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Understanding performance in touch selections: Tap, drag and radial pointing drag with finger, stylus and mouse

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Abstract

Touch-based interaction with computing devices is becoming more and more common. In order to design for this setting, it is critical to understand the basic human factors of touch interactions such as tapping and dragging; however, there is relatively little empirical research in this area, particularly for touch-based dragging.

To provide foundational knowledge in this area, and to help designers understand the human factors of touch-based interactions, we conducted an experiment using three input devices (the finger, a stylus, and a mouse as a performance baseline) and three different pointing activities. The pointing activities were bidirectional tapping, one-dimensional dragging, and radial dragging (pointing to items arranged in a circle around the cursor). Tapping activities represent the elemental target selection method and are analysed as a performance baseline. Dragging is also a basic interaction method and understanding its performance is important for touch-based interfaces because it involves relatively high contact friction. Radial dragging is also important for touch-based systems as this technique is claimed to be well suited to direct input yet radial selections normally involve the relatively unstudied dragging action, and there have been few studies of the interaction mechanics of radial dragging. Performance models of tap, drag, and radial dragging are analysed.

For tapping tasks, we confirm prior results showing finger pointing to be faster than the stylus/mouse but inaccurate, particularly with small targets. In dragging tasks, we also confirm that finger input is slower than the mouse and stylus, probably due to the relatively high surface friction. Dragging errors were low in all conditions. As expected, performance conformed to Fitts' Law.

Our results for radial dragging are new, showing that errors, task time and movement distance are all linearly correlated with number of items available. We demonstrate that this performance is modelled by the Steering Law (where the tunnel width increases with movement distance) rather than Fitts' Law. Other radial dragging results showed that the stylus is fastest, followed by the mouse and finger, but that the stylus has the highest error rate of the three devices. Finger selections in the North-West direction were particularly slow and error prone, possibly due to a tendency for the finger to stick–slip when dragging in that direction.

Keywords: Touch interaction; Dragging; Radial menus

1. Introduction

Direct-touch interfaces are now becoming common in computing devices such as tablets, smart phones, handheld game platforms, and digital surfaces. Touch-based interaction is natural and simple, and can be easily carried out in mobile settings using a stylus or finger. As this style of input becomes a standard approach for designing interactive systems, it is important to understand the underlying human factors of input techniques that involve direct contact with the input surface. However, there are surprisingly few empirical results available to help designers understand the fundamental performance issues involved in carrying out basic interface actions with direct touch.

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To provide an initial foundation for understanding these issues, this paper describes the results of an experiment investigating and comparing three input techniques (finger-based direct touch, direct stylus, and indirect mouse as a performance baseline) across three different types of low-level pointing activity (traditional target acquisition via 'tapping', drag-based target acquisition, and radial dragging as required by pie menus (Callahan et al., 1988; Kurtenbach et al., 1993)).

We analysed tap and drag interactions because they are elemental and although they have been comprehensively studied with indirect pointing devices (e.g., Gillan et al. (1990), Kabbash et al. (1993), and MacKenzie et al. (1991)) there has been very little analysis of their performance in touch-based computing. We also analysed radial dragging, which is important for four reasons. First, it has been noted that radial controls such as pie menus are well suited to direct input techniques (Kurtenbach and Buxton, 1991), such as touch or stylus. Second, radial selections normally use a directional dragging action, and consequently they provide a platform for examining how contact with the display surface can influence dragging in different directions. Third, the basic human factors of radial pointing with any form of input device are not well understood (Ahlström et al., 2010). This is surprising given that radial 'pie menus' (Callahan et al., 1988) and gestural 'marking menus' (Kurtenbach and Buxton, 1993; Kurtenbach et al., 1993) have been evaluated and refined for more than two decades. Fourth, radial marking menus facilitate a natural transition from novice to expert use (Kurtenbach and Buxton, 1993), and they are therefore increasingly deployed in high end software systems (e.g., Autodesk Maya and computer games).

The two main contributions of this paper are as follows:

We demonstrate that the comparative efficiency of finger, stylus and mouse input depends on the pointing task. In particular, we show that the finger is slower than the stylus or mouse in dragging and radial dragging tasks (probably due to its susceptibility to surface friction). Although slow for dragging, we confirm prior results showing that the finger is the fastest (but least accurate) technique for tapping tasks.

We provide the first comprehensive analysis of human performance in radial dragging. Prior studies have examined radial gestures with marking menus, but there has been little analysis of radial selections where the users' actions are guided by visual feedback. Our results show that radial dragging selection time and movement distance are linear functions of the number of items, and we demonstrate that selection time is modelled by an interesting case of the Steering Law (where tunnel width increases with distance) rather than by Fitts' Law. We also provide insights into the relative performance of the different input devices in radial dragging, including the observation that finger selections are particularly slow and error prone when moving to targets in a North-West direction, probably due to a tendency for the finger to stick–slip when moving co-linearly in the direction it points.

The next section presents related work on direct input devices and on radial selections. We then present our experimental method and results, followed by a discussion and conclusions.

2. Related work

Target acquisition with a pointing device is an elemental activity in most graphical user interfaces. It is therefore unsurprising that human performance in target acquisition has been closely scrutinised, partly because several key parameters combine to produce an extremely large space for empirical analysis. These parameters include the following: *pointing directness*—the presence or absence of a physical separation between the input device and the object being selected (e.g., Forlines and Balakrishnan, 2008; Forlines et al., 2007; Sasangohar et al., 2009); *selection metaphor,* such as tapping/pressing on the object (Balakrishnan, 2004; MacKenzie, 1991; Ren and Moriya, 2000), dragging over it (MacKenzie et al., 1991), crossing its boundary (Accot and Zhai, 2002; Forlines and Balakrishnan, 2008), directional movements (Callahan et al., 1988; Fitzmaurice et al., 2003), and gesture (Kurtenbach and Buxton, 1993; Kurtenbach et al., 1993); *input device,* such as mouse, trackball, joystick, trackpad, stylus, touch, etc.; *control-display gain*, which is the nature of the mapping from control stimulus to output effect in indirect pointing (Casiez et al., 2008); and *target properties and feedback effects,* such as particularly small targets (Benko et al., 2006) and their feedback (Cockburn and Brewster, 2005; Cockburn and Brock, 2006), and target aware versus target agnostic pointing metaphors (Grossman and Balakrishnan, 2005; Ramos et al., 2007).

This section reviews prior work on target acquisition, focusing on the key issues addressed in this paper: first, performance comparisons across input devices; second, studies of radial interfaces.

2.1. Comparisons across input devices and input styles

Fitts' (1954) seminal experiments investigating the human motor system involved participants using a hand-held stylus to directly tap on targets of controlled width (W) and separation amplitude (A), yielding a strong linear relationship between target acquisition time and the logarithm of the ratio of amplitude to width. Many subsequent studies (e.g., MacKenzie (1992) and Balakrishnan (2004)) have also confirmed that the relationship holds for *indirect* pointing where there is a physical separation between input device and display. Typically, the Shannon formulation (MacKenzie, 1991) of Fitts' Law is used to express the relationship as $T = a + b \times \log_2 (A/W+1)$. While Fitts' Law models the acquisition of discrete targets, Accot and Zhai's (1997) Steering Law models movement time through a constrained path of length A that is composed of arbitrarily short straight segments s of width $W(s)$ as follows:

$$T = b\int_0^A \delta s / W(s)$$

In an early study, Mack and Lang (1989) compared mouse, direct stylus, finger-touch, and keyboard interaction using tasks that involved compound interactions, such as comparing two documents across windows. They concluded that the stylus was significantly faster than the keyboard, similar to the mouse, and slightly faster than direct touch, and that there were accuracy problems with finger pointing. The fast performance of the stylus was confirmed by MacKenzie et al. (1991) who scrutinised pointing tasks across mouse, indirect stylus, and trackball devices. Their results showed that the stylus and mouse performed similarly, and that the trackball was much slower and more error prone. Kabbash et al. (1993) replicated the method, adding a factor for preferred and non-preferred hand, producing similar results to the previous study, and showing that the preferred hand is superior for precise targeting activities.

