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Evaluation of Flick and Ring Scrolling on Touch-Based Smartphones

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This study examined the performance of two scrolling techniques (*flick* and *ring*) for document navigation in touch-based mobile phones using three input methods (*index finger, pen*, and *thumb*), with specific consideration given to two postures: *sitting* and *walking*. The findings are as follows: (a) in both sitting and walking postures, for the three input methods, flick resulted in shorter movement time and fewer crossings than ring, suggesting flick is superior to ring for document navigation; (b) for sitting posture, regarding pen and thumb input, ring led to shorter movement time than flick for large target distances, indicating ring has a potential interaction advantage; (c) regarding sitting and walking postures, both flick and ring document scrolling in touch-based mobile phones can be modeled by the Anderson model (Andersen, 2005). Designers of future scrolling techniques should consider these differences, as well as exploit the advantages and avoid the disadvantages of ring and flick scrolling.

1. INTRODUCTION

Advances in processing speed and memory allow mobile phones to support a number of applications such as text view and edit. However, the small screen area of mobile phones restricts the size of displayed text. Therefore, the user has to interact more fluently with the device to get to the desired location in the text. Thus scrolling is important for the support of many document-related tasks in mobile phones.

As two commonly employed techniques for document and list navigation, *flick* and *ring* are present in a wide range of electronic devices including touch-based mobile phones and portable media players. In the flick gesture a finger slides in a line along the screen. As an intuitive and natural form, flick has been commonly employed in touch-based mobile phones like the iPhone. On the other hand, ring is used to effect document scrolling by means of circular strokes. Ring serves as an efficient scrolling technique in mobile devices such as the Apple iPod.

For efficient interaction with digital devices for scrolling documents, much research in recent years has focused on the design and analysis of flick and ring techniques (Aliakseyeu, Irani, Lucero, & Subramanian, 2008; Diehl, Möllers, & Borchers, 2008; Moscovich & Hughes, 2004; Schraefel, Smith, & Baudisch, 2005; Smith & Schraefel, 2004; Wherry, 2003). For example, Aliakseyeu et al. (2008) systematically investigated the effectiveness of multiflick in pen-based interfaces by designing several flick-based scrolling techniques and comparing their performance with that of a scrollbar. In the study, multiflick technique achieved as good a performance as the scrollbar. Inspired by the hardware scrolling rings like the famous "iPod click wheel" on the Apple iPod, Moscovich and Hughes (2004) proposed a technique for scrolling through documents by means of a virtual scroll ring.

However, to the best of our knowledge, the performances of these two techniques in touch-based mobile phones have never been directly compared in a formal evaluation. The widespread use of flick and ring for document scrolling in touch-based mobile devices signified the importance of these two scrolling gestures. According to the findings by Bragdon, Nelson, Li, and Hinckley (2011) that free-form gestures and mark-based gestures had different speed and accuracy under various levels of mobile environmental demands on attention, the performance of flick and ring may vary under diverse application environments. This raises an open question about how to design and employ scrolling techniques in the context of document navigation tasks with regard to different input methods (e.g., pen and finger) and different postures (e.g., sitting and walking). Finding the advantages and disadvantages of each scrolling technique can expedite the design of scrolling techniques and result in significant benefits to users. This article aims to explore the design space of scrolling techniques on mobile devices and evaluate these designs in two postures: *sitting* and *walking*.

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The present article described two experiments in which we examined the performance of flick and ring scrolling for document navigation in touch-based mobile phones using three input methods (*index finger, thumb*, and *pen*), under two mobile environments: sitting and walking respectively. In index finger input, the nondominant hand holds the device and the index finger of the dominant hand is used for gesturing. In thumb input, the dominant hand holds the device, and the thumb of the dominant hand is used for gesturing. Although pen input is not prevalent in touch-based mobile phones, it can be an alternative to finger input in some cases, such as when users operate small targets in mobile phones (Ren & Moriya, 2000). Hence, we also compared the performances of flick and ring with pen input. A variant of Fitts's reciprocal tapping task, which is similar to that used by Hinckley, Cutrell, Bathiche, and Muss (2002), was used to thoroughly compare flick scrolling and ring scrolling.

This article begins with a review of related work, covering literature on flick scrolling, ring scrolling, device-independent scrolling, and movement time (MT) models for scrolling. This is followed by a description of the experiment design. Then we present two quantitative experiments. After each experiment, we discuss the results for that experiment. Finally, we provide several guidelines for the design of scrolling techniques in mobile phones.

2. RELATED WORK

This work builds upon four areas of previous research, most of which focused on pen-based interaction. The first refers to the flick scrolling technique. The second is a body of work on ring scrolling technique. The third one is about device-independent scrolling. The last is MT models for scrolling. We review each in turn.

2.1. Flick Scrolling Technique

Flick scrolling is an intuitive and natural scrolling method for mobile touch devices such as the iPhone. Aliakseyeu et al. (2008) designed four flick-based scrolling (multiflick) techniques and compared them with the traditional scrollbar for navigating lists and documents on different devices (PDA, tablet PC, large table). In the study, the multiflick technique performed as well as the scrollbar technique. Yin and Ren (2007) used pen pressure to improve the performance of flick-based and ring-based scrolling techniques. Experimental results indicated that techniques with pressure information performed better than those without pressure information. However, they did not compare flick and ring techniques.

2.2. Ring Scrolling Technique

Ring gesture is a circular motion. The rotating scroll wheel is one of the most widely adopted scrolling techniques in devices such as the iPod. Earlier work by Wherry (2003) investigated the performance of a touchpad scroll ring, a mouse scroll wheel, and touchpad scroll zone in a variant of Fitts's tapping task; the scroll ring performed faster with fewer errors. To improve list selection performance, Diehl et al. (2008) designed a novel scroll ring with pressure sensitivity.

