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Optimal Entry Size of Handwritten Chinese Characters in Touch-Based Mobile Phones

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1. INTRODUCTION

Touch-based mobile phones have received much attention in recent years, for they allow users to directly manipulate digital information using fingers instead of a pen or keyboard. For mobile phones such as the iPhone, which does not have a physical keyboard, one of the commonly used character entry styles is handwritten character entry. This entry style is important in script languages such as Chinese, Japanese, and other nonalphabetic languages (Sarcher, Tng, & Loudon, 2001). However, the small screen area of mobile phones restricts the handwriting entry area size. To design a rational screen layout that can display more information and allow users to write with ease and high efficiency, it is important to determine the optimal entry area for the handwriting of characters. For example, when a user edits a text file in a mobile phone, it is desirable that the screen display as many characters as possible and that the probability of the user having to drag the scrollbar to view text information be as low as possible. Although some devices provide unframed handwriting interfaces, the optimal entry area parameter is still important for determining the display area of the possible recognized characters corresponding to an inputted character; a larger area can support the designer to design a more suitable display style for the recognized characters (Ren, Tamura, Kong, & Zhai, 2003) and can allow the user to select a recognized character more easily with a finger (Parhi, Karlson, & Bederson, 2006).

The optimal size of handwriting character input boxes for a stylus on personal digital assistants (PDAs) has already been investigated by Ren and Zhou (2009). The optimal entry size in that study was defined as the smallest input area in which the user can input characters with short writing time (WT), small number of error corrections, small number of stroke protrusions outside the area, and high subjective assessment (e.g., ease of writing and degree of fatigue). Ren and Zhou considered entry boxes for different kinds of characters, different box sizes and shapes, different user postures, and different user age groups. Four dependent variables, including number of protruding strokes (NPS), number of error corrections, WT, and subjective preference of participants, were used to assess handwriting performance for each entry box size (EBS). The optimal size of an entry box for the input of alphanumeric characters was found to be 1.2 \( \times \) 1.4 cm (rectangular), whereas for kanji (Chinese characters) mixed with kana characters and for hiragana and katakana characters, the optimal size of an entry box was found to be 1.4 \( \times \) 1.4 cm (square). However, finger input is less precise than stylus input, and writing characters using a pen is more familiar for users than writing with a finger. Therefore, the conclusions drawn by Ren and Zhou may not apply to touch-based mobile phones. There remains a need for investigation of optimal finger-based character entry size in touch-based mobile phones.

In this article, we define the optimal entry size for character handwriting as the smallest input area in which the user can input characters with high-entry-area utilization rate, great writing speed, high character recognition rates, small number and short length of stroke protrusions outside the area, and high subjective assessment (e.g., ease of writing and degree of fatigue). For touch-based mobile phones, two commonly used
handwriting styles with fingers are (a) two-handed entry with the nondominant hand holding the device and the index finger of the dominant hand entering characters, usually with the user sitting, and (b) one-handed entry with the dominant hand holding the device and the thumb of the dominant hand entering characters, usually with the user walking. This study focuses on determining the optimal entry size of handwritten characters through two experiments—one to investigate the optimal entry size for two-handed entry, and the other to examine the optimal entry size for one-handed entry. To determine the optimal EBS, we defined a set of dependent variables for handwriting performance measures and proposed a variation of an existing experimental paradigm.

In the following sections of this article, related work on handwriting input is first described. This is followed by a description of experiment design, including the selection of EBSs, determination of entry box position, definition of dependent variables for performance measures, and a report on experimental devices. Two experiments are then reported, and after each experiment, experimental results are discussed. Then we present a general discussion of the results and discuss future work, after which a conclusion is finally drawn.

2. RELATED WORK

This work builds upon three distinct areas of previous research. The first refers to the design of handwriting entry boxes. The second is a body of work on the improvement of handwriting performance. The last is two-handed and one-handed use of touch-based mobile phones. We review each in turn.

2.1. Handwriting Entry Box Design

This section reviews handwriting entry box design from aspects of fundamental research and commercial product design. In a noteworthy fundamental study, Ren and Zhou (2009) compared different EBSs and shapes for pen-based handwriting on PDAs and found that the optimal size for an entry box for the input of alphanumeric characters is 1.2 × 1.4 cm (rectangular), whereas for kanji (Chinese characters) mixed with kana characters and for hiragana and katakana characters the optimal size is 1.4 × 1.4 cm (square). On the basis of that work, we conducted a series of experiments to determine the optimal handwriting EBS in touch-based mobile phones. On the other hand, for the common mobile operating systems (OS) used by modern touch-based mobile phones, such as Microsoft’s Windows Mobile and Windows Phone, Apple’s iOS, and Google’s Android, the position and size of the handwriting entry box may differ according to software applications supported by these OSs. Taking Apple iPhone 4 as an example, the handwriting entry box is set at the bottom of the screen with a size of 3.3 × 4 cm. However, it remains unclear whether this entry area can support fast, accurate, and ease of handwriting with high-entry-area utilization rate.

2.2. Improvement of Handwriting Performance

The aim of this study is to determine the optimal entry box area within which users can handwrite characters quickly and accurately. We review some studies that have paid attention to the analysis of handwriting speed and accuracy, and to the improvement of handwriting speed and the reduction of handwriting errors.