Mack and Lang's (1989) study used *direct* stylus input while MacKenzie et al. (1991) used an *indirect* stylus (a Wacom digitising tablet). A recent study by Forlines and Balakrishnan (2008) investigated the impact that pointing directness has on performance, comparing indirect versus direct stylus pointing, finding that the two modes are essentially equivalent for pointing activities, but that direct input outperforms indirect for *crossing* activities. Crossing selections are distinct from both pointing and dragging activities because selections are completed by dragging across the item's boundary rather than with an explicit action over the item (e.g. button release or lift off). Forlines and Balakrishnan's (2008) study builds on earlier work investigating different selection modalities for touch (Potter et al., 1988) and stylus (Ren and Moriya, 2000) interactions, which examined various terminating states for touch based selections, including first-contact, slide-over, lift-off, and so on. In general, selection modalities performed better when they allowed users to hit the surface before sliding into the target, then lifting off to confirm the selection.

Sasangohar et al. (2009) recently compared finger touch and mouse performance in a Fitts' Law bidirectional tapping task, finding that finger touch was generally faster, but less accurate than the mouse, particularly with small targets. Their analysis followed up an earlier study by Forlines et al. (2007), which suggested that touch outperforms the mouse for bimanual tabletop interaction, but that the mouse may be more appropriate than touch for interactions requiring a selection point. Finger accuracy problems were also noted by Lee and Zhai (2009) in their comparison of finger and stylus pointing on mobile devices using various feedback cues. They also observed that the finger was slightly slower than the stylus when audio and tactile feedback were absent, but that there was no performance difference when either of these feedback modalities were present.

Dragging interactions have received relatively little attention, which is surprising for two reasons: first, dragging is an important and elemental interaction, and second, friction differences are likely to have a major impact on performance with different devices (e.g., mouse, stylus, and finger). MacKenzie et al. (1991) conducted one of the few comparative analyses of how dragging performance is influenced by input device, examining mouse, trackball and indirect stylus (a Wacom Tablet). Their results showed dragging to be slower than pointing, and that performance degraded more between pointing and dragging with the mouse than with the stylus or trackball. The only prior study of finger-touch dragging (that we are aware of) is that of Forlines et al. (2007), which included performance comparisons of the mouse and finger in a composite task that required tapping from a circular starting target to a square intermediate target, then dragging the square until it 'docked' with a terminating third target (also square). The terminating state for the dragging activity was automatically detected when the centre of the dragged square was within 5 pixels of other's centre. Their results showed that touch was faster than the mouse for tapping tasks, but slower for docking activities.

Forlines et al.'s (2007) experiment provides important insights into touch based dragging. Like all experiments, however, the specific method selected gives rise to certain threats to validity. First, all dragging actions required a high level of precision (within 5 pixels), regardless of the target's size. Second, the completion of dragging actions was automatically detected (within the 5 pixel offset), which is atypical of real actions where the user explicitly lifts from the surface to complete the drag. These experimental decisions lead to concerns that the results may not generalise to typical desktop dragging actions where the cursor needs to be enclosed by the target to complete the dragging action and where the user explicitly terminates the action. (These concerns are addressed by the design of our study described below.)

Table 1 summarises these studies, showing how various projects have compared across different aspects of target acquisition performance using different input devices and selection styles.

While touch-based dragging has been only lightly studied, the 'fat finger' problem of precise target acquisition in finger interactions have been reported in many studies (Albinsson and Zhai, 2003; Mack and Lang, 1989; Potter et al., 1988). This has led to a variety of design solutions based on offsetting the cursor from the finger (e.g., Potter et al. (1988)), zooming (e.g., Roudaut et al. (2008) and Olwal and Feiner (2003)), bimanual interaction (e.g., Benko et al. (2006)), and on-screen widgets that provide large controls for precise positioning (e.g., Albinsson and Zhai (2003)).

Table 1
Studies comparing performance across different input devices.

Style	Study	Trackball	Mouse	Stylus Indirect	Stylus Direct	Finger
Desktop tasks	Mack and Lang (1989)		⟷		⟷	⟷
Tap	Sasangohar *et al.* (2009)		⟷			⟷
	Lee and Zhai (2009)				⟷	⟷
Tap & Cross	Forlines & Balakrishnan (2008)			⟷	⟷	
Tap & Drag	MacKenzie *et al.* (1991) Kabbash *et al.* (1993)	⟷	⟷	⟷		
	Forlines *et al.* (2007)		⟷			⟷
Tap, Drag, Radial-drag	Study reported here		⟷		⟷	⟷

2.2. *Radial interfaces and studies*

Arranging command alternatives like segments of a circular pie that is centred on the cursor's location has important theoretical performance advantages over traditional linear menu arrangement. First, target items can be specified with very small directional movements—rather than moving over a series of intervening candidate items to reach the target, all items are accessible just off the circle's centre, resulting in a very small Fitts' Law amplitude of movement. Second, the effective width of each item increases the further the user moves from the circle centre, allowing users flexibility in their speed/accuracy considerations—for example, when travelling on a bumpy road the user can move further into the segments to create wider targets, something that is not necessary when comfortably seated at a desk. Third, radial menus facilitate a natural progression from novice to expert performance—while novices can rely on visual feedback to guide their directional selections, experts can exploit muscle memory to make rapid gestural selections by flicking in the appropriate direction.

Callahan et al. (1988) provide the first empirical evaluation of performance with radial selections using a pie menu, demonstrating a 15–20% performance advantage over traditional linear menus. Kurtenbach et al. (1993) extended pie menus into 'marking menus' by allowing experts to select items with directional gestures that preempt the pie menu's visual display. Their primary interest was in understanding upper performance levels for experts, including hierarchical layouts (Kurtenbach and Buxton, 1993; Kurtenbach and Buxton, 1994). Note that radial selections with marking menus require a dragging action regardless of input device—when issued via a touch sensitive surface lifting the finger or device completes the action, and when executed with a mouse, releasing the mouse button completes the action. If marking menu selections were completed with discrete taps (one to initiate the selection, and another to terminate it) software would be unable to accurately discriminate between two rapid but different item selections and one continuous marking menu selection.

Enticed by the natural transition from novice to expert performance, and by the potential for high performance ceilings, many subsequent researchers have extended and refined radial menu designs in many different contexts. These include supporting eyes-free menu selections with 'earPod' (Zhao et al., 2007), focus+context zooming designs (Huot and Lecolinet, 2006), hierarchical designs (Francone et al., 2009) for long lists on mobile devices, designs that increase the breadth of the command vocabulary by using directional deviations at the end of gestural strokes (Bailly et al., 2008), variants specifically designed for bimanual use (Benko et al., 2006), and designs that remain visibly ready-to-hand by tracking the cursor (Fitzmaurice et al., 2003).

Although researchers have closely examined expert gestural selections and have extensively explored the design space of radial menus, there is a surprising lack of low-level performance analysis into how users point or drag to radial targets. The only study we are aware of is our earlier work (Ahlström et al., 2010), which used radial menus as an exemplar design for testing a performance model. In that paper we made a passing observation that radial selections appeared to deviate from Fitts' Law, but we noted that our experimental method allowed two explanations for the deviation—in our experiment radial menu diameter increased with number of items, so either the diameter or the number of items (or a combination) caused the effect. The experiment described in this paper removes this ambiguity.

3. Experiment

The experiment is designed to characterise the relative merits of different input devices (mouse, direct-stylus, and finger) for different types of elemental pointing activities (selecting targets by tapping, dragging, and radial dragging). Tapping tasks are included as a critical performance baseline. Dragging is included because it is an elemental interaction that has received little attention in prior research. The study by Forlines et al. (2007) (described in Section 2.1) is an important exception, but their method required high precision (5 pixel accuracy) and used automatic detection of completion, both of which are unusual in desktop interaction. Radial dragging is analysed because it is a special case of drag-based interaction (in which drag direction is a critical factor) and because human performance in radial acquisition is not well understood.