Inspired by the hardware scrolling ring such as the iPod click wheel on the Apple iPod, Moscovich and Hughes (2004) proposed a technique for scrolling through documents by means of a virtual scroll ring. The technique used the amplitude and frequency of a repetitive circular movement, rather than angle and radius, to better support ring document scrolling. Results showed that the virtual scroll ring performed at least as well as a mouse wheel for medium and long distances, and it was preferred by users.

To better support scrolling on touch displays, Smith and Schraefel (2004) designed a radial scroll widget: the scrolling time for the scroll widget was shorter than that for the traditional scrollbar for short scrolling distances. However, the scroll widget suffered a drawback, which was that the user must maintain visual focus on it. Curve dial (Schraefel et al., 2005) can support eyes-free parameter entry for document scrolling, as it tracked the curvature arc rather than the center. Radial scroll tool and curve dial selected a minimum of three points to determine the angle of curvature, which inspired the ring technique design in our study.

2.3. Device-Independent Scrolling

As an easy-to-implement technique, the scrollbar has been widely used for navigating documents in a wide range of electronic devices including computers, graphing calculators, mobile phones, and portable media players (Inkepen et al., 2006). Igarashi and Hinckley (2000) proposed a novel navigation technique for browsing large documents named speed-dependent automatic zooming (SDAZ), which uses scrolling combined with an automatic zooming mechanism to provide fast visual search. A user study demonstrated the effectiveness of their technique. Flipper (Sun & Guimbretiere, 2005) is a variation of the SDAZ technique, which can enable the user to quickly scroll one page at a time. Cockburn, Savage, and Wallace (2005) proposed displacement-dependent automatic zooming, which can be used to navigate documents by scrolling and zooming in proportion to the amount of cursor displacement. Results show that displacement-dependent automatic zooming was faster for scrolling than SDAZ. With a view to eliminating most scrolling, Cockburn, Gutwin, and Alexander (2006) proposed Space-Filling Thumbnails, which aims to provide fast document navigation by using an overview display. OrthoZoom Scroller (Appert & Fekete, 2006) is a 1D multiscale navigation technique in which panning is performed along the slider dimension, whereas zooming is performed along the orthogonal one. Cockburn, Quinn, Gutwin, and Fitchett (2012) proposed a method for applying gain to events reported by scrolling input devices such as scroll wheels.

Content-aware scrolling technique (Ishak & Feiner, 2006) uses the various characteristics of document content to determine scrolling direction, speed and zoom. Chen et al. (2009) developed a device employing a range sensor and rotary encoder to track finger movement for document navigation. The variety in scrolling techniques demands that we examine the performance of these techniques, so as to identify the advantages and disadvantages of each technique and to improve technique design. Therefore, taking flick and ring as two examples, this study systematically investigates their performance so as to advance scrolling technique studies and provide an informed basis for future studies.

2.4. MT Model for Scrolling

A quantitative human performance model would facilitate the design and evaluation of scrolling techniques by quantitatively predicting their efficiency before running extensive user studies. In an early study, Zhai, Smith, and Selker (1997) investigated the performance of three input methods (mouse with isometric joystick, mouse with a track wheel, and two handed joystick and mouse) in a task that involved both scrolling and pointing. The results showed that a mouse with a finger wheel did not improve user performance, whereas the other input methods significantly improved user performance. In a noteworthy analytical study, Hinckley et al. (2002) showed that Fitts's law can model certain scrolling patterns. In the study, participants were asked to perform a variant of Fitts's reciprocal tapping task by means of an IBM ScrollPoint and an IntelliMouse Wheel. However, the study did not examine the applicability of Fitts's law for ring and flick document scrolling in touch-based mobile phones. Another MT model for scrolling was proposed by Andersen (2005; the Andersen model), taking into account that Fitts's law was developed for "aimed" movement; however, for scrolling tasks the target position is usually not known. The study indicated that movement time was linearly dependent on the target distance. In our study, we further examined the effectiveness of Fitts's Law and Andersen's model for the prediction of MT with ring and flick document scrolling in touch-based mobile phones.

3. METHOD

3.1. Flick and Ring Techniques

The flick technique used here was designed based on the method proposed by Yin and Ren (2007). As illustrated in Figure 1a, p2(x2, y2) and p1(x1, y1) respectively denote the current and previous points in a gesture trajectory. The document scrolling distance is equal to the absolute value of (y2 – y1). The document scrolling direction is determined by the sign of (y2 – y1): if the sign is negative, the document will scroll forward. Otherwise, the document will scroll backward.

On the other hand, for ring technique, we utilized a method similar to that used in (Schraefel et al., 2005; Smith & Schraefel,

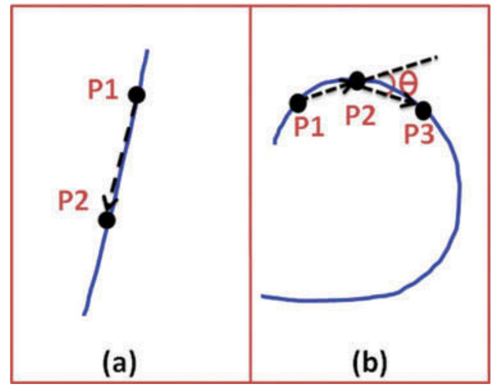


FIG. 1. (a) Flick scrolling and (b) ring scrolling.

2004; Yin & Ren, 2007). As illustrated in Figure 1b, there are a minimum of three points—p1, p2 and p3 (p1 is a previous point of p2, and p2 is a previous point of p3)—in a gesture trajectory. θ denotes the angle that rotates from the vector (p1, p2) to the vector (p2, p3). The document scrolling distance is equal to $\theta \times R/2\Pi$(R is a constant with a value of 220 pixels). The scrolling direction is determined by the sign of the dot product of the vector (p1, p2) and the vector (p2, p3): If the sign is positive, the document will scroll forward. Otherwise, the document will scroll backward. Scrolling by angle indicates that fast and small circles can cause fast scrolling, whereas slow and large circles can cause slow scrolling.