In a noteworthy analytical study, MacKenzie, Nonnecke, Riddersma, McQueen, and Meltz (1994) experimentally analyzed three character entry methods for pen-based computers, with evaluation in terms of entry speed and accuracy, for aspects including handwriting input, tapping on a soft keyboard with a QWERTY layout, and tapping on a soft keyboard with an ABC layout. Handwriting produced a writing speed of 16 wpm, slower than the writing speed for tapping on a QWERTY soft keyboard but quicker than the writing speed produced by tapping on the ABC soft keyboard; handwriting led to 8.1% entry errors, which is greater than the error rate of the other two techniques. Commarford (2004) compared the usability of Graffiti and a virtual keyboard on a PDA running Microsoft Windows CE and found that participants performed better with the virtual keyboard but showed no preference for the program. On the other hand, to investigate unconstrained handwriting performance, Kristensson and Denby (2009) conducted an experimental study based on unconstrained handwriting recognition. In the recognition method, the recognizer simultaneously accepted handprinted characters and cursive script. The mean difference in entry rate and error rate between software keyboard and unconstrained handwriting recognition was not significant, which indicates that performance in the two entry techniques is similar.

There have also been some studies of speed enhancement and error reduction. Wobbrock, Myers, and Chau (2006) proposed a word-level stroking system, which aims to improve the speed of character-level unistrokes. Kurihara, Goto, Ogata, and Igarashi (2006) proposed a multimodal input system that can provide multiple prediction characters, enabling greater handwriting speed and fewer handwriting errors. That system provides multiple predictions based on speech recognition and handwriting recognition, and the user selects one item and pastes it in the edit board, avoiding tedious manual writing. For correcting handwriting errors, Shilman, Tan, and Simard (2006) proposed a mixed-initiative approach, which can continually evolve the recognizer’s results using the additional information from user corrections. A user study demonstrated the effectiveness of this error correction approach. Various handwriting methods have also been proposed for computer-based speed writing. As a well-known single stroke shorthand handwriting recognition, Graffiti (Palm Computing, Inc.) has been widely used in PDAs based on the Palm OS. Unistrokes alphabet is a gesture alphabet for stylus-based text entry (Goldberg & Richardson, 1993), in which every letter is written with a single stroke, but the more frequent ones are assigned to simpler strokes. Shapewriter (Zhai & Kristensson, 2003), a novel form of writing that uses pen
strokes on graphical keyboards to write text, can enable users to enter text efficiently at a faster rate than previously possible on mobile phones, handheld computers, and other mobile devices. Wobbrock, Myers, and Kembel (2003) proposed EdgeWrite, a new unistroke text entry method for handheld devices designed to provide high accuracy and stability of motion for people with motor impairments.

2.3. Two-Handed and One-Handed Use of Touch-Based Mobile Phones

Two-handed and one-handed use of touch-based mobile phones has generated considerable recent research interest. We focused on the studies that investigated appropriate target size for two-handed and one-handed use, because these studies inspired our approach of examining optimal EBS.

For a data entry task on a PDA with a stylus, Sears and Zha (2003) investigated the effect of soft keyboard size (small, medium, and large) for two kinds of soft keyboard. According to the analysis on three measures, data entry rate, uncorrected error rates, and subject preferences, they drew the conclusion that keyboard size does not affect data entry rates, error rates, and preference ratings. However, for text entry on a desktop-sized touch screen with a finger, Sears, Revis, Swatski, Crittenden, and Shneiderman (1993) found that larger key size text resulted in higher entry rates for both novice and experienced users and that novices committed significantly fewer errors on the largest keyboard than on the smallest one.

Regarding one-handed use, Karlson, Bederson, and Contreras-Vidal (2006) conducted a systematical study to understand single-handed mobile device interaction. The study revealed that users can tap faster in the center area of mobile phone screen than other screen regions for small candy bar phones, flip phones, large candy bar phones, and PDAs. According to this finding, we set the entry box position in the center area of the mobile phone screen in our experiment. Parhi et al. (2006) investigated target size for one-handed thumb use on small touch screen devices. With analysis in terms of task time, error rate, hit distribution, and user preference, they found that a target size of 9.2 mm for single-target pointing and a target size of 9.6 mm for a sequence of taps should be sufficiently large without degrading performance and preference. They also found that users can tap faster in the center area of mobile phone screen than in other screen regions, which is consistent with Karlson et al.’s finding.

Our review indicates that little study has been undertaken to determine optimal handwriting EBS for two-handed use as well as one-handed use for touch-based mobile phones. Therefore, we set out to perform a systematic investigation of optimal finger-based handwriting EBS, so as to provide guidelines on user interface design of handwriting.

3. EXPERIMENT DESIGN

In our experiment, an entry box was shown in the screen of the experimental mobile phone, and experimental participants were asked to write the corresponding character within the entry box according to a prototype character that was displayed in the mobile phone. Selection of EBS, determination of entry box position and shape, and selection of prototype characters are described in the following three subsections, after which a set of dependent variables for performance measures and configurations of experimental devices are detailed.

3.1. EBS

Five levels of EBS—1.5 × 1.5 cm, 2.0 × 2.0 cm, 2.5 × 2.5 cm, 3.0 × 3.0 cm, and 3.5 × 3.5 cm—were used in our experiment. The setting of the minimum EBS at 1.5 × 1.5 cm is based on the results obtained in Ren and Zhou (2009), which suggested that the optimal size of a pen-input box for a stylus-based PDA was 1.09 × 1.66 cm, 1.44 × 1.44 cm for alphanumeric characters, and 1.44 × 1.44 cm for kanji and kana. We suspected that 1.5 × 1.5 cm size would be more challenging for finger input than for stylus input. In the following sections, EBS (1.5 × 1.5), EBS (2.0 × 2.0), EBS (2.5 × 2.5), EBS (3.0 × 3.0), and EBS (3.5 × 3.5) are used to denote the EBS with 1.5 × 1.5 cm, 2.0 × 2.0 cm, 2.5 × 2.5 cm, 3.0 × 3.0 cm, and 3.5 × 3.5 cm, respectively.