The experiment used a within-subjects design, with all participants using all three input devices and all pointing tasks. Each participant completed the radial dragging tasks in one experimental session, and then returned the following week to complete a second session analysing tapping and dragging tasks. We used this separation of sessions because candidate participants expressed a strong preference for two shorter sessions of intense target selections rather than a single long one, and as we had no intention to compare radial performance with tap/drag there was little reason to ignore their preference.

Each experimental session lasted approximately 30 min.

3.1. Apparatus and participants

The mouse and stylus tasks were completed using an HP Compaq 2710p Tablet PC with a 12.1 in. display set to its native resolution of 1280×800 pixels (see Fig. 1a). Mouse input was received through a cordless laser mouse (Logitech MX610) and stylus input was achieved using the actively tracked stylus, which had a hover detection range of approximately 15 mm. When used with the mouse, the screen was folded up (as shown in Fig. 1a), and when used with stylus input the screen was folded down into tablet mode, with the device resting on the table to give a horizontal input surface.

Finger input tasks were performed using a HP TouchSmart 600 PC with a 23 in. display set to its native resolution of 1920×1080 pixels. It was horizontally placed on a table to provide comfortable finger based interaction (Fig. 1b).

To enable performance comparisons across the differently sized hardware platforms, the physical sizes of all targets were controlled to match across conditions. For example, the radius of all radial menus was 8 cm, regardless of hardware platform (as shown in Fig. 1a and b).

To minimise the impact of different system feedback across input device (mouse, stylus, and finger) the same cursor representation was used with all conditions: a traditional white 'arrow' cursor, pointing in the 11 o'clock direction. With the finger, however, the system registered contact point is approximately centred in the middle of the finger, which occludes the cursor. For finger tapping tasks, in which selections were completed by touching the display surface, the system registered contact point was used and the cursor location was not modified. For finger dragging and radial selections, however, the displayed cursor location was dynamically adjusted 6.6 mm West and 10.6 mm North of the system-registered contact point (see Fig. 2). This adjustment was carried out after pilot studies showed cursor occlusion to be a major limiting factor in performance during finger dragging and finger radial selections.

Eighteen volunteers (six female) aged 21–59 years (mean 31.33 years, s.d. 9.54) participated in the experiment. All participants used a computer and mouse on a daily basis. None reported using a stylus computer or touchscreens more than "a few" times. All participants were right handed.

3.2. Method

The experiment consisted of two sessions for each participant: one for radial dragging and another for bidirectional tapping/dragging tasks completed the following week. The method for tapping and dragging tasks is described first, followed by the radial dragging method.

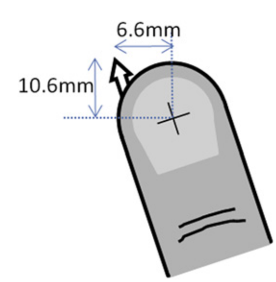

Fig. 2. Adjustment to the cursor location, as used with Finger input in the dragging and radial dragging conditions.

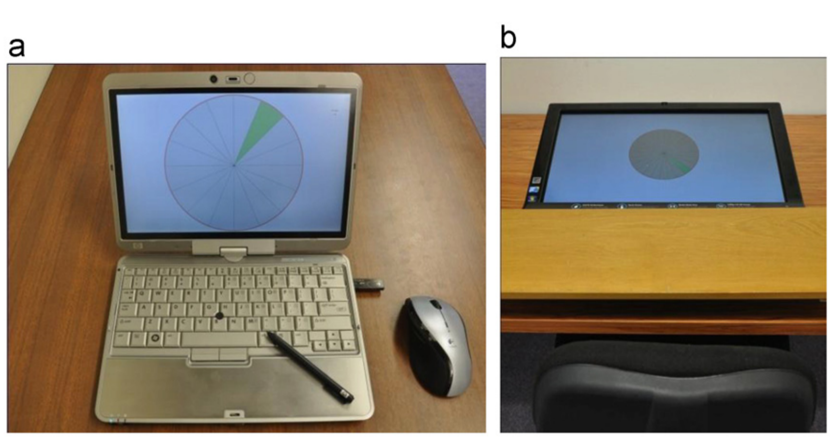

Fig. 1. Hardware apparatus. (a) HP Compaq 2710p and (b) Horizonal HP TouchSmart 600.

3.2.1. Tapping and dragging

Tapping and dragging performance were analysed using a one-dimensional pointing task, consisting of horizontal movement between initial and target locations shown on the screen as vertical bars that extended to the screen height (see Fig. 3). Tapping selections were initiated and terminated by tapping the surface or clicking the mouse button—between taps the stylus/finger was off the surface, and with the mouse, its button was released. Timing began when the finger/stylus was lifted from the display surface or when the mouse button was released, and timing stopped when the finger/stylus/mouse-button was next released (completing a second tap). Dragging tasks were initiated by pressing the mouse button or touching the surface, and terminated by releasing the button or lifting off the surface—the stylus/finger remained in contact with the surface during movement between initial and target regions, and with the mouse its button was held down. Drag timing began when the cursor exited the initial region, and terminated when the finger/stylus/mouse-button was released. Trials that were terminated outside the target bar were logged as errors and were re-cued until successfully completed.

Each trial proceeded as follows. The initial and target bars were both displayed on the screen, with the initial location blue, the target green, and the area between them pink. The participant then moved the cursor over the initial region and pressed the mouse button or made contact with the display surface and remained stationary for a one second timeout period. While stationary over the initial region a green halo was shown around it (Fig. 3), indicating that the within-region state was attained, and that the timeout had not expired. When the timeout expired, the halo disappeared and the pink shading between the initial and target region was replaced with a white background. This indicated that the participant could begin the trial when ready. There was no feedback to indicate that the cursor was over the target except for the collocation of the cursor and the target. When completing tapping tasks with the finger, there was no cursor while the finger was off the surface. Similarly, there was no cursor feedback with the stylus when the stylus tip was more than 15 mm from the display surface. We decided to not provide target-highlighting feedback of the over-target state for either tapping or dragging tasks following pilot studies. The preliminary studies suggested that such feedback differently influences tapping and dragging. When tapping, pilot study participants did not use the feedback, and instead treated the selecting tap as a single discrete action (rather than waiting for feedback to confirm the over-target state prior to release). With dragging, however, pilot study participants appeared to rely on the visual feedback prior to release. As we intended to compare mechanical performance between tapping and dragging we removed over-target feedback from both conditions. For similar reasons of facilitating comparison between mechanical aspects of tap and drag selections, we chose to not show the dragged item moving with the cursor. Participants were trained in this procedure using a practice block of eight selections (four leftward, four rightward). Practice blocks were used before each combination of input device and interaction type (tap or drag). Half of the participants completed all dragging trials with the three input devices before proceeding to tapping tasks, and the other half completed tapping trials first. Each participant used the same input device order for tapping and dragging tasks, but this order was balanced across participants using an incomplete Latin Square.

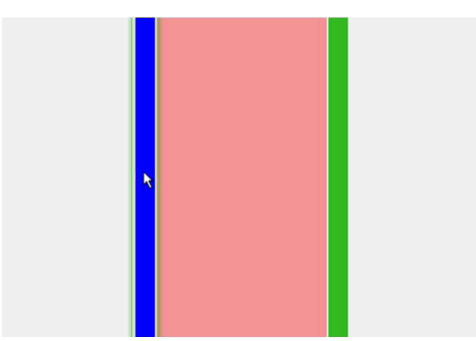

Fig. 3. A tapping or dragging task. Participants remained stationary over the initial region until a timeout expired, at which point the colour of the inter-target region changed from pink to white. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The experimental tasks were administered in seven blocks of eight selections each (four to the left, four to the right). All trials within each block used the same width and amplitude of movement to give seven levels of Fitts' Law index of difficulty, from 2.32 bits (width $W=12.5$ mm, amplitude $A=50$ mm) to 5.36 bits ($W=5$ mm, $A=200$ mm), created from three levels of width (5, 12.5, and 20 mm) and four levels of distance (50, 100, 150, and 200 mm), uncrossed. Table 2 shows the combinations of A and W used to give the seven levels of index of difficulty. The order of exposure to the seven levels of index of difficulty was randomised.