3.2. Reciprocal Framing Task for Scrolling

The experimental task was similar to Hinckley et al. (2002), which was a variant of Fitts's reciprocal tapping task. In the experiment, participants were instructed to scroll down and up, moving back and forth between two target lines in a document using the flick or the ring technique. As illustrated in Figure 2, a document that consisted of 288 lines with a line height of 21 pixels (0.30 cm) was used. We assigned every line a unique number, starting at 1 for the first line and incrementing by 1 for each successive line. We expected that these numbers would help participants find the target lines easily. The initial target line appeared with red, and the second one was marked by blue. A frame was placed at the left of the task window and always centered on the screen. Participants were asked to scroll the target line toward the range of the screen identified by the frame. Once the target line fully entered the identified screen range, participants were asked to press the end button to complete the current scrolling task and continue to the next scrolling task; meanwhile, the target line disappears. If participants pressed the end button without the target line fully entering the identified screen range, a warning beep tone would sound, but we asked them to continue to scroll toward the next target, that is, not to repeat the failed task.

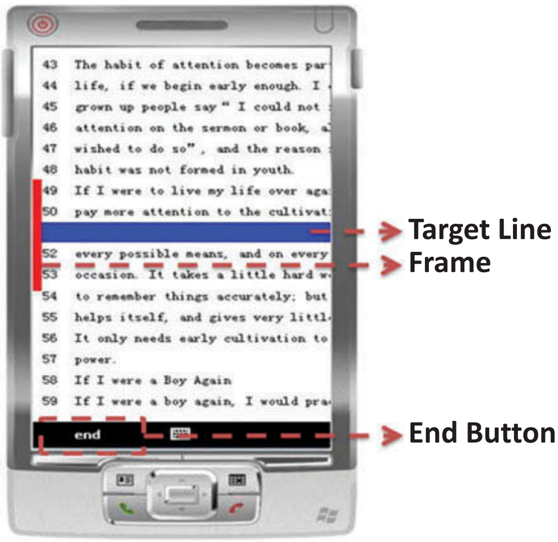


FIG. 2. Experimental interface.

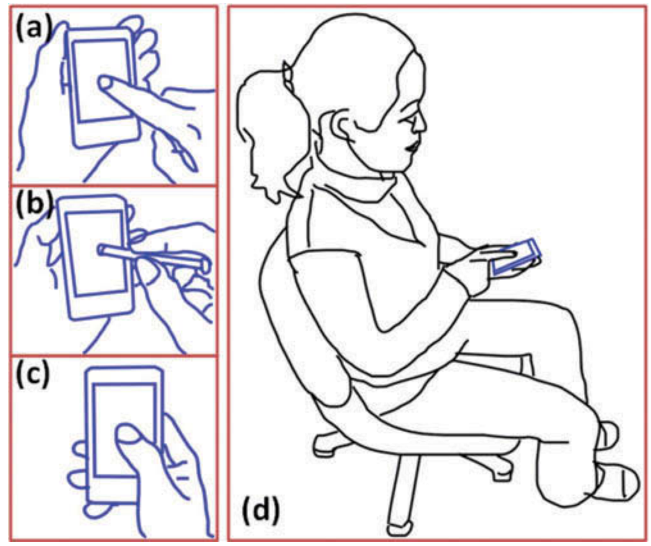


FIG. 3. (a) Index finger input. (b) Pen input. (c) Thumb input. (d) Participant in the experimental environment.

4. EXPERIMENT 1: IN SITTING POSTURE

One of the most common postures while using a mobile device is sitting. In this experiment, we investigated the performance of flick and ring scrolling in a sitting environment. Some preliminary results of this experiment were published in Tu, Wang, Tian, and Ren (2012).

4.1. Participants

Ten participants—nine male and one female, from 20 to 27 years of age—took part in this experiment. All of them were right-handed and had prior experience with bare finger operation on touch screen devices such as the iPhone. Six of them had prior experience operating digital screens with digital styli.

4.2. Apparatus

The study was conducted on an HTC Touch HD mini smartphone equipped with a capacitive touch screen with HVGA resolution. The screen size was 3.2 in. and its resolution was 320 × 480 pixels. The platform was Windows Mobile 6.5 Professional with HTC Sense. The experimental program was designed in the C# environment.

4.3. Task and Procedure

When performing the experimental task, the participant was asked to sit in a chair (see Figure 3d). The experiment used a 3 × 2 × 4 × 3 within-factor design with a variety of planned comparisons. The independent variables were input method (index finger, pen and thumb, see Figure 3a, 3b, 3c, respectively), scrolling technique (flick and ring), target distance (20, 60, 120, and 200 lines), and frame width (three, six, and 12 lines). A (partially balanced) Latin-square was used to counterbalance the order of the presentation of the input method and scrolling technique. For each input method and scrolling technique, the order of the four target distances for the three frame widths was randomized. For each target distance and frame width, the participants completed seven individual target acquisitions (phases). The participants took 60 min on average to complete the experiment. In summary, experiment data collection consisted of

10 subjects ×
3 input methods ×
2 scrolling techniques ×
4 target distances ×
3 frame widths ×
7 phases
= 5,040 trials

At the end of the experiment, a questionnaire was administrated to gather subjective opinions. Participants were asked to rate flick and ring for each input method on 7-point Likert scales regarding *movement speed, easy to position target line*, and *hand fatigue* (7 for highest preference and 1 for lowest preference).

4.4. Results and Discussion

Learning effects. For each target distance and frame width, each participant performed seven phases. To ensure data stability, we first checked the learning effect on MT over the seven phases to see if the data we collected have reached a level of stability. MT is defined as the duration from the moment the pen or finger touches the screen to the moment the target line last enters the region specified by the frame before the "end" button is pressed.