3.2. Entry Box Position and Shape

Because our study focuses on determining the optimal EBS for handwriting input, the entry box should be set in a position in which users can perform handwriting input quickly and easily. Although entry box position may not influence two-handed entry performance, it does affect one-handed entry performance. The study conducted by Karlson et al. (2006) showed that thumb interaction performance on the surface of mobile phones is related to the screen region; different regions result in different tap speeds. For flip phones, the center of the screen was found to be able to support high tap speed. In our experiment, therefore, the entry box was always shown in the center of the screen of the experimental device. The entry box shape was set as square due to the fact that the bounding box of almost all Chinese characters is square.

To examine one-handed handwriting performance in a center entry box with 2.5 × 2.5 cm, we conducted a preliminary experiment with four people—two male and two female. In the experiment, the participants were asked to write 10 arbitrary Chinese characters within the entry box. All participants stated that the writing task was easy to perform. Therefore, we believe a square entry box placed in the center can support fast and easy handwriting input.

3.3. Prototype Character Categories

To investigate character entry performance among the five EBSs, we selected 27 commonly used Chinese characters (see Table 1), which were divided into three groups (simple, medium, complex) according to the number of strokes making up the character. The structures of these characters were
divided into left to right, top to bottom, and mixed structure, respectively.

### 3.4. Performance Measures

As mentioned in the Introduction section, Ren and Zhou (2009) used four dependent variables to determine the optimal handwriting character input box size for stylus on PDAs. Referring to these four dependent variables, we defined a set of dependent variables and sorted these variables into five aspects illustrated in Table 2. The five aspects were handwriting speed, utilization rate of entry area, accuracy, ease of writing, and subjective evaluation.

**Writing time (WT).** The WT is defined as the time duration from the moment the finger touches the screen to the moment the last stroke is finished. It should be noted that WT involves the time interval from the end of a stroke to the start of the subsequent stroke. This performance measure describes the overall time of the writing procedure.

**Stroke writing speed (SWS).** The SWS is calculated by the ratio of an inputted character’s length and the corresponding stroke WT, which is defined as the length of time (duration) that the finger touches the screen for handwriting input.

**Size ratio (SR).** The participants may or may not write the character exactly the same size as the entry area. There is a possibility that they would tend to write the character within an area that is smaller or larger than the entry area. To examine the utilization rate of entry area, we measured “size ratio,” defined as the ratio of the size of the bounding box of the written character and the size of entry box. A higher SR indicates that the user utilizes a larger area for an entry box for handwriting input.

**Length of protruding strokes (LPS) and NPS.** If a part of a writing stroke is outside an entry box, a protruding stroke is detected. The NPS and LPS are recorded, respectively, to describe the difficulty of inputting handwriting within the entry box. If the user inputs a character easily within a given area, there should be only short length and a small NPS outside of the defined input area.

**Number of writing attempts (NWA).** The NWA is used to describe handwriting accuracy. Microsoft Windows XP Tablet PC Edition 2005 Recognizer software, which can recognize Chinese and Japanese handwriting, was applied to written character recognition. If an inputted character can be recognized as the corresponding prototype character, the current writing trial will finish and the subsequent writing trial will start; otherwise, the NWA increased by one and participants were asked to input the character again. Our approach for handwritten character recognition is totally different from Ren and Zhou’s (2009), in which the recognition result relied on participants’ subjective judgment.

**Subjective preference.** Writing performance for each entry box was rated by participants according to five dimensions: writing speed, utilization rate of entry area, ease of writing, writing accuracy, and fatigue of the finger used for writing. Participants were required to rate these entry boxes on a 5-point scale (1 for worst and 5 for best).

### 3.5. Experimental Device

This study was conducted on a HTC Touch HD mini smartphone for handwriting input and a 1.66 GHz Intel Core2 PC with Microsoft Windows XP Professional SP2 for handwritten character recognition. The smartphone has a capacitive touch screen with HVGA resolution; the screen size is 3.2 in., and its resolution is $320 \times 480$ pixels. The smartphone platform is Microsoft Windows Mobile 6.5 Professional with HTC Sense.

### TABLE 2

<table>
<thead>
<tr>
<th>Handwriting Speed</th>
<th>Utilization Rate of Entry Area</th>
<th>Accuracy</th>
<th>Ease of Writing</th>
<th>Subjective Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Writing time</td>
<td>1. Size ratio</td>
<td>1. Number of writing attempts</td>
<td>1. Number of protruding strokes</td>
<td>1. Preference ratings on writing speed, utilization rate of entry area, writing accuracy, ease of writing and finger fatigue</td>
</tr>
<tr>
<td>2. Stroke writing speed</td>
<td></td>
<td></td>
<td>2. Length of protruding strokes</td>
<td></td>
</tr>
</tbody>
</table>
OPTIMAL ENTRY SIZE OF CHINESE CHARACTERS

The smartphone was connected to the PC via Wi-Fi networks. In both devices, experimental programs were designed in the C# Environment.

4. EXPERIMENT 1 (TWO-HANDED ENTRY)

4.1. Participants

Nine participants—two male and seven female—from 20 to 32 years of age participated in this experiment. Three of them were Japanese and the others were Chinese. All of them were right-handed and had prior experience with bare finger operation on touch screen devices such as an iPhone. The physical sizes of each subject’s finger-tips (end joints) were recorded. The average values of physical width (W) and physical length (L) were listed in Table 3.