In summary, the tapping and dragging data consisted of:

18 participants ×
3 input devices ∈ {*mouse, finger, stylus*} ×
2 interaction types ∈ {*tap, drag*} ×
7 indexes of difficulty ∈ {*2.32, 2.58, 3.09, 3.46, 4.09, 4.95, and 5.36 bits*} ×
2 target directions ∈ {*left, right*} ×
4 repetitions = 6048 correct trials.

3.2.2. Radial dragging

Radial dragging performance was analysed using a similar method to that of tapping and dragging, described above. However, instead of seven levels of index of difficulty there were seven different numbers of radial

Table 2
Widths and distances used for the seven levels of index of difficulty.

Width (mm)	12.5	20	20	5	12.5	5	5
Distance (mm)	50	100	150	50	200	150	200
ID (bits)	**2.32**	**2.58**	**3.09**	**3.46**	**4.09**	**4.95**	**5.36**

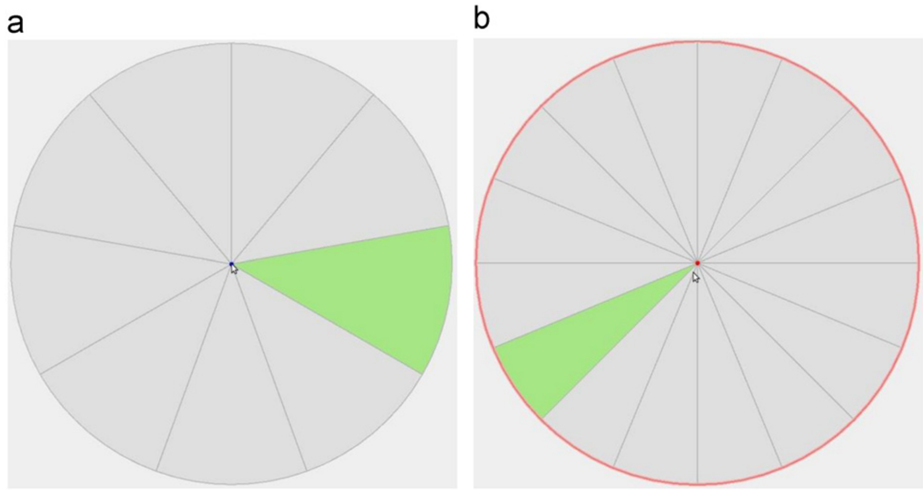

Fig. 4. Visual states during radial selections (a) target preview and (b) premature movement. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

items (2, 4, 9, 16, 25, 36, and 49 items). Also, instead of two directions (left and right), we analysed selection performance across four directional quadrants (North to East, East to South, South to West, and West to North).

Each experimental trial proceeded as follows. Participants initially moved over a small blue square (2×2 mm^2) shown at the centre of the screen, and pressed the mouse button or made contact with the surface using the finger/stylus. This displayed a 16 cm diameter dark grey radial menu, with a small (2 mm diameter) blue centre circle, and a green target item (Fig. 4a). After remaining stationary over the centre circle for 1 s, the dark grey colour was removed, indicating that the user could drag to select the item. The stationary timeout period was intended to assure that the participants had visually identified their target before beginning movement. Timing began when the cursor left the centre circle, and terminated with the lift-off selection (regardless of correct item selection). Moving outside the blue centre circle before the timeout expired resulted in red highlighting around the radial menu, indicating the need to re-enter the centre region (Fig. 4b). Participants were familiarised with this procedure by completing 12 selections using a 16 item radial menu before completing experimental trials with each of the three input devices.

Note that the targeting movement was completed with a dragging action: the mouse button remained down, and the stylus/finger remained in contact with the display throughout the movement. Consequently, these radial selections can be considered to be a special case of dragging. Other radial selection modalities are possible, such as tap-to-post followed by tap-to-select, but we selected drag-based movement because it is consistent with marking menu designs, where novices target radial items with a visually guided dragging action and experts use a directional 'flick' in contact with the display surface (or mouse button depressed). The risks of generalising our results to other radial selection modalities are discussed in Section 5.3.1.

All participants completed seven blocks of trials with all three input devices (mouse, finger and stylus; order balanced using a Latin square). All blocks with one input device were completed before moving on to the next. One block was used for each number of items (2, 4, 9, 16, 25, 36, and 49 items; random order), and each block consisted of 24 selections—six selections in each of the four directional quadrants. Failed trials (incorrect item selected or a selection outside the radial menu) were logged and re-queued at a random position among the unfinished trials within the running block.

In summary, the radial selections consisted of:

18 participants ×
3 input devices ∈ {*mouse, finger, stylus*} ×
7 numbers of items ∈ {*2, 4, 9, 16, 25, 36, and 49 items*} ×
4 target directions ∈ {*NE, SE, SW, NW*} ×
6 repetitions = 9072 correct trials.

4. Results

The results are presented in the order Tapping, Dragging, and Radial Dragging. In each case the primary analyses concern error rate and error-free target acquisition time. Direction (East versus West) had no significant effect on results for tapping and dragging, so in these cases we collapse across levels of the factor for brevity.

4.1. Tapping

Data from one of the participants was discarded due to equipment failure (affecting only the tapping trials). The remaining data is analysed using a 3×7 repeated measures Analysis of Variance (ANOVA) for factors *input device* and *index of difficulty*.

4.1.1. Error rate

The overall error rate was 5.2%, but it was not evenly distributed across input device. There was a 6.8% error rate with the finger, 3.1% with the mouse, and 2.2% with the stylus, giving a significant main effect of input *device* ($F_{2,32}=16.3$, $p<.001$). There was also a significant effect of *index of difficulty* ($F_{6,96}=9.8$, $p<.001$) due to errors increasing with harder targets (from 0.87% with large and close targets to 8.3% with small distant ones). Finally, there was a significant *device* × *difficulty* interaction ($F_{12,192}=5.5$, $p<.001$), best explained by the contrast between a relatively constant error rate with the mouse across index of difficulty, versus an abrupt increase with the finger. These results are summarised in Fig. 5a.

Fig. 5a shows that the finger was particularly inaccurate (error rates of 13–14%) at index of difficulty levels 3.46, 4.94, and 5.36. Table 2 explains this finding, revealing that only these levels used the smallest sized targets, with $W=5$ mm. The 'fat finger' problem is clearly evident with 5mm targets, yet many touch activated controls on mobile devices are much smaller.

Fig. 5a also shows an error spike with the stylus (8.4%) with the highest level of index of difficulty. Further experiments are needed to examine the reliability of this effect, but the spike suggests that acquiring distant small targets with the stylus is error prone, while acquiring near small targets is not. We suspect this is due to problems of parallax when observing the correspondence between stylus tip and cursor location—the parallax displacement is small when the target is near the eye, but larger when the target is distant and therefore viewed from a more oblique angle. Similar effects were observed by Forlines et al. (2007) with distant finger-based selections.

4.1.2. Target acquisition time

The overall mean selection time (errors removed) was 730 ms (s.d. 299). The finger (mean 572 ms, s.d. 213) was substantially faster than the stylus (mean 751, s.d. 337) and mouse (mean 866, s.d. 207), giving a significant main effect of *device*: $F_{2,32}=14.9$, $p<.001$. As expected, there was a significant main effect of *index of difficulty* ($F_{6,96}=98.6$, $p<.001$), with the increase in task time across levels of the factor summarised in Fig. 5b. As suggested by the nearly parallel regression models in Fig. 5b, there was no *device* × *difficulty* interaction ($F_{12,192}=0.5$, $p=0.92$). As expected, Fitts' Law models for the tapping tasks are good, with R^2 values of 0.97, 0.97, and 0.99 with stylus, finger, and mouse, respectively (also shown in Fig. 5b).

4.2. Dragging

Error and timing data for the 18 participants are examined using a 3 × 7 repeated measures ANOVA for factors *input device* and *index of difficulty*.

