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Pointing Device Performance in Steering Tasks

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Abstract

Use of touch-screen-based interactions is growing rapidly. Hence, knowing the maneuvering efficacy of touch screens relative to other pointing devices is of great importance in the context of graphical user interfaces. Movement time, accuracy, and user preferences of four pointing device settings were evaluated on a computer with 14 participants aged 20.1 ± 3.13 years. It was found that, depending on the difficulty of the task, the optimal settings differ for ballistic and visual control tasks. With a touch screen, resting the arm increased movement time for steering tasks. When both performance and comfort are considered, whether to use a mouse or a touch screen for person–computer interaction depends on the steering difficulty. Hence, a input device should be chosen based on the application, and should be optimized to match the graphical user interface.

Keywords

control-display ratio, Fitts' law, index of difficulty, movement time, pointing device, steering law

Introduction

The operation of present day smart devices comprises predominantly tapping and traversing (or steering or maneuvering) movements. These include menu selection (Figure 1), gaming applications, and so on. With the rapid growth of smart devices such as phones, tablets, and the like, the way people operate various devices has somewhat changed because functions are accessed with

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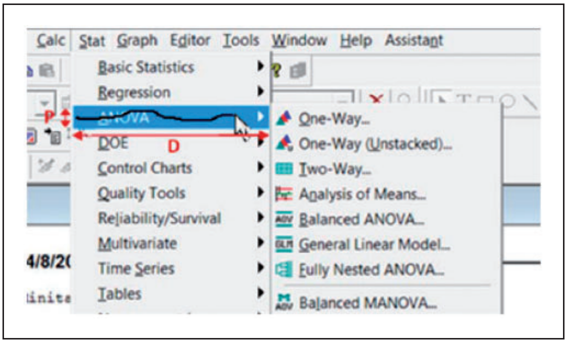

Figure 1. Traversing movements in a graphical user interface submenu.

differing gestures (Bailly, Müller, & Lecolinet, 2012). However, at a more microscopic level, the basic operations are relatively unchanged. For example, a tap of a smart device is equivalent to a left mouse click; tap twice to a double click; a tap-and-hold is equivalent to right mouse click; a one-finger drag on a tablet to select text or for operating scroll bars just like a mouse and so on. So even though the gesture operations and mouse operations are similar at a functional level, the similarities and differences in finger use and mouse use have not received adequate attention.

A significant number of applications exist where the user of a device has to click, drag and click, or click and swipe (Wacom, 2016). Some examples include Tap'n'swipe, a type of new keyboard for Android devices (Android Apps, 2012). This particular feature allows a tap and a swipe or a drag in any available direction to get the necessary characters. It is claimed that this is a faster means of typing than on a "keyboard." Such traversing movements are likely to be more prevalent in other devices in the future (Varcholik, LaViola, & Hughes, 2012).

Although many different types of technology are available, hardly any or very few human performance models exist in relation to such gestural inputs. Fitts' law predicts movement time (MT) to a target such as an icon, given the distance one has to move and the width of the target. Mathematically, MT is proportional to the index of difficulty (ID), which is defined as $\log_2(2 \times \text{distance}$ to target/width of target). Pointing devices and graphical user interfaces (GUIs) should be designed to minimize the ID for a person to efficiently interact with computers. Hence, metrics based on Fitts' law (Fitts, 1954; Guiard & Beaudouin-Lafon, 2004) are used in computer input device evaluations in ISO standards (ISO9241-9, 2000; ISO/TS9241-411, 2012; Soukoreff & MacKenzie, 2004) and other research studies (Chiu et al., 2011; Forline, Wigdor, Shen, & Balakrishnan, 2007; Kvalseth, 1973, 1975; Liu, 2007). However, Fitts' law alone is not sufficient, as some movements such as swiping and traversing when using a computer are within constrained areas or spaces. In these cases, a tracking model is more appropriate. Even though a model for tasks that have targeting and tracking exists (Senanayake, Hoffmann, & Goonetilleke, 2013; Senanayake, Goonetilleke, & Hoffmann, 2015), it has not been used to compare different devices or to assess traversing performance. This study investigated the performance of today's interfaces in steering types of tasks.

Steering tasks in a GUI

Drury (1971) developed a probabilistic model for traversing movements, i.e. travel through a laterally constrained path or tunnel, in terms of each visually controlled submovement. In computer software, traversing can be considered as maneuvering the mouse pointer through a menu (Accot & Zhai, 1999), as shown in Figure 1. The mathematical model for MT is as follows:

$$\mathrm{MT} = a + b\left(\frac{D}{P}\right) = a + b(\mathrm{ID}) \tag{1}$$

where D is the length of the path, P is the width of the path, and ID is a measure of the task difficulty. The reciprocal of coefficient b (Equation 1) is defined as the index of performance (IP), an indicator of the input device efficiency (Accot & Zhai, 1999, 2001). This MT versus ID relationship has been studied in considerable detail (Drury, Barnes, & Daniels, 1975; Goonetilleke & Hoffmann, 2009; Goonetilleke, Hoffmann, & Luximon, 2009; Montazer, Drury, & Karwan, 1988).