4.2. Task and Procedure

When performing the experimental task, participants were asked to sit in a chair and hold the device with the nondominant hand. In each test trial, a prototype character was shown in the top left corner (see Figure 1), and participants were asked to write a corresponding character using the index finger of the dominant hand within the red box as quickly and clearly as possible (see Figure 2). After finishing writing the character, participants were instructed to press the send button so that information about the inputted character could be sent to a PC on which the handwriting recognition software was running. The character recognition process was detailed in the NWA subsection. Each participant completed two blocks of 27 prototype characters in five sizes. Within each block, the order of the 27 characters in five different sizes was randomized. In summary, experiment data collection consisted of

9 subjects ×
2 blocks of trials ×
27 characters ×
5 target entry sizes
= 2,430 drawing trials

![FIG. 1. Experimental interface (color figure available online).](image1)

![FIG. 2. User in the two-handed entry environment (color figure available online).](image2)

At the end of the experiment, a questionnaire was administrated to gather subjective opinions.

4.3. Results and Analysis

Writing time (WT). A repeated measures analysis of variance (ANOVA) showed that EBS had no significant main effect

<table>
<thead>
<tr>
<th>Finger Tip</th>
<th>Thumb</th>
<th>Index Finger</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
<td>W</td>
</tr>
<tr>
<td>AVG</td>
<td>31.2</td>
<td>21.2</td>
</tr>
<tr>
<td>SD</td>
<td>2.8</td>
<td>2.9</td>
</tr>
</tbody>
</table>
on WT, $F(4, 32) = 0.592, p = .671$. Post hoc comparisons using the Bonferroni adjustment for multiple comparisons found no significant difference between all EBSs. For EBS (1.5 × 1.5), EBS (2.0 × 2.0), EBS (2.5 × 2.5), EBS (3.0 × 3.0), and EBS (3.5 × 3.5), the mean WT was 2,497 ms, 2,532 ms, 2,523 ms, 2,532 ms, and 2,557 ms, respectively. There was no interaction effect on WT for character complexity × EBS, $F(8, 64) = 0.42, p = .908$.

SWS. A repeated measures ANOVA showed a significant main effect on SWS for EBS, $F(4, 32) = 46.284, p < .001$ (see Figure 3). Also, there was an interaction effect on SWS for character complexity × EBS, $F(8, 64) = 4.432, p < .001$. Post hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons, and it found no significant difference between EBS (2.5 × 2.5; $M = 5.948$ cm/s) and EBS (3.5 × 3.5; $p = .129$) from EBS (3.0 × 3.0; $M = 6.543$ cm/s) and EBS (3.5 × 3.5; $p = .124$). Although these three EBSs can be grouped on similar SWSs, they were significantly faster than EBS (1.5 × 1.5; $p < .005$; $M = 4.560$ cm/s) and EBS (2.0 × 2.0; $p < .005$; $M = 5.327$ cm/s).

SR. A repeated measures ANOVA showed that EBS had a significant main effect on SR, $F(4, 32) = 40.912, p < .001$. As illustrated in Figure 4, smaller EBS usually led to larger SR. For EBS (1.5 × 1.5), EBS (2.0 × 2.0), EBS (2.5 × 2.5), EBS (3.0 × 3.0), and EBS (3.5 × 3.5), the mean SR was 0.929, 0.723, 0.598, 0.514, and 0.443, respectively. There was also a significant interaction between character complexity and EBS, $F(8, 64) = 27.703, p < .001$. Post hoc comparisons using the Bonferroni adjustment showed significant difference ($p < .005$) between all EBSs except EBS (1.5 × 1.5) and EBS (2.0 × 2.0; $p = .023$). Therefore, these two EBSs can be grouped on their similar SRs.

LPS. An analysis of normality found that data of LPS were skewed, so a square root transformation was applied to remedy the data. A repeated measures ANOVA showed that EBS had a significant main effect on LPS, $F(4, 32) = 48.682, p < .001$. Figure 5 shows that LPS tended to be reduced when EBS increased. Also, there was an interaction effect on LPS for Character Complexity × EBS, $F(8, 64) = 39.982, p < .001$. Post hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons. The LPS of EBS (3.5 × 3.5) was the smallest with a mean of 0.061 cm, which showed no significant difference ($p = .123$) from EBS (3.0 × 3.0; $M = 0.124$ cm). No significant difference was found on LPS between EBS (3.0 × 3.0) and EBS (2.5 × 2.5; $M = 0.273$ cm). Moreover, the LPS produced by these three EBSs are significantly smaller than the LPSs produced by EBS (1.5 × 1.5; $M = 0.714$ cm; $p < .005$) and EBS (2.0 × 2.0; $M = 0.453$ cm; $p < .005$). Therefore, EBS (2.5 × 2.5), EBS (3.0 × 3.0), and EBS (3.5 × 3.5) can be grouped on their similar LPSs.