4.2.1. Error rate

Overall, there was a smaller proportion of dragging errors (1.6%) than tapping errors (5.2%). This is best explained by the availability of continual feedback with the finger, as in finger-dragging tasks the offset cursor could be used to confirm the over-target state (in tapping tasks the finger occluded the cursor, so finger selections were completed without visual feedback). There was no significant difference between mean error rates with the different input *devices* ($F_{2,34}=0.8$, $p=0.46$), at 1.0%, 1.4%, and 1.7% with the finger, mouse, and stylus, respectively (see Fig. 6a). The presence of continual guiding feedback to assist accuracy also explains the absence of significant differences across levels of *index of difficulty* ($F_{6,102}=1.27$, $p=0.28$). Finally, there was no *device* × *difficulty* interaction ($F_{12,204}=1.34$, $p=0.2$).

4.2.2. Target acquisition time

Like tapping tasks, there was a significant main effect of *input device* ($F_{2,34}=14.1$, $p<.001$), but the relative performance of the devices is in a different order to tapping, with the stylus fastest (mean 728 ms, s.d. 283), followed by the mouse (mean 838 ms, s.d. 250) and the finger slowest (mean 922 ms, s.d. 360). There was also a significant main effect of *index of difficulty* ($F_{6,102}=202.7$, $p<.001$), and a significant *device* × *difficulty* interaction ($F_{12,204}=3.28$, $p<.001$). As Fig. 6b shows, the interaction is best explained by the mouse performing relatively poorly with low index of difficulty targets (large, near ones), but relatively well with hard ones (far and small targets). Fitts' Law models with all three devices are good ($R^2 \geq 0.98$).

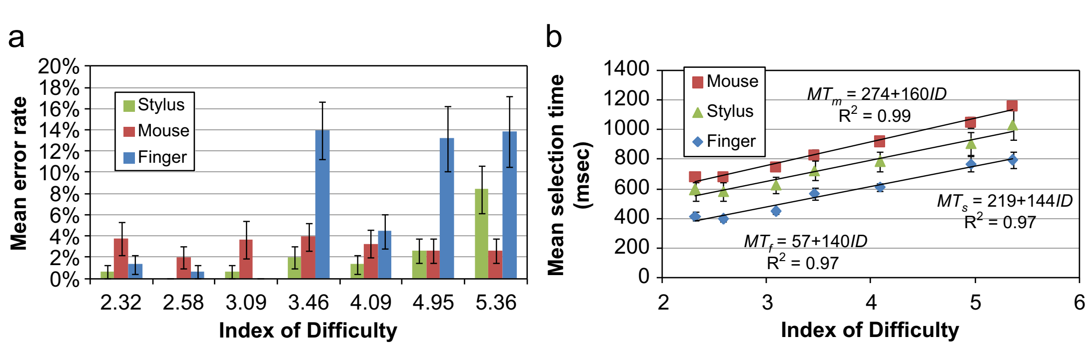

Fig. 5. Tapping task results for the three devices across index of difficulty. Percentage error rates (left) and mean acquisition times (right, including linear regression models). Error bars show ±1 standard error of the mean. (a) Error rate and (b) selection time.

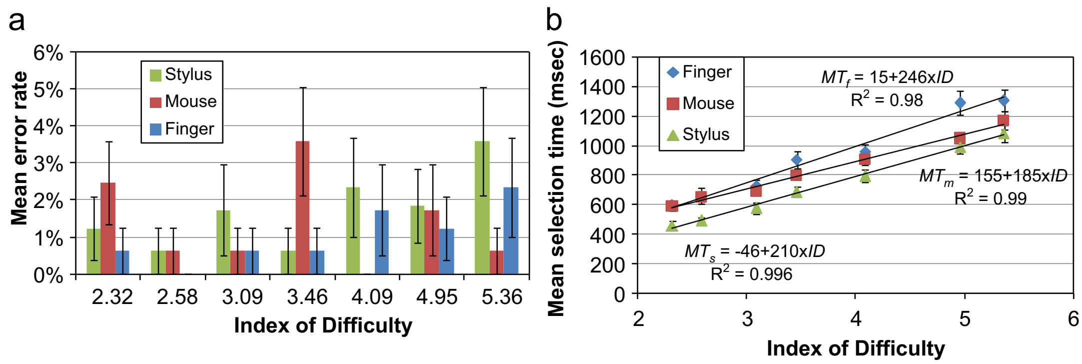

Fig. 6. Dragging results for the three devices across index of difficulty. Percentage error rates (left) and mean acquisition times (right, including linear regression models). Error bars show ± 1 standard error of the mean. (a) Error rate and (b) selection time.

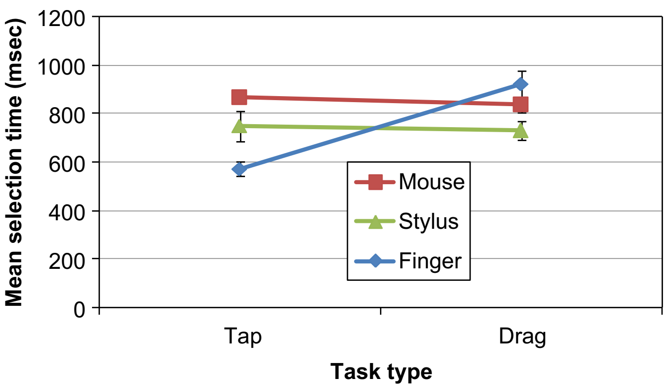

Fig. 7. Mean selection time for the three input devices across tapping and dragging tasks. Error bars show ± 1 standard error of the mean.

4.3. Summary of tapping and dragging, and comparison across tasks

In summary, tapping trials were relatively inaccurate, particularly with the finger. Two factors explain the finger's inaccuracy with tapping. First, there was no system feedback about the location of the finger prior to completing selections by tapping the screen. This is unlike selections with the stylus and mouse, where the cursor is dynamically displayed throughout the pointing activity, so the user can confirm the over-target state before completing the action. Second, the 'fat finger' problem (see related work) means that the finger is a large and relatively crude pointing device for small targets.

There is an interesting finding that the relative efficiency of the different devices depends on the task type: for example, the finger was fastest in tapping tasks but slowest with dragging. To scrutinise this relative efficiency difference we conducted an additional 3×2 repeated measures ANOVA for the three *devices* and for the two *task types* (tapping or dragging). The results are summarised in Fig. 7. It shows that the mouse and stylus perform similarly across tasks, while performance with the finger degrades substantially between tapping and dragging (giving a significant *device* $\times$ *task* interaction; $F_{2,32}=31.4$, $p<.001$).

4.4. Radial selections

Error, timing, and movement data for the 18 participants are examined using a $3 \times 4 \times 6$ repeated measures ANOVA for factors *input device* (finger, stylus and mouse), *quadrant* (target item located in the North East, SE, SW, or NW quadrant of the radial menu), and *number of items* (4, 9, 16, 25, 36, and 49 items). Data for two-item radial menus are also reported, but are not included in the analysis of variance as two-item radial menus do not support four quadrants. The dependent measures were: percentage of trials that included an error, and selection time.

As noted in the Related Work section, there has been little work on performance models and characterizations of radial dragging. Therefore, in addition to error rates and acquisition times, we also analyse radial dragging movement characteristics and performance models.

4.4.1. Error rate

The overall error rate was a low 2.3% of trials. There was a significant main effect of *input device* ($F_{2,34}=5.9$, $p<.01$), with the stylus being the most inaccurate device (mean 3.4%), followed by the finger (2.0%) and mouse (1.4%). As expected, there was a significant effect of *number of items* ($F_{5,85}=13.7$, $p<.001$), with errors increasing from 0.4% with 2 items to 4.9% with 49 items (Fig. 8a). More surprisingly, there was also a significant effect of *quadrant* ($F_{3,51}=5.0$, $p<.005$), with many more errors when selecting items in the North Western quadrant. Fig. 8b shows this effect, with the stylus and finger showing marked increases in errors for the NW quadrant. Fig. 8b suggests that the mouse is less heavily influenced by errors across quadrants than the other two devices, but this is not supported by a *device* $\times$ *quadrant* interaction: $F_{6,102}=1.8$, $p=.11$. However, Fig. 8a confirms a significant *device* $\times$ *number of items* interaction ($F_{10,170}=2.2$, $p<.05$), which can be mainly attributed to errors increasing more slowly across number of items with the mouse than with the finger or stylus.