As shown in Figure 4, for flick technique, repeated measures analysis of variance (ANOVA) showed that phase had a significant main effect on MT, $F(6, 54) = 12.43$, $p < .001$. Post hoc

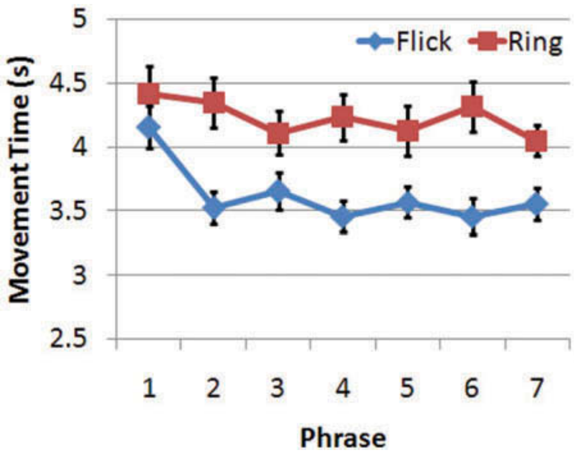


FIG. 4. Mean movement time for each phase and scrolling technique. *Note*. Error bars represent 0.95 confidence interval.

comparisons revealed that the first phase had a significant longer MT than the other phases ($p < .05$). Therefore, we excluded the data for the first phase for the rest of our analysis. On the other hand, with respect to ring technique, although no significant main effect was found on MT for phase, $F(6, 54) = 2.06$, $p = .07$, it was found that the first phase resulted in a significantly longer MT than the third, fifth and seventh phases ($p < .05$ for all); in these four phases, the experimental tasks were the same: moving the red target line into the region specified by the frame. Hence, the data from the first phase were excluded from the rest of our analysis.

Number of crossings (NC). When moving the target line into the screen region specified by the frame, participants sometimes crossed the frame more than once. The NC is defined as the number of times the target line enters or leaves the specified frame region for a particular trial with one target distance and frame width, minus 1.

Regarding index finger input, a repeated measures ANOVA analysis showed a significant main effect on NC for scrolling technique, $F(1, 9) = 107.37$, $p < .001$. The mean NC was 2.14 in the flick condition and 5.05 in the ring condition for each target distance and frame width. Other independent variables influenced NC. A significant main effect was found on NC for target distance, $F(3, 27) = 7.08$, $p < .01$, and frame width, $F(2, 18) = 47.49$, $p < .001$. Of interest, although there was no significant interaction effect on NC for frame width, there was an interaction between scrolling technique and target distance, $F(3, 27) = 3.76$, $p < .05$.

For pen input, there was a significant main effect on NC for scrolling technique, $F(1, 9) = 41.90$, $p < .001$. The mean NC was 1.83 in the flick condition and 5.04 in the ring condition for each target distance and frame width. There was a significant main effect on NC for target distance, $F(3, 27) = 5.88$, $p < .01$, and frame width, $F(2, 18) = 47.49$, $p < .001$. Although no significant interaction effect was found between scrolling technique and target distance, there was a strong interaction between scrolling technique and frame width, $F(2, 18) = 4.14$, $p < .05$.

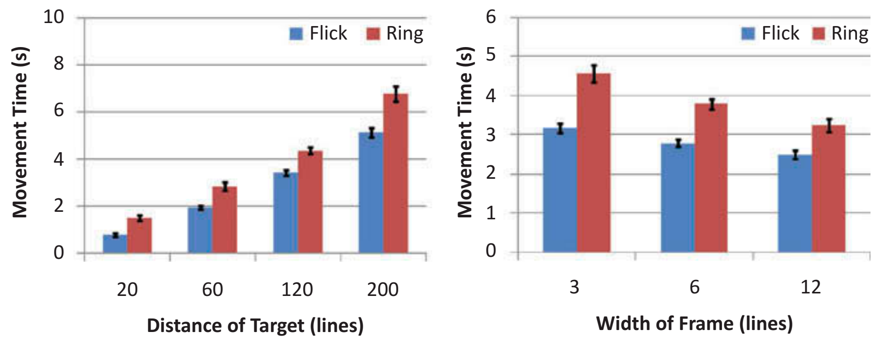
With respect to thumb input, a significant main effect was found on NC for scrolling technique, $F(1, 9) = 75.21$, $p < .001$. The mean NC was 0.73 in the flick condition and 3.08 in the ring condition for each target distance and frame width. The frame width had a significant main effect on NC, $F(2, 18) = 35.07$, $p < .001$. Although there was no significant interaction between scrolling technique and target distance, there was a strong interaction between scrolling technique and frame width, $F(2, 18) = 8.66$, $p < .05$.

Overall, for index finger, pen and thumb input, ring technique resulted in more NC than flick technique, indicating it is difficult for participants to position the target line within the frame using ring technique. More NC meant that it would take more time to position the target line within the frame, which may yield a false measurement of the MT for scrolling. Therefore, for the analysis of MT, we excluded the data of the experimental trial in which NC was greater than 3.

MT. MT, as defined in the subsection "learning effects," is another basic measure of the performance of scrolling technique. For index finger input, a repeated measures ANOVA analysis showed that scrolling technique had a significant main effect on MT, $F(1, 9) = 51.54$, $p < .001$. The mean MT was 2.82 s for flick technique and 3.86 s for ring technique. Other independent variables influenced MT. A significant main effect was found on MT for target distance, $F(3, 27) = 567.55$, $p < .001$, and frame width, $F(2, 18) = 87.23$, $p < .001$. There was an interaction between scrolling technique and target distance, $F(3, 27 = 6.65$, $p < .01$ (see Figure 5a). In addition, there was a significant interaction between scrolling technique and frame width, $F(2, 18) = 14.59$, $p < .001$ (see Figure 5b). The results indicated that flick performed faster than ring when users performed scrolling tasks by means of the index finger.