NPS. Because an analysis of normality found that the data of NPS were skewed, a square root transformation was used to remedy the data. A repeated measures ANOVA showed that EBS had a significant main effect on NPS, $F(4, 32) = 146.438, p < .001$. As illustrated in Figure 6, smaller EBS led to larger NPS. For EBS (1.5 × 1.5), EBS (2.0 × 2.0), EBS (2.5 × 2.5), EBS (3.0 × 3.0), and EBS (3.5 × 3.5), the mean NPS was 1.457, 0.996, 0.608, 0.323, and 0.178, respectively. There was also an interaction effect on NPS for Character Complexity ×
EBS, $F(8, 64) = 29.761, p < .001$. Post hoc comparisons using the Bonferroni adjustment showed a significant difference ($p < .005$) between all EBSs except EBS (3.0 $\times$ 3.0) and EBS (3.5 $\times$ 3.5); $p = .030$). Therefore, EBS (3.0 $\times$ 3.0) and EBS (3.5 $\times$ 3.5) can be grouped on their similar NPSs.

NWA. Data of NWA were analyzed by using the chi-square test based on standardized residuals. On the frequency of NWA, we found that there is a statistically significant relationship between NWA and EBS, $\chi^2 = 11.31, p < .05$ (see Figure 7). Of interest, EBS (2.5 $\times$ 2.5) seemed to support the most accurate handwriting input, because it resulted in the fewest NWA with a standardized residual at –4.6. EBS (3.5 $\times$ 3.5) and EBS (3.0 $\times$ 3.0) produced almost the same NWAs ($z = -3.6$ and $z = -2.6$, respectively) as EBS (2.5 $\times$ 2.5). The largest NWA was produced by EBS (1.5 $\times$ 1.5), $z = 9.4$.

Subjective preference. There was a significant difference found in the effect of the five EBSs on the overall preference rating, $F(4, 32) = 53.059, p < .001$ (see Table 4). Post hoc comparisons using the Bonferroni adjustment showed that EBS (3.5 $\times$ 3.5), EBS (3.0 $\times$ 3.0), and EBS (2.5 $\times$ 2.5) were rated significantly higher than the other two EBSs ($p < .005$). Moreover, no significant difference was found between EBS (3.5 $\times$ 3.5), EBS (3.0 $\times$ 3.0), and EBS (2.5 $\times$ 2.5). Therefore, these three EBSs can be grouped on the similar subjective preference.

4.4. Discussion

Handwriting speed. WT and SWS are used to quantify handwriting speed. Of interest, our results show that for the five EBSs, users spent similar writing time on the handwriting task. However, the analysis on SWS reveals that different EBSs can lead to different stroke writing speeds. According to the analysis results, EBS (2.5 $\times$ 2.5) is regarded as the smallest EBS in which users can perform handwriting task with high speed.

Utilization rate of entry area. It is evident that users prefer a large entry area for handwriting input. However, a larger entry area may lead to a lower utilization rate of entry area; a handwriting character may occupy only a small area. In this study, SR is applied to quantification of entry area utilization rate; larger SR represent higher utilization rate. Our results indicate that EBS (1.5 $\times$ 1.5) and EBS (2.0 $\times$ 2.0) resulted in a similar high utilization rate of entry area. Although the SR produced by EBS (2.5 $\times$ 2.5) was smaller than that produced by EBS (1.5 $\times$ 1.5) and EBS (2.0 $\times$ 2.0), it was significantly larger than that produced by EBS (3.0 $\times$ 3.0) and EBS (3.5 $\times$ 3.5), suggesting that EBS (2.5 $\times$ 2.5) could also generate a high utilization rate of entry area.

Ease of writing. LPS and NPS are applied to the description of the ease of writing; shorter LPS and smaller NPS represent easier handwriting input within a given area. Although the NPS produced by EBS (2.5 $\times$ 2.5) was larger than that produced by EBS (3.0 $\times$ 3.0) and EBS (3.5 $\times$ 3.5), these three EBSs resulted in similar LPSs. Therefore, EBS (2.5 $\times$ 2.5) can be considered to be the smallest EBS in which users can perform a handwriting task easily.

Entry accuracy. The NWA is used to describe entry accuracy. Although the entry accuracy mainly depends on the recognition ability of handwriting recognition software, our results indicate that EBS had an effect on entry accuracy. For EBS (1.5 $\times$ 1.5), the reason why this size produced the lowest entry accuracy may be that users cannot write each stroke clearly within the small area. EBS (2.5 $\times$ 2.5) seems to support the most accurate handwriting input, because it resulted in the fewest NWA. Moreover, EBS (3.0 $\times$ 3.0) and EBS (3.5 $\times$ 3.5) led to similar entry accuracy as that produced by EBS (2.5 $\times$ 2.5). Therefore, we believe EBS (2.5 $\times$ 2.5) is the smallest EBS in which users can perform handwriting input with high entry accuracy.
TABLE 4
The participants’ preferences for each entry ox size (EBS) with two-handed entry

<table>
<thead>
<tr>
<th>Dimension</th>
<th>EBS (1.5 × 1.5)</th>
<th>EBS (2.0 × 2.0)</th>
<th>EBS (2.5 × 2.5)</th>
<th>EBS (3.0 × 3.0)</th>
<th>EBS (3.5 × 3.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Writing speed</td>
<td>1.4</td>
<td>2.2</td>
<td>3.4</td>
<td>4.6</td>
<td>4.7</td>
</tr>
<tr>
<td>Utilization rate</td>
<td>4.9</td>
<td>4.6</td>
<td>4.1</td>
<td>3.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Writing accuracy</td>
<td>1.4</td>
<td>2.2</td>
<td>3.9</td>
<td>4.3</td>
<td>4.8</td>
</tr>
<tr>
<td>Ease of writing</td>
<td>1.2</td>
<td>2.3</td>
<td>3.4</td>
<td>4.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Fatigue of the finger</td>
<td>1.4</td>
<td>2.1</td>
<td>3.6</td>
<td>4.4</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Subjective preference. According to the preference ratings of these five EBSs, EBS (2.5 × 2.5) had a comparatively high overall rating. The result is fairly consistent with the analysis of handwriting speed, utilization rate of entry area, ease of writing and entry accuracy. In summary, for two-handed handwriting input, the optimal EBS was found to be 2.5 × 2.5 cm.