4.4.2. Target acquisition time

The overall mean selection time for radial menu selections was low, at 554 ms (s.d., 328). ANOVA showed a significant

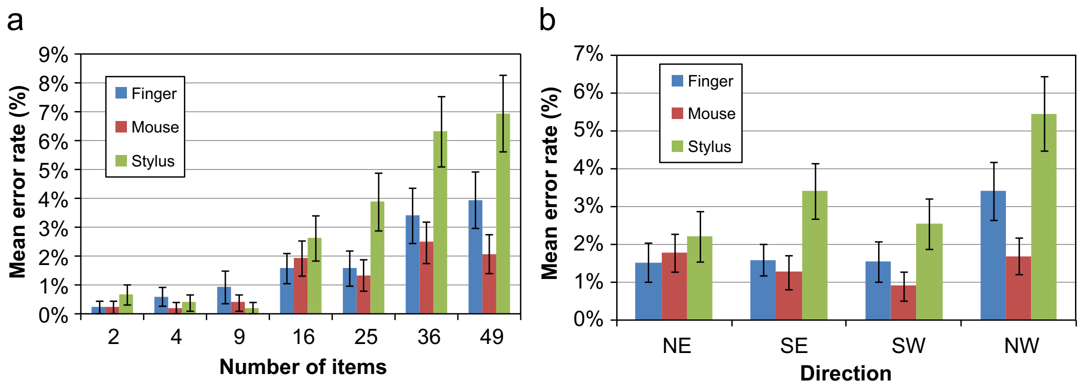

Fig. 8. Radial selection error rates with the three devices across number of items (left) and across directional quadrant (right). (a) Error rate by number of items and (b) error rate by direction.

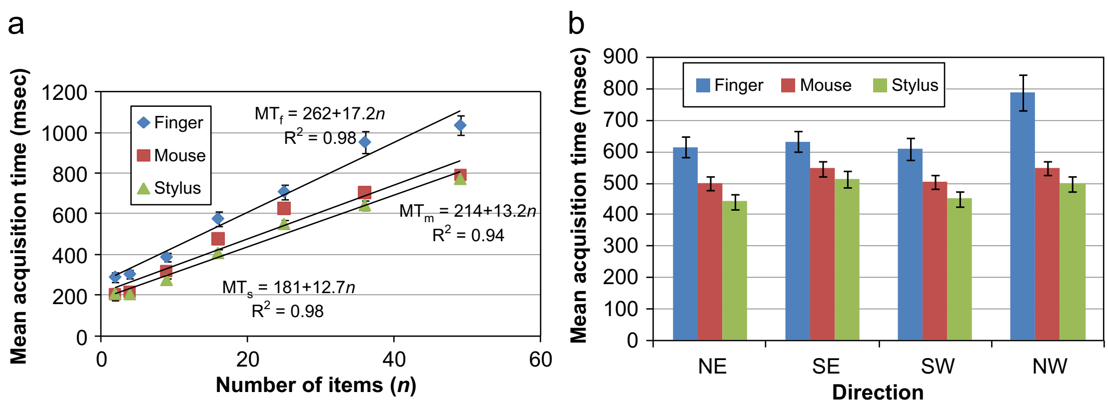

Fig. 9. Radial selection times with the three techniques across number of items (left, including linear best fit models) and directional quadrant (right) in the radial menu. (a) Time by number of items and (b) time by direction.

main effect of *input device* ($F_{2,34}=13.9$, $p<.001$), with the stylus fastest (476 ms, s.d. 259), followed by the mouse (525 ms, s.d. 241), and finger slowest (662 ms, s.d. 424). This is the same overall performance trend as dragging (stylus, followed by mouse and finger), which is unsurprising given that radial selections were completed with a dragging action. As expected, there was a significant effect of *number of items* ($F_{5,85}=191.8$, $p<.001$), with acquisition time increasing linearly with the number of items in the radial menu (all R^2 values ≥ 0.94). This data is summarised in Fig. 9a.

There was also a significant effect of *quadrant* ($F_{3,51}=13.6$, $p<.001$), with mean performance slowest in the NW quadrant (mean 612, s.d., 410) and fastest in the NE (518, 291). However, this effect is most strongly attributed to the particularly poor performance of the finger in the NW quadrant, which is also the main cause of a significant *device* × *quadrant* interaction ($F_{6,102}=5.5$, $p<.001$), as shown in Fig. 9b.

4.4.3. Movement distance

Radial target acquisition is unusual in that users have partial control over the width of their targets—by moving further from the menu centre, users can enlarge the target's effective width. How far do users choose to move with menus containing differing numbers of items, and is movement distance influenced by input device? To answer these questions, we analysed movement distance (from menu centre to point of selection completion) using the same 3 × 4 × 6 RM-ANOVA as used for error rate and selection time.

The mean movement distance was highest with the finger (mean 19.6 mm, s.d. 12.2), followed by the mouse (14.6 mm, s.d. 7.4) and stylus (10.8 mm, s.d. 5.5), giving a significant main effect of *device*: $F_{2,34}=17.2$, $p<.001$. Movement distance increased linearly with the number of items in the menu (see Fig. 10a), with strong linear coefficients of determination ($R^2 \geq 0.96$) for each of the devices. A significant *device* × *number of items* interaction ($F_{10,85}=52.8$, $p<.001$) is evident in Fig. 10a, with finger movement distance increasing more rapidly across number of items than mouse or stylus.

Finally, there was a significant main effect of *quadrant* ($F_{3,51}=11.8$, $p<.001$) and a significant *device* × *quadrant* interaction ($F_{6,102}=4.2$, $p<.005$), as shown in Fig. 10b. Both of these effects are best attributed to the relatively short movements in the SE quadrant with the finger. Potential explanations for these findings are discussed in Section 5.2.

4.4.4. Modelling radial target acquisition

Is radial target acquisition best characterised as a pointing activity (modelled by Fitts' Law), a steering activity (modelling by the Steering Law), or neither? To

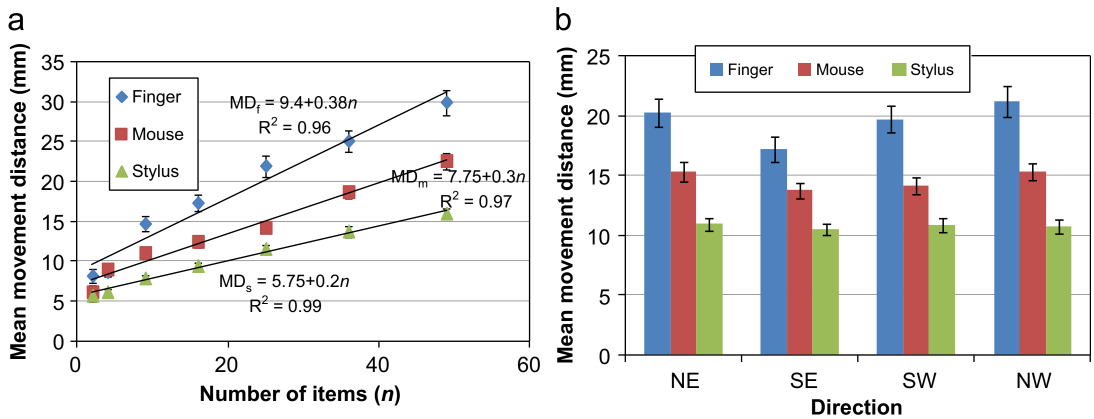

Fig. 10. Radial movement distances with the three techniques across number of items (left, including linear best fit models) and directional quadrant (right) in the radial menu. (a) Distance by number of items and (b) distance by direction.

answer this question we adapted the equations for Fitts' Law and the Steering Law to radial selections, as follows.