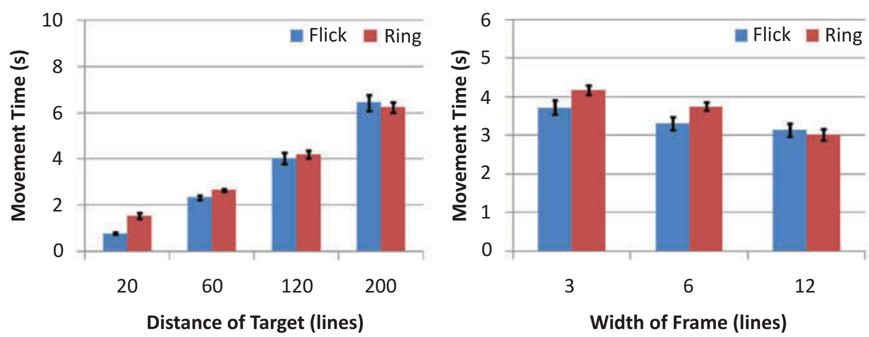
With respect to pen input, there was no significant main effect on MT for scrolling technique, $F(1, 9) = 2.59$, $p = .14$. The mean MT was 3.39 s for flick technique and 3.65 s for ring technique. There was a significant main effect on MT for target distance, $F(3, 27) = 588.87$, $p < .001$, and frame width, $F(2, 18) = 98.64$, $p < .001$. A significant interaction effect on MT was found between scrolling technique and frame width, $F(2, 18) = 12.12$, $p < .001$ (see Figure 6b). Of interest, as illustrated in Figure 6a, there was also an interaction between scrolling technique and target distance, $F(3, 27) = 3.85$, $p < .05$. Ring resulted in a longer MT than flick for the target distances of 20, 60, and 120 lines but shorter MT for the target distance of 200 lines.

With regard to thumb input, there was no significant main effect on MT for scrolling technique, $F(1, 9) = 0.92$, $p = .36$. The mean MT was 4.40 s in the flick condition and 4.75 s in the ring condition. Other independent variables influenced MT. It was found that there was a significant main effect on MT for target distance, $F(3, 27) = 383.83$, $p < .001$, and frame width,



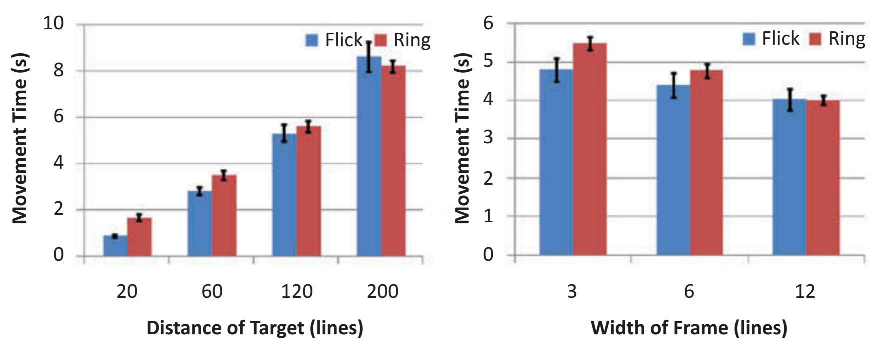
(a) (b)

FIG. 5. Regarding index finger input, mean movement time for two scrolling techniques for each (a) target distance and (b) frame width. *Note.* Error bars represent 0.95 confidence interval.



(a) (b)

FIG. 6. Regarding pen input, mean movement time for two scrolling techniques for each (a) target distance and (b) frame width.



(a) (b)

FIG. 7. Regarding thumb input, mean movement time for two scrolling techniques for each (a) target distance and (b) frame width.

$F(2, 18) = 71.27$, $p < .001$. There was a significant interaction between scrolling technique and frame width, $F(2, 18) = 6.69$, $p < .01$ (see Figure 7b). In addition, an interaction effect on MT was found between scrolling technique and target distance, $F(3, 27) = 3.11$, $p < .05$ (see Figure 7a). Ring produced a longer MT than flick for the target distances of 20, 60, and 120 lines but shorter MT for the target distance of 200 lines.

The fit of Fitts' Law and Andersen model. We examined the relationship between MT and scrolling task with respect to each scrolling technique and each input method. It was found that for each scrolling technique and input method, linear regression of the MT by ID showed low correlations with Fitts's law ($R^2 < 0.8$). However, as shown in Figure 8, for the Andersen model (Andersen, 2005), regression of D against MT for each scrolling technique and input method yielded a good fit, with regression coefficients of .99. The results verified the applicability of Andersen's model in flick-based and ring-based scrolling in touch-based mobile phones.

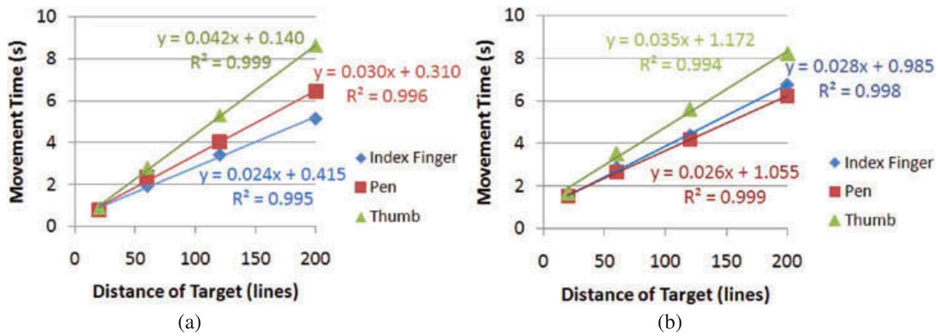


FIG. 8. Movement time for each target distance in (a) flick scrolling and (b) ring scrolling.