5. EXPERIMENT 2 (ONE-HANDED ENTRY)

5.1. Participants and Equipment

The same nine subjects who participated in Experiment 1 took part in Experiment 2. The same equipments were used as in Experiment 1.

5.2. Task and Procedure

A similar writing task and procedure used in Experiment 1 was carried out in this experiment. The only difference was that in this experiment participants were asked to perform the writing task with the thumb of their dominant hand while holding the device with the dominant hand (see Figure 8). The mean physical width and mean physical length of the thumb used for writing were listed in Table 3.

5.3. Results and Analysis

WT. A repeated measures ANOVA showed that EBS had no significant main effect on writing time, $F(4, 32) = 0.805, p = .531$. Post hoc comparisons using the Bonferroni adjustment for multiple comparisons revealed no significant difference between all EBSs. For EBS (1.5 × 1.5), EBS (2.0 × 2.0), EBS (2.5 × 2.5), EBS (3.0 × 3.0), and EBS (3.5 × 3.5), the mean WT was 3,149 ms, 3,127 ms, 3,185 ms, 3,204 ms, and 3,167 ms, respectively. There was also no significant interaction between character complexity and EBS, $F(8, 64) = 0.495, p = .855$.

SWS. A repeated measures ANOVA showed that EBS had a significant main effect on SWS, $F(4, 32) = 49.531, p < .001$ (see Figure 9). However, there was no interaction effect on SWS for Character Complexity × EBS, $F(8, 64) = 2.031, p = .057$. Post hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons, and it found no significant

![User in the one-handed entry environment (color figure available online).](image-url)
Therefore, EBS (1.5 × 3.0) was the smallest with a mean of 0.062 cm, which was found significantly slower than EBS (3.5 × 3.0); \( M = 0.586 \text{ cm}; p = .037 \). Moreover, the LPSs produced by these four EBSs are significantly smaller than the LPS produced by EBS (1.5 × 1.5); \( M = 0.843 \text{ cm} \), so these four EBSs can be grouped on their similar LPSs.

**LPS.** An analysis of normality found that the data for LPS were skewed, so a square root transformation was used to remedy the data. A repeated measures ANOVA showed that EBS had a significant main effect on LPS, \( F(4, 32) = 39.111, p < .001 \). Figure 11 shows that LPS tended to be reduced when EBS increased. Also, there was an interaction effect on LPS for Character Complexity × EBS, \( F(8, 64) = 16.982, p < .001 \). Post hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons. The LPS of EBS (3.5 × 3.5) was the smallest with a mean of 0.062 cm, which was found to have no significant difference (\( p = .353 \)) from EBS (3.0 × 3.0); \( M = 0.197 \text{ cm} \). There was no significant difference on LPS between EBS (3.0 × 3.0) and EBS (2.5 × 2.5); \( M = 0.369 \text{ cm}; p = .100 \), and between EBS (2.5 × 2.5) and EBS (2.0 × 2.0); \( M = 0.586 \text{ cm}; p = .037 \). Moreover, the LPSs produced by these four EBSs are significantly smaller than the LPS produced by EBS (1.5 × 1.5); \( M = 0.843 \text{ cm} \), so these four EBSs can be grouped on their similar LPSs.

**NPS.** Because an analysis of normality found that data of NPS were skewed, a square root transformation was applied to remedy the data. A repeated measures ANOVA showed that EBS had a significant main effect on NPS, \( F(4, 32) = 110.422, p < .001 \). As illustrated in Figure 12, smaller EBS generally led to larger NPS. For EBS (1.5 × 1.5), EBS (2.0 × 2.0), EBS (2.5 × 2.5), EBS (3.0 × 3.0), and EBS (3.5 × 3.5), the mean NPS was 1.610, 1.169, 0.782, 0.446, and 0.172, respectively. There was also an interaction effect on NPS for Character Complexity × EBS, \( F(8, 64) = 14.815, p < .001 \). Post hoc comparisons were performed using the Bonferroni adjustment for multiple comparisons, and it found significant difference (\( p < .005 \)) between all EBSs except EBS (3.0 × 3.0) and EBS (3.5 × 3.5); \( p = .101 \). Therefore, these two EBSs can be grouped with their similar NPSs.

**NWA.** The chi-square test based on standardized residuals was applied to NWA analysis. On the frequency of NWA, no statistically significant relationship was found between NWA and EBS (\( \chi^2 = 5.938, p = .204 \); see Figure 13). EBS (3.5 × 3.5) resulted in the fewest NWA with a standardized residual.
at –5.4. EBS (2.5 × 2.5) produced almost the same NWAs (z = –3.4) as EBS (3.5 × 3.5), EBS (2.0 × 2.0) and EBS (3.0 × 3.0) resulted in almost the same NWAs (z = 0.6 and z = –0.4, respectively). The largest NWA was produced by EBS (1.5 × 1.5; z = 8.6).

