Fig. 2).

The coefficients of determination in this newly constructed mobile-phone thumb-pressing modelare 0.9194 in the column direction and 0.8442 in the row direction, significantly higher than those of the basic Fitts' Law model and of the Welford model, demonstrating better explanatory power. To simplify the model, we use the method of completing the square and simplify the first-order and second-order terms in L_c and L_r into a single square term.
In the column direction,

$$MT = 1.08 + 0.0110\left(L_c - 25.07\right)^2 + 8.01\log_2 D \qquad (10)$$

In the row direction,

$$MT = 0.52 + 0.0064\left(L_r - 40.73\right)^2 + 7.46\log_2 D \qquad (11)$$

From Eq. (10), we find that when L_c=25.07, the key located 25.07 mm from the mobile-phone panel's right edge possesses the minimal movement time in the column direction. By the same token, we find in Eq. (11) that the minimal movement time in the row direction occurs at L_r=40.73, namely, the key located 40.73 mm from the bottom of the mobile-phone panel. When keying on the mobile-phone keypad, this is the location of the thumb tipin a naturally relaxed condition.

IV. CONCLUSION

When pressing keys with the thumb for mobile-phone text entry, the key-pressing movement time increases with increased key-center distances. In the row direction, a key with either too large or too small of a width will increase the movement time. In the column direction, however, the effect of key width on the movement time is not significant. This does not conform to the hypothesis of Fitts' Law, which states that the movement time will decrease with increased target width. Our experiment adopts three key widths, viz., 2, 6, and 12 mm, and our result indicates that the 6-mm key has the best entry performance in the row direction.

Since the matching between the basic Fitts' Law model and the mobile-phone thumb-pressing operation is poor, we adopt the Welford concept to modify the model in this study and introduce the column-row locations of the keys as explanatory variables. We observe that the constructed mobile-phone thumb-pressing model possesses better explanatory power for the key-pressing movement time. The model also indicates that, when thumb pressing with the right hand as the dominant hand, the optimal location in the keypad lies in the column direction 25.07 mm from the right edge of the mobile-phone panel and, in the row direction, 40.73 mm from the bottom of the mobile-phone panel.

The results of this study can provide a useful reference in geometric keypad layout for mobile-phone panel designers and/or R&D personnel to offer mobile-phone users more operating comfort and efficiency. However, in this study, the effect of key width on key-pressing movement time, due to the influence of the thumb-tip pressing area, is found to be more complex. The experimental results for the column direction and the row direction are not consistent. Due to its poorer explanatory power, this effect is not included in the mobile-phone thumb-pressing model constructed in this study. Furthermore, since the purpose of this study is to explore the effect of the geometric keypad layout on the thumb-pressing operation and thus to investigate the effect of the geometric dimensions of the keys in the column and row layout, we only investigate the pressing operations in the column and row directions, leaving the relationships between other movement directions and the movement time un-explored.

However, some studies (MacKenzie& Buxton, 1992) have observed that the diagonal-line direction movement time is significantly longer than that of other movement directions; while other studies (Card et al., 1978) have indicated that movement-direction-angle variation has an unnoticeable effect on movement time; thus far, study results are inconsistent. Follow-up studies might include variations of finger-tip pressing area and movement-direction angle in the model, for further exploration, to clarify the effects of key width and movement direction on key-pressing movement time so as to strengthen the explanatory power of the model for mobile-phone thumb-pressing movements.

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