Error rates. The error rate is defined as the percentage of target acquisition trials in which the participants pressed the "end" button but the target line was not in the range specified by the frame. It was found that for each input method and scrolling technique, the error rate was very low with a value less than 4%.

Subjective evaluation. A repeated measures ANOVA analysis showed that for index finger input, flick was rated significantly higher than ring in terms of movement speed, ease in positioning the target line and hand fatigue ($p < .05$ for all). With respect to pen input and thumb input, although there was no main effect on *movement speed* or *hand fatigue* for scrolling technique, scrolling technique had a significant effect on *easy-to-position target line* ($p < .05$); flick was rated higher than ring. The subjective preference was fairly consistent with the MT and with the NC performance.

5. EXPERIMENT 2: IN WALKING POSTURE

Users sometimes rely on mobile devices to view and edit documents while walking. Hence, it is important to examine the performance of flick and ring in walking environments as well.

5.1. Participants and Equipment

The same 10 subjects who participated in experiment one took part in Experiment 2. The same mobile device was used as in Experiment 1. We asked the participants to walk on a treadmill when performing the experiment task.

5.2. Task and Procedure

A similar task and procedure used in Experiment 1 was carried out in this experiment. When performing the experimental task, participants were asked to walk on the treadmill (walking speed was set as 0.91 m/s according to Knoblauch, Pietrucha, & Nitzburg, 1996). The experiment used a 3 × 2 × 3 × 3 within-factor design with a variety of planned comparisons. The independent variables were input method (index finger, pen, and thumb), scrolling technique (flick and ring), target distances (20, 60, and 200 lines), and frame widths (three, six, and 12 lines). A (partially balanced) Latin-square was used to counterbalance the order of the presentation of the input method and scrolling technique. For each input method and scrolling technique, the order of the three target distances for the three frame widths was randomized. For each target distance and frame width, the participants completed four individual target acquisitions (phases). The participants on average took 30 min to complete the experiment. In summary, experiment data collection consisted of

10 subjects ×
3 input methods ×
2 scrolling techniques ×
3 target distances ×
3 frame widths ×
4 phases
= 2,160 trials

It should be noted that, in this experiment, in order to avoid user fatigue after a long walk, we selected only three target distances, rather than the four used in Experiment 1. Also the number of phases was reduced to four. At the end of the experiment, a questionnaire was administered to gather subjective opinions. Participants were asked to rate flick and ring for each input method on 7-point Likert scales regarding *movement speed, easy to position target line*, and *hand fatigue* (7 for highest preference and 1 for lowest preference).

5.3. Results and Discussion

Learning effects. Subjects performed the same process as in Experiment 1, and we first examined the learning effects for further data analysis. Figure 9 illustrates the average MT for each phase regarding each scrolling technique. For both flick and ring techniques, a repeated measures ANOVA analysis showed that phase had a significant main effect on MT ($p < .001$). With respect to flick, post hoc comparisons revealed that the first phase had a significantly longer MT than the other phases ($p < .01$). Hence the data in the first phase were excluded for the rest of our analysis. With respect to ring technique, it was found that the first phase resulted in a significantly longer MT than the third phase ($p < .05$ for all). Moreover, in the two phases, the experimental tasks were the same—moving the red target line into the region specified by the frame. As a result,

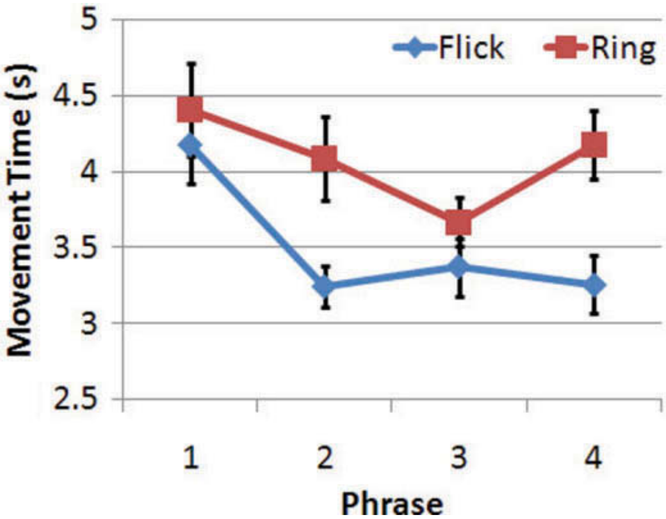


FIG. 9. Mean movement time for each phase and scrolling technique.

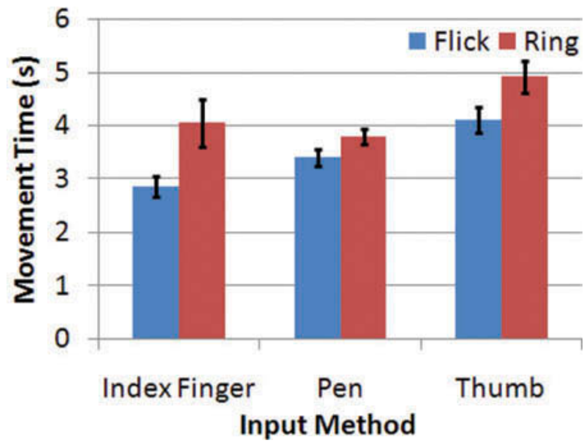


FIG. 10. Mean movement time for two scrolling techniques (flick and ring) for each input method (index finger, pen and thumb).

data excluding the first phase were applied to the rest of our analysis.

NC. Regarding index finger input, a repeated measures ANOVA analysis showed a significant main effect on NC for scrolling technique, $F(1, 9) = 32.61$, $p < .001$. The mean NC was 2.12 in the flick condition and 5.23 in the ring condition for each target distance and frame width. Other independent variables influenced NC. A significant main effect was found on NC for target distance, $F(2, 18) = 10.91$, $p < .01$, and frame width, $F(2, 18) = 30.04$, $p < .001$.