**Subjective preferences.** There was a significant difference found in the effect of five EBS on the overall preference rating, F(4, 32) = 47.963, p < .001 (see Table 5). Post hoc comparisons using the Bonferroni adjustment showed that EBS (3.5 × 3.5), EBS (3.0 × 3.0), and EBS (2.5 × 2.5) were rated significantly higher than the other two EBSs (p < .005). Moreover, no significant difference was found between EBS (3.5 × 3.5) and EBS (3.0 × 3.0; p = 1.000), EBS (3.0 × 3.0) and EBS (2.5 × 2.5; p = .516), and EBS (3.5 × 3.5) and EBS (2.5 × 2.5; p = .790). Therefore, these three EBSs can be grouped with similar subjective preferences.

**Learning effect.** We collected two blocks of data to investigate the learning effect. A repeated measures ANOVA showed no obvious learning effect on the WT, F(1, 8) = 4.201, p = .075; SRS, F(1, 8) = 2.074, p = .188; and LPS, F(1, 8) = 4.459, p = .068, between the two experimental blocks. As well, no learning effect was found on the frequency of NWA (χ² = 0.01, p = .913) using a chi-square analysis. Although there is a significant main effect for block on NPS, F(1,8) = 9.186, p < .05, the overall results showed that the learning effect was minor and participants had already reached a steady performance from Block 1.

### 5.4. Discussion

**Handwriting speed.** WT and SWS are used to quantify handwriting speed. The writing times of all EBSs were similar, but different EBSs resulted in different SWSs. Analysis results of WT and SWS suggest EBS (2.5 × 2.5) is the smallest EBS in which users can perform handwriting tasks with high handwriting speed.

**Utilization rate of entry area.** SR is applied to quantification of entry area utilization rate. The results of entry area utilization rate for one-handed entry are consistent with the results obtained in the experiment with two-handed entry; EBS (1.5 × 1.5) and EBS (2.0 × 2.0) resulted in a similar high utilization rate of the entry area. It should be noted that the SR produced by EBS (2.5 × 2.5) was smaller than that produced by EBS (1.5 × 1.5) and EBS (2.0 × 2.0) but significantly larger than that produced by EBS (3.0 × 3.0) and EBS (3.5 × 3.5). This indicates that EBS (2.5 × 2.5) could also generate a high utilization rate of entry area.

**Ease of writing.** LPS and NPS are applied to description of ease of writing. Although the NPS produced by EBS (2.5 × 2.5) was significantly larger than that produced by EBS (3.0 × 3.0) and EBS (3.5 × 3.5), these three EBSs resulted in similar LPSs. The similar LPS was also obtained in EBS (2.0 × 2.0), but the NPS for EBS (2.0 × 2.0) was significantly larger than that for EBS (2.5 × 2.5). Therefore, EBS (2.5 × 2.5) can be regarded as the smallest EBS in which users can perform handwriting task easily.

**Entry accuracy.** The NWA is used to describe entry accuracy. For one-handed entry, EBS (3.5 × 3.5) produced the fewest NWA. However, it should be noted that EBS (2.5 × 2.5) and EBS (3.5 × 3.5) resulted in almost the same NWA, suggesting that EBS (2.5 × 2.5) can also support accurate handwriting input.

**Subjective preferences.** According to the preference ratings of these five EBSs, EBS (2.5 × 2.5) had a comparatively high overall rating. The subjective rating result was in fairly good agreement with the analysis results of handwriting speed, utilization rate of entry area, entry accuracy, and ease of writing.

### Table 5

The participants’ preferences for each entry box size (EBS) with one-handed entry

<table>
<thead>
<tr>
<th>Dimension</th>
<th>EBS (1.5 × 1.5)</th>
<th>EBS (2.0 × 2.0)</th>
<th>EBS (2.5 × 2.5)</th>
<th>EBS (3.0 × 3.0)</th>
<th>EBS (3.5 × 3.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Writing speed</td>
<td>1.7</td>
<td>2.0</td>
<td>3.4</td>
<td>3.8</td>
<td>4.6</td>
</tr>
<tr>
<td>Utilization rate</td>
<td>4.9</td>
<td>4.8</td>
<td>4.1</td>
<td>3.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Writing accuracy</td>
<td>1.4</td>
<td>2.0</td>
<td>3.9</td>
<td>4.1</td>
<td>4.4</td>
</tr>
<tr>
<td>Ease of writing</td>
<td>1.0</td>
<td>1.7</td>
<td>3.0</td>
<td>4.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Fatigue of the finger</td>
<td>1.1</td>
<td>2.0</td>
<td>3.2</td>
<td>4.0</td>
<td>4.1</td>
</tr>
</tbody>
</table>
According to the overall analysis results of handwriting speed, utilization rate of entry area, entry accuracy, ease of writing, and subjective preference, for one-handed handwriting input, the optimal EBS was found to be \(2.5 \times 2.5\) cm.