4.4.4.1. Radial Fitts' Law. Fitts' Law predicts that target acquisition movement time is a linear function of the logarithm of the ratio of movement amplitude to width

$$MT_{fitts} = a + b\log_2\left(\frac{A}{W} + 1\right)$$

where a and b are empirically derived intercept and slope constants. In radial selections, the ratio of amplitude to width is a trigonometric function of the number of items, n, in the radial menu (since the width of the pie segment increases as the user moves further from the centre). Consequently, in radial selections, Fitts' Law predictions can be rewritten as

$$MT_{fitts} = a + b\log_2\left(\frac{1}{2}\cot\left(\frac{\pi}{n}\right) + 1\right).$$

As the cotangent of π/n rapidly asymptotes to a linear function of n (for $n > 2$), the Fitts' Law prediction for radial selections is essentially a logarithmic function of the number of radial menu items. Fig. 11 shows the prediction trend across increasing values of n, using arbitrary values for a and b ($a = 100$ ms and $b = 500$ ms).

4.4.4.2. Radial Steering Law. Using the Steering Law (Accot and Zhai, 1997), radial menu selection time can be predicted by treating each selection as being comprised of a sequence of N straight tunnels, each of length $s_{i+1} - s_i$, and width $W(s_i)$

$$MT_{steer} = a + \sum_{i=1}^{N} b\frac{s_{i+1} - s_i}{W(s_i)}$$

where a and b are empirically derived intercept and slope constants, respectively. The width of the tunnel for any movement distance N from the menu centre can be calculated as a function of the tangent of the number of

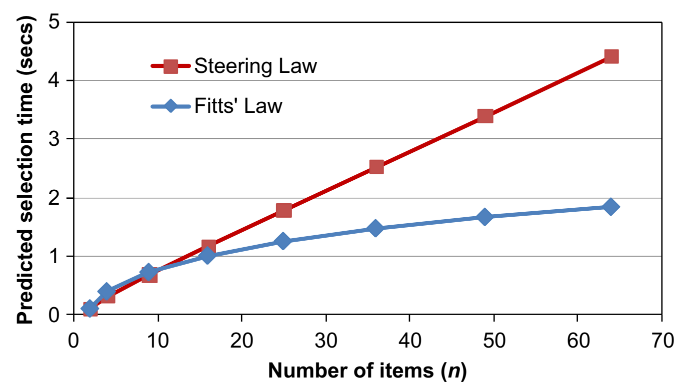

Fig. 11. Fitts' Law and Steering Law prediction trends across increasing numbers of radial menu items. The predicted values are based on arbitrary intercept and slope values. The Fitts' Law prediction is predominantly a log function of n, while the Steering Law prediction is predominantly a linear function of n.

items (n) in the menu

$$W(s_i) = 2N\tan\left(\frac{\pi}{n}\right).$$

Substituting this width value into the Steering Law equation for MT, for any value of N resolves to

$$MT_{steer} = a + \frac{b}{2}H_N\cot\left(\frac{\pi}{n}\right)$$

where H_N is the Nth harmonic number (a constant). For any fixed movement distance, this function predicts that movement time asymptotes to a linear function of the number of menu items. A prediction across n for 50 pixel movements is shown in Fig. 11, using arbitrary slope constants $a = b = 100$ ms.

As Fig. 9a shows, linear regression models of the actual mean acquisition times from the experiment against number of items were particularly strong with the finger and stylus (both $R^2 = 0.98$), and slightly less strong with the mouse ($R^2 = 0.94$). Logarithmic regression models were weaker in all three cases (0.88, 0.88, and 0.93 with the finger, stylus, and mouse, respectively).

Consequently, the regression models suggest that radial dragging is better modelled as a Steering activity than as Fitts' Law pointing. Although this may have been unsurprising with the benefit of empirical hindsight, prior to the empirical analysis the authors had differing opinions about which model would hold and rational arguments in support of their differing views.

5. Discussion

In summary, finger input was the fastest method for tapping tasks, but the slowest for dragging and radial selections. Finger selections were also error prone when tapping on the small (5 mm) targets. The comparatively large finger size in contrast to the small target size (the 'fat finger' problem) partially explains the high error rate with small targets, but data from the dragging condition shows that users can achieve good finger accuracy rates with small targets when they can adjust their selections in response to system feedback (in this case, a cursor, as shown in Fig. 2). Finger radial selections were slower for targets located in the NW quadrant of the radial menu, which we discuss further below.

The stylus was the fastest input device for dragging and radial selections, and the second fastest for tapping selections. Somewhat surprisingly, it had the lowest mean error rate in tapping selections, but the highest in radial selections. Stylus errors in radial selections also increased more rapidly across number of items than they did with the mouse and finger. This rapid increase in stylus error rates across number of items is possibly caused by a tendency to complete selections by extending and contracting the fingers rather than moving the forearm to reposition the hand. This explanation is supported by Fig. 10a, which shows that stylus selections were completed with comparatively short movements away from radial menu centres (roughly half the distance of the finger movements). Consequently, participants were completing their selections at a low level of target width and making associated errors. Further experimentation is required to confirm this explanation. Radial selection errors with the stylus were particularly pronounced when moving towards the NW quadrant, which we discuss in Section 5.2.

A final result worth summarising is that radial selections are best modelled using the Steering Law (rather than Fitts' Law), treating the selection movement as a constrained tunnel where the width of the tunnel increases as a function of the amplitude of movement.

5.1. Comparison with prior findings

Sasangohar et al. (2009) compared tapping performance between direct finger touch input and a mouse. They report that movement times ranged from 403 ms to 1051 ms using touch and from 607 ms to 1323 ms using the mouse, giving a 33% performance benefit for the finger with low index of difficulty tasks and a 26% benefit in high difficulty tasks. These results support our findings for the finger and mouse comparison in tapping tasks, where the finger's performance benefit over the mouse ranged from 39% (low difficulty) to 32% (high difficulty). Sasangohar et al. (2009) also reported that the error rate with the finger (mean 9.8%) was much higher than the mouse (2.1%), which reflects our results (finger mean 6.8%; mouse mean 3.1%).

Lee and Zhai (2009) compared finger and stylus input (via tapping) on mobile devices. Their tasks involved typing a series of ten characters into a mobile phone calculator (e.g., '$1450 \times 9276 =$'), giving a dependent measure of characters input per second. Data from their 'no feedback' Experiment 1 condition (most similar to our own study) showed mean performance with the finger was 2.35 characters per second (equivalent to 426 ms per key) and 2.65 characters per second with the stylus (equivalent to 378 ms per key), giving an 11% performance advantage for the stylus. Our experiment, in contrast, showed a 24% performance advantage for the finger over the stylus. The difference in results between these studies is most likely to stem from the divergent experimental methods, with three particular points of difference: first, their study involved a series of button presses while our acquisitions were discretely cued; second, Lee and Zhai's (2009) target layout left no space between targets (which may have elevated the perceived need for precise finger movement) while ours were well separated; third, and most importantly, our timing analysis removed erroneous trials (separately analysing errors and error-free performance), while Lee and Zhai's analysis included error correction within the overall time data for the typing task. Both our study and Lee and Zhai's showed much higher error rates with the finger than stylus for tapping tasks.

MacKenzie et al.'s (1991) analysis of tapping and dragging tasks with the mouse, indirect stylus and trackball showed that the mouse and stylus performed similarly in tapping tasks, with a slight performance advantage for the stylus over the mouse. Our results show the same slight advantage. One difference between MacKenzie et al.'s (1991) results and our own is that their dragging tasks were completed more slowly than tapping tasks (particularly so with the mouse), while ours were not. This difference across studies warrants further investigation, but we suspect it stems from a major difference in experimental methodology. In MacKenzie et al.'s (1991) study, ten bidirectional trials at the same amplitude and width were completed together, with the completion of one trial automatically initiating the next. Consequently, participants could adapt across the ten repeated trials to the precise motor actions required for the acquisitions. In our experiment, however, blocks of trials at the same A and W value were shorter (four to the left and four to the right) and involved a stationary timeout between each trial. Our methodology may have provided less opportunity for participants' to calibrate their finger, forearm and wrist movement to the same paired targets.

Table 3
Summary of main comparative performance findings: $a < b$ indicates a is faster or less error prone than b.