For pen input, there was a significant main effect on NC for scrolling technique, $F(1, 9) = 103.12$, $p < .001$. The mean NC was 2.00 in the flick condition and 5.17 in the ring condition for each target distance and frame width. There was a significant main effect on NC for target distance, $F(2, 18) = 7.82$, $p < .01$, and frame width, $F(2, 18) = 100.24$, $p < .001$.

With respect to thumb input, a significant main effect was found on NC for scrolling technique, $F(1, 9) = 16.40$, $p < .01$. The mean NC was 0.73 in the flick condition and 3.31 in the ring condition for each target distance and frame width. The frame width had a significant main effect on NC, $F(2, 18) = 20.79$, $p < .001$.

For all three input methods, no interaction effect was found on MT for target distance or for frame width.

In summary, ring technique led to more NC than flick technique for index finger, pen, and thumb input. For the analysis of MT, we excluded the data of the experimental trial in which NC was greater than 3.

MT. For index finger input, repeated measures ANOVA showed that scrolling technique had a significant main effect on MT, $F(1, 9) = 7.02$, $p < .05$ (see Figure 10). The mean MT was 2.85 s for flick technique and 4.04 s for ring technique. Other independent variables influenced MT. A significant main effect was found on MT for target distance, $F(2, 18) = 102.22$, $p < .001$, and frame width, $F(2, 18) = 6.69$, $p < .01$. The results indicated that flick performed faster than ring when users performed scrolling tasks by means of the index finger.

In respect to pen input, there was no significant main effect on MT for scrolling technique, $F\ (1, 9) = 3.10$, $p < .11$ (see Figure 10). The mean MT was 3.99 s for flick technique and 4.29 s for ring technique. There was a significant main effect on MT for target distance, $F(2, 18) = 352.82$, $p < .001$, and frame width, $F(2, 18) = 32.08$, $p < .001$.

With regard to thumb input, there was a significant main effect on MT for scrolling technique, $F(1, 9) = 6.55$, $p < .05$ (see Figure 10). The mean MT was 4.11 s in the flick condition and 4.91 s in the ring condition. Other independent variables influenced MT. It was found that there was a significant main effect on MT for target distance, $F(2, 18) = 186.84$, $p < .001$, and frame width, $F(2, 18) = 8.40$, $p < .01$.

For index finger, pen, and thumb input, there was no interaction effect on MT for target distance or for frame width.

In summary, flick achieved significantly shorter MTs than ring with index finger input and thumb input.

The fit of Fitts's Law and Andersen model. In the walking environment, we examined the relationship between MT and scrolling task with respect to each scrolling technique and each input method. It was found that for each scrolling technique and input method, linear regression of the MT by ID showed low correlations with Fitts's law ($R^2 < 0.8$). However, for Andersen's model (Andersen, 2005), regression of D against MT for each scrolling technique and input method yielded a good fit, with regression coefficients of .99. The results verified the applicability of the Andersen model in flick-based and ring-based scrolling on touch-based mobile phones while walking.

Error rates. Flick and ring led to a very low error rate in the context of document navigation by means of pen, index finger, and thumb input (less than 4%).

Subjective evaluation. A repeated measure ANOVA analysis showed that for pen, thumb, and index finger input, flick was rated significantly higher than ring in terms of movement speed, ease of target positioning, and hand fatigue ($p < .05$ for all).

6. GENERAL DISCUSSION

6.1. Advantages and Disadvantages of Flick and Ring Scrolling

Flick and ring scrolling techniques were examined in the context of mobile document navigation tasks in two postures, respectively: sitting and walking. In both experiments, the participants were instructed to perform flick and ring scrolling tasks by means of the pen, thumb, and index finger, respectively. We designed the experiment task with full consideration of two factors: target distance and frame width. For each input method, we analyzed the performance of flick and ring scrolling under the combined use of different target distances and frame widths.

As illustrated in Table 1, in the sitting environment, for index finger input, flick resulted in shorter MTs than ring and was preferred by the participants, indicating that flick is a superior technique for document scrolling. The flick gesture is analogous to a throwing motion in the real world, whereas the ring gesture is a circular motion. Therefore, compared to ring gesture, flick gesture may be more natural and intuitive for index finger input. Regarding pen and thumb input, no significant difference was found in MT for ring and flick techniques. The interaction effects on MT for scrolling technique may have design implications. Flick led to shorter MTs than ring for short scrolling distances (target distance $\leq$ 120 lines). However, when scrolling actions were longer than 200 lines, ring tended to be faster than flick. With respect to pen input, the greater degrees of freedom afforded by the pen may allow participants to use the ring technique more comfortably than the flick technique. For thumb input, the thumb's movement range on the screen may have an effect on scrolling performance; it is difficult to move the thumb up and down but easy to rotate it around a circle (Hirotaka, 2003). Overall these interaction effects suggest that ring is a promising scrolling mechanism for pen and thumb input.

In the walking environment, as shown in Table 1, flick produced significant shorter MTs than ring with index finger and thumb input. In addition, in the process of the experiment, eight of the 10 participants stated that it was more difficult to use ring than to use flick when walking, because they felt that moving the finger up and down was easier than moving the finger around a circle on the screen. The experimental analysis and the subject evaluation indicated that flick can serve as an effective and a preferred scrolling technique for users when walking.

TABLE 1
A Summary of Movement Time Analysis of Flick and Ring for each Input Method (Pen, Index Finger, and Thumb) and for Each Posture (Sitting and Walking)

	Pen	Index Finger	Thumb
Sitting	No	Yes	No
Walking	No	Yes	Yes

Note. No = no significant difference between ring and flick regarding movement time; Yes = a significant difference between ring and flick regarding movement time.