6. GENERAL DISCUSSION AND FUTURE WORK

6.1. Handwriting Performance Within an Entry Area

Handwriting activity is both cognitive and physical, the coordinated movement of thoughts, hand and eye (Smith & Smith, 1991). This study deeply explored handwriting performance within an entry area. Before designing the experiment, we expected that larger entry size would lead to greater writing speed, higher accuracy, greater ease of writing, and higher subjective evaluation but lower utilization rate of entry area; and that for smaller entry size, the result would be the opposite for all criterions. We aimed to find out the optimal EBS in terms of a trade-off among the aforementioned criterions. Therefore, we defined the optimal entry size for character handwriting as the smallest input area in which the user can input characters with high-entry-area utilization rate, great writing speed, high character recognition rates, small number and short length of stroke protrusions outside the area, and high subjective assessment (e.g., ease of writing and degree of fatigue). According to this definition, we defined seven dependent variables and sorted them into five measures: handwriting speed, utilization rate of entry area, accuracy, ease of writing, and subjective evaluation. Inspired by previous studies (Parhi et al., 2006; Ren & Zhou, 2009; Sears & Zha, 2003), we performed a detailed analysis for each measure to find the optimal EBS. For both one-handed entry and two-handed entry, the results show that there was no significant difference among EBS (2.5 \(\times\) 2.5), EBS (3.0 \(\times\) 3.0), and EBS (3.5 \(\times\) 3.5) in terms of handwriting speed, ease of writing, entry accuracy, and subjective evaluation. In addition, although utilization rate of entry area produced by EBS (2.5 \(\times\) 2.5) was smaller than that produced by EBS (1.5 \(\times\) 1.5) and EBS (2.0 \(\times\) 2.0), it was significantly larger than that produced by EBS (3.0 \(\times\) 3.0) and EBS (3.5 \(\times\) 3.5), suggesting that EBS (2.5 \(\times\) 2.5) could also generate a high utilization rate of entry area. Therefore, it can be concluded that EBS (2.5 \(\times\) 2.5) is large enough for fast, accurate, and easy handwriting with a high-entry-area utilization rate and subjective evaluation. This result reveals that different EBSs can result in different handwriting performance and highlights the importance of EBS for handwriting input.

Handwriting speed and handwriting accuracy are two important factors in handwriting performance. High handwriting speed usually indicates that the user can write characters easily. Our results show that the user can achieve a high handwriting speed if the entry area is larger than \(2.5 \times 2.5\) cm. Although the participants generally reported that larger entry area can lead to greater writing speed, for entry areas larger than \(2.5 \times 2.5\) cm, there was no significant speed increase according to the experimental data analysis. Another important point in evaluation of handwriting performance is handwriting accuracy. Our results indicate that inputted characters can be recognized well if the entry area size is \(2.5 \times 2.5\) cm or larger. The analysis of handwriting speed and LPS and NPS shows that the user wrote faster with shorter and fewer protruding strokes in a large entry area than in a small one. From this, we infer that the user can write characters more clearly in a larger entry area. Therefore, inputted characters in a large area should be clear enough for the handwriting recognition software to recognize them correctly. The same can also be inferred from the subjective reports of the experimental participants; more than half of them said, “The entry box with 1.5 cm \(\times\) 1.5 cm is too small to write strokes clearly and comfortably.”

6.2. Controlled Factors and Uncontrolled Factors in the Experiment

We carefully designed the experiment and controlled the possible confounding factors for the purpose of our study. The main controlled factors in the experiment were as follows:

1. Entry box position: The entry box was set in the center of the screen of the experimental device. According to the study conducted by Karlson et al. (2006), this entry area can support fast tapping, hence may also support fast handwriting.

2. Prototype Chinese characters: These characters are commonly used Chinese characters. The participants may write these characters faster and easier than they can write rarely used characters.

3. Participants: The participants were younger adults and were familiar with the Chinese characters used in the experiment; these subjects may perform better than children and elder adults as well as users who are not familiar with these characters.

4. Body posture: The participants were asked to sit in a chair to perform the tasks, which may lead to a better performance than standing or walking.

5. Experimental device: The experiment was conducted on a HTC touch HD mini smartphone, a popular touch-based mobile phone with a HVGA screen.

The conclusion that \(2.5 \times 2.5\) cm is the optimal EBS was drawn by using the controlled experiment setup described previously. This EBS will help the user interface designer design a rational screen layout, which can display more information and allow users to write with ease and high efficiency. If the screen area is large enough, the designer can enlarge the EBS accordingly, although this may not significantly improve the user’s handwriting performance according to the results of this study. For other scenarios, such as walking, the results of this study provide important guidelines to help the user interface designer set up some handwriting EBSs for evaluation. By examining the handwriting performance within these boxes, the designer can
determine the optimal EBS according to the methodology proposed in this study. On the other hand, the uncontrolled factors in the experiment mainly referred to the participants, such as their moods and fatigue level when performing the experiment.

Because our goal was to determine optimal entry box dimensions by measuring handwriting performance variables in different EBSs, the experiments were designed and conducted in a lab setting that allowed us to efficiently collect a large amount of data for quantitative analysis. In our experiments, the entry box position was set in the center of the screen of the experimental device. However, in mobile phones such as the iPhone 4, the entry box is set at the bottom of the screen. Nevertheless, using the methodology of our study, optimal EBS can be determined for any entry box position. In future work, we would like to examine optimal EBS in different regions of the screen. Also, we will continue to explore the impact of user age (younger or older subjects) and body posture (sitting, standing, and walking) on handwriting input, and we will identify the optimal EBS for different body postures and different user age groups.

7. CONCLUSION

Two experiments were conducted to investigate the optimal finger-based entry size in touch-based mobile phones for two commonly used Chinese handwriting input styles: two-handed entry with the nondominant hand holding the device and the index finger of the dominant hand entering characters, and one-handed entry with the dominant hand holding the device and the thumb of the dominant hand being used for character entry. A set of variables for performance measure were proposed and a detailed analysis procedure was carried out here, which enabled the determination of the optimal EBS for handwriting input. For both one-handed entry and two-handed entry, the optimal EBS was found to be $2.5 \times 2.5$ cm, suggesting that this size of entry box is large enough for fast and accurate handwriting with high-entry-area utilization rate and few, short protruding strokes. We believe the user interface design for handwriting in touch-based mobile phones can benefit from the experimental results and the methodology of this study.

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