Activity	Comparative performance	Notes
Tapping		
Time	Finger < stylus < mouse	Treatment of errors and target size are important. Finger errors are high with small targets.
Errors	Stylus < mouse < finger	Our analysis removed errors in time analysis while Lee and Zhai (2009) did not, explaining divergent results. High amplitude acquisitions are also likely to increase errors with direct pointing methods due to parallax errors (Forlines et al., 2007).
Dragging		
Time	Stylus < mouse < finger	Note that our method used a displaced cursor from the fingertip (Fig. 2) to reduce the high
Errors	Finger ≈ mouse ≈ stylus	incidence of errors observed with small targets in pilot testing.
Tap versus drag		
Finger	Tap < drag	Finger difference is possibly due to surface friction effects. The similarity of tap and drag tasks
Stylus	Tap ≈ drag	with stylus and mouse diverges from MacKenzie et al.'s (1991) results, which showed tapping
Mouse	Tap ≈ drag	to be faster than dragging with an indirect stylus and mouse.
Radial		
Time	Stylus < mouse < finger	Similar to dragging
Errors	Mouse < finger < stylus	Indicating a speed/accuracy trade off with the stylus due to short movement distances (Fig. 10b).
Direction	NW direction particularly slow with finger and inaccurate with stylus	Possibly due to stick–slip effects with the finger and effects of finger extension with the stylus.
Model	Steering law	Steering law models radial acquisition times better than Fitts' Law.

Our results mostly support those of Forlines et al. (2007), who analysed mouse and touch tapping and dragging, with the finger being faster for tapping and the mouse faster for dragging. However, several differences in the studies and results are worth noting. First, the smallest targets used in our study were much smaller than those in Forlines et al. (2007) (5 mm versus ~18 mm). Like us, Forlines et al. (2007) note a significant effect of target size, with errors increasing for harder targets, yet our tapping error rates were much lower than theirs. Our finger error rates peak at ~14% with 5 mm targets at 200 mm amplitude compared to theirs at ~40% for ~18 mm targets at 548 mm amplitude. Forlines et al. (2007) included high amplitude selections (up to ~658 mm) because they were specifically interested in tabletop interactions, and they observed that distant finger selections were error prone due to problems with both parallax and finger posture. The differences in our studies mean that while some of our results may not generalise to high amplitude touch interactions, they provide accuracy guidelines for touch interactions with small targets at the amplitudes that can be expected on tablet computers and mobile devices. Furthermore, our dragging results show that users can maintain high levels of touch dragging accuracy, even with small targets, because dragging naturally allows over-target feedback. (Forlines et al. (2007) also showed good touch-dragging accuracy, but errors were only made when users lifted off the surface before the system automatically detected task completion).

Prior studies of radial selections have focussed on analysing gestural marking menu selections or on comparing variants of marking menus with traditional menus (see Section 2.2). There is only one prior study of the pointing component of radial item selection that we are aware of (Ahlström et al., 2010), which included a brief mention of a linear relationship between radial selection time and the number of radial menu items, stating "This is an interesting result that warrants further investigation" (pp. 1376). Our study supports this observation and extends the findings. This study also eliminates the experimental confound reported by Ahlström et al. (2010), which varied radial menu diameter with the number of menu items.

Table 3 summarises the main results and notes points of divergence from prior work.

5.2. Effects of direction in radial selections

The direction of movement in the radial selection tasks had a marked impact on performance with the stylus and finger, but not with the mouse. Figs. 8b and 9b show that finger movements in the north-west direction were more error prone and slower than other directions. We attribute this effect to the tendency for the finger to 'judder' when moving collinearly in the direction the finger naturally points (NW for right-handed users). When moving in the NW direction, friction induces a tendency for the finger to bend. Any bend reduces the angle of friction and consequently increases the force required to overcome the friction according to the angle of friction equation: $\tan\alpha = F/N$, where α is the angle of the finger from vertical, F is the directional friction, and N is the vertically downwards force. This changing friction induces a 'stick–slip' effect, or finger judder. When dragging in directions other than NW, there is much less tendency for the finger to bend as the forces oppose the finger's skeletal structure rather than the extensor muscles. The judder effect has been noted in other touch interaction research such as Moscovich (2009) who states "Specifically, participants cited difficulty sliding their finger upwards on the screen, saying that they felt that their finger would often stick or skip when sliding up'' (pp. 20).

Somewhat surprisingly, the stylus was also much more inaccurate in the NW direction (and a little more inaccurate in the SE direction), as shown in Fig. 8b. We suspect this is due to two musculoskeletal factors. First, to make a NW selection, the fingers can be extended to reach the stylus tip toward the target, but this is an unnatural pen/stylus posture in which precise control is likely to be compromised. Second, to avoid finger extension, users must lift their hand and move their entire forearm to reach the target. This large-scale repositioning is not required for NE and SW targets where wrist flexion and extension can be used.

5.3. Study limitations and opportunities for further work

5.3.1. Selection modality

Stylus and touch interactions can be completed in many ways, including first-contact, slide-over, lift-off, and so on. The performance of these different modalities has been compared in several studies, as outlined in Section 2.1. In our experiment the selection modalities for tapping and dragging tasks were largely dictated by the tasks themselves—for dragging tasks, departure from the starting location and lift-off are the obvious starting and terminating actions; and for tapping tasks there are few logical alternatives to lift off (to initiate and terminate).

Similarly, for radial selections we used the modality that we felt would be the most commonly used design alternative—a dragging action terminated with a lift-off selection. However, other radial selection modalities are also feasible, such as tap-to-post followed by tap-to-select. Further work is needed to determine how a change in radial selection modality would influence the results—for example, a tap-to-post and tap-to-select selection modality should eliminate any stick-slip effect for selections in the NW quadrant.

5.3.2. Impact of feedback in tapping and dragging selections

Current touch input technology does not register the finger's location until it makes contact with the surface. Consequently, our finger-tapping trials provided no cursor feedback during movement through the air. This is unlike the mouse and stylus condition, where the cursor dynamically indicates position throughout the movement (assuming the stylus remains within tracking range on the screen). Much of the inaccuracy observed for the finger with small targets can be attributed to this lack of feedback, as suggested by the relatively low error rate in finger-drag tasks. Also, our experimental method did not provide target highlighting to indicate the over-target state, nor did it show an underlying object moving in response to dragging actions. Further experiments are required to tease out the impact of these feedback effects.

New finger input technologies will remove this limitation. For example, proximity- or camera-based technologies are emerging (e.g., SideSight (Butler et al., 2008)) that will dynamically track finger location off the display surface, and new studies will be required to determine their efficiency.

As well as visual feedback of the cursor's location, many researchers are examining the use of haptic effects to assist in touch-based target acquisition. These include simple clicks and buzzes (Poupyrev and Maruyama, 2003) as well as variable friction effects (Levesque et al., 2011), all of which may improve touch-based target acquisition.

5.3.3. Understanding and controlling the impact of display friction

We have used contact friction with the display surface as an explanation for some of the results, such as the slow performance of the finger in dragging tasks, and when targeting radial items located in the NW quadrant. To validate this explanation, further work is needed to either control or measure the level of friction experienced. While new technologies such as variable friction displays (Levesque et al., 2011) allow relative friction levels to be varied (so that users feel increased or decreased friction over particular items) they do not allow control of absolute friction levels due to differences in skin texture and moisture. In further work we intend to measure the level of friction experienced by mounting a touch sensitive device on a force metre.

6. Conclusions

The form factor of computing devices is rapidly expanding beyond traditional desktop computers to include handheld mobile devices, tablets, kiosk touchscreens, and tabletop computing. New pointing methods, particularly direct finger touch, are being deployed to further enrich the user's experience with these devices. We have analysed and compared the performance of three input devices (the mouse, the stylus and the finger) across three different types of target acquisition activity (tapping, dragging, and radial dragging). The results show that the relative performance of these devices is dependent on the task—the finger is fastest for tapping activities (though inaccurate with small targets), but slowest for dragging. The finger was also particularly slow and inaccurate for dragging in the North-West direction, which we attribute to a friction stick–slip effect causing finger judder. While the stylus is fast for dragging activities, it can be inaccurate, particularly for targets in the North-West direction. Finally, we demonstrated that radial target acquisition performance is a linear function of the number of items. We also show that this is predicted by a special case of the Steering Law, where the tunnel width increases with distance, rather than Fitts' Law.

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