In summary, our study reveals that in the linear mapping function, flick scrolling differed from ring scrolling in MT and in the NC. Overall, flick is superior to ring for document navigation in touch-based mobile phones, but ring has a potential interaction advantage. In addition, ring scrolling resulted in more crossings than flick scrolling. The results remind us that future scrolling technique design should consider these differences as well as exploit the advantages and avoid the disadvantages of ring and flick scrolling. For example, ring scrolling can be considered as an alternative technique to flick scrolling when designing scrolling techniques for long documents using the thumb. To improve the effectiveness of ring scrolling, it is important to involve the use of scrolling mechanisms such as the inertial scrolling mechanism used in the iPhone to achieve "smooth" scrolling. As flick and ring have already been used as two popular scrolling techniques in touch-based mobile phones, even tiny improvements may result in significant benefits to users. The present work is one step toward this purpose.

6.2. Smooth Scrolling for Ring Technique

Smooth scrolling is a feature used to reduce what the user would perceive as "jumps" (discontinuous movement) in document scrolling. However, in this study, the NC was larger for ring than for flick technique, indicating that the participants could not perform ring smoothly. Also, participants reported that it was more difficult with ring than with flick to position the target line within the region specified by the frame. As expected, larger NC led to longer MTs. Therefore, for more effective ring scrolling technique design, it is better to increase the smoothness of response to sample points.

As introduced in the Flick and Ring Techniques section, the document scrolling distance was calculated according to the angle between two vectors indicating current and previous finger or pen positions on the screen. With respect to the ring scrolling mechanism, sufficiently fine control of ring was difficult to achieve, and as a result, participants could not achieve smooth scrolling. Several methods have been proposed to support smooth scrolling, such as linear least squares fit (Moscovich & Hughes, 2004), and increasing the gap between sampling points selected (Schraefel et al., 2005). These methods will be used in our future examination of the performance of ring scrolling.

6.3. Mapping Function for Flick and Ring Techniques

Aliakseyeu, Irani, Lucero, and Subramanian (2008) proposed three mapping functions for flick technique and demonstrated their effectiveness in the context of document and list navigation tasks. However, we did not use those mapping functions for two reasons. First, we wanted to avoid complicating our results with different varieties of mapping functions (e.g., inertial scrolling mechanism) in the preliminary investigation of the performance of flick and ring, so we designed our scrolling techniques based on a simple mapping function which performed a linear translation of the displacement of input method to the distance of document scrolling. Second, the aim of this study was to compare flick and ring scrolling techniques, so it is essential to use a mapping function that is "fair" for both scrolling techniques (i.e., one that does not prejudice [/favor] either scrolling technique). As the mapping functions in (Aliakseyeu et al., 2008) were designed for evaluating flick scrolling only, they may favor flick over ring. Admittedly mapping function selection is a tricky balance with many considerations. We need to select the mapping function that can not only be used to effectively examine the performance of flick and ring scrolling without prejudice for either scrolling technique but also that has been widely adopted in the human–computer interaction research field. To meet this requirement, we selected the linear mapping function proposed in Schraefel et al. (2005), Smith and Schraefel (2004), Wherry (2003), and Yin and Ren (2007) to provide a baseline mapping mechanism for the comparison of flick and ring scrolling. We aimed to conduct a preliminary investigation into the performance of flick and ring scrolling based on the mapping function used. As a fundamental study, our study provides a methodology and some preliminary conclusions for future study (e.g., flick is superior to ring for document navigation in touch-based mobile phones; ring has a potential interaction advantage; ring scrolling led to more crossings than flick scrolling; both flick and ring document scrolling in touch-based mobile phones can be modeled by Anderson's, 2005, model). Future work should further explore the performance of flick and ring document scrolling in the context of different mapping functions (Quinn, Cockburn, Casiez, Roussel, & Gutwin, 2012; Quinn, Malacria & Cockburn, 2013).

For ring technique, *R*, a constant coefficient, plays an important role in determining scrolling speed. Hence, we conducted a pilot study to select a proper *R*. We designed three ring techniques, in which *R* was set as 110, 220, and 330 pixels, respectively (R110, R220, and R330 were used to denote the three ring techniques, respectively). Six participants were asked to perform these three ring techniques. The experiment procedure was similar to that introduced in subsection "experiment design." As a result, R220 resulted in significantly shorter MTs than R110 and fewer NC than R330. In addition, no significant difference was found in MT between R330 and R220. Hence, *R* was set as 220 pixels for our study.

7. CONCLUSION

Flick and ring are document scrolling techniques that have been widely employed in mobile devices for a variety of application scenarios. To investigate the performance of flick and ring scrolling in regard to different input methods and user postures, this article presented two controlled experiments, which empirically evaluated the performance of two commonly used scrolling techniques (flick and ring) for document navigation by means of index finger, pen, and thumb input in touch-based mobile phones, in the contexts of sitting and walking postures, respectively. First, it was found that under the use of the linear mapping function, flick overall performed better than ring for the three input methods. In addition, in the sitting posture, with regard to pen input and thumb input, ring performed faster than flick for long target distances, indicating ring has a potential interaction advantage and should be deeply explored for future scrolling technique design. Second, ring scrolling led to more crossings than flick scrolling. Future scrolling technique design should consider how to achieve "smooth" scrolling, especially for ring scrolling. Finally, both flick and ring document scrolling in touch-based mobile phones can be modeled by Anderson's (2005) model in both sitting and walking postures. Overall, the results just presented reveal that flick differed from ring in the context of document navigation tasks by means of pen input and finger input. Future scrolling technique design should exploit the advantages and avoid the disadvantages of ring and flick techniques. Also, our study provides a methodology to help the designer better examine the performance of scrolling techniques for the purpose of better scrolling technique design. We believe these findings can be useful in improving the performance of flick and ring document scrolling in touch-based mobile phones.

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