Model (1) was verified by Drury (1971) and is known as Drury's law or the steering law (Hoffmann, 2009). The model has been successfully used as a quantitative tool to design and evaluate 3D human–machine interface designs (Accot & Zhai, 1997; Zhai & Woltjer, 2003). Although the model has been validated in various applications, several characteristics of the model are yet to be evaluated (Hoffmann, 2009). The steering law cannot be applied for paths with low ID values (Drury et al., 1975; Drury and Daniels, 1975; Lin, Drury, & Paquet, 2006) where continuous visual control is not required (Hoffmann, 2009). According to Thibbotuwawa, Hoffmann, and Goonetilleke (2012a), the ID ratio has to exceed a value of around 10, if visual control is to be required to remain within the path. For lower ID values, where the control action is made in open-loop mode, Equation 2 will be valid (Thibbotuwawa et al., 2012a). That is, MT is solely dependent only on the distance moved.

$$\mathrm{MT} = c + d\sqrt{D} \tag{2}$$

Effect of device gain on human performance

The control-display (C/D) ratio has a significant effect on human performance in pointing tasks. Gibbs (1962) was the first to study in detail the effects of the C/D ratio of a joystick. Many other researchers (Arnaut & Greenstein, 1990;

Buck, 1980; Jellinek & Card, 1990; Johnsgard, 1994; Koester, LoPresti, & Simpson, 2005; Lin, Radwin, & Vanderheiden, 1992) have also studied the effects of gain and obtained contrasting results, but a comprehensive experiment was reported by Casiez, Vogel, Balakrishnan, and Cockburn (2008) where it was claimed that the relationship between MT and gain follows an "L-shaped" curve.

Even though the effect of device gain (or control–display ratio) on MT, in pointing tasks, has been studied extensively, less is known for steering tasks as pointing and steering are quite different. Fitts' law is applicable for pointing tasks while Drury's law holds for steering tasks. As the two tasks are perceptually different, the effects on MT and error are also different. The majority of studies have focused on just MT alone rather than time, error, and user experience. Accot and Zhai (2001) investigated the scale effects of graphic tablets on steering tasks with ID of 3.57, 6.25, 8.33, 14, 25, and 33. According to Thibbotuwawa, Goonetilleke, and Hoffmann (2012b), tasks with an ID of 3.57 are ballistic and values such as 6.25 and 8.33 are between the ballistic and visual control regions, known as the transition region. Hence, the ID used by Accot and Zhai may be confounded by the type of control, i.e. ballistic or visual control. Another issue is the applicability of their results for optical mice that are used today. This study aims to:

1. Determine the optimum gain for a computer mouse and a touch screen setting for steering tasks or those with lateral constraints.
2. Evaluate the performance differences between the use of a touch screen and that of a computer mouse in a default configuration.

Method

Participants

Fourteen (seven males and seven females) right-handed students with backgrounds in business, social sciences, humanities, and engineering were recruited through announcements in various classes and electronic notice boards at the Hong Kong University of Science and Technology. They were 18 to 30 years ($M \pm SD = 20.1 \pm 3.1$). The participants reported that they had no past record of hand disabilities and had 20/20 corrected vision. All were well versed in computer use with a mean usage of 3.82 ± 1.93 hours per day. Each was compensated with HK$ 50 for their time. Participants took part under the institutional ethical guidelines and were fully informed of the aims of the experiment.

Equipment

A desktop computer with a 2.19 GHz clock rate central processing unit was used for the experiment. Specialized software was developed using C++

programming language on the Windows 8 operating system for the steering task. The program recorded the position of the mouse cursor and the task completion time for each experimental condition. At the same time, the number of attempts to perform each condition without any errors was recorded. An Acer T232HL capacitive touch screen monitor (58.0 cm diagonally) with a screen resolution of 1920×1080 was used. The display can be oriented at 20° and 60° from the horizontal plane (Figure 2(a) and (b)). Though the monitor had a multitouch (multiple fingers input) capability, only single-touch input was used to simulate the ubiquitous condition found today in phones, tablets, and other smart devices.

The other two input devices were a Logitech G9X high precision (5,700 dpi) optical mouse (Figure 2(c)) with the polling rate set to $1{,}000\,s^{-1}$ and a Genius wireless pen mouse (Figure 2(d)) with an 800 dpi setting. The pen mouse has the same technology as a normal optical mouse, but it has a "pen-like" shape and normally held with the fingers. Even though pen mice are not widely used, we wanted to evaluate its performance relative to others, as both use the same

Figure 2. Four device settings (a) Touch screen monitor at 20° that allows resting the forearm on table. (b) Touch screen monitor at 60° (no arm resting was allowed). (c) Logitech mouse. (d) Genius pen mouse.

internal technology even though they are different in shape and size. For the two mice, a Sports Dasher gaming mouse pad was used as the movement surface. A local coordinate system is used by mice while a fixed world coordinate system is used in touch screens.

Accot and Zhai (1999) used a touchpad, trackball, pointing stick, graphics tablet, and mechanical mouse to verify the steering law. Some of these devices are hardly used today. Hence, a touch screen and an optical mouse, ubiquitous in today's technologies, were part of the experiment reported here. The pen mouse was chosen as it is somewhat different, and also because it is somewhat new in the input device market, and not as popular.

In the pilot experiments, it was seen that participants rest their arm when the touch screen display is at a 20°incline and then they generally have to have their arm/hand "floating" when the display is at 60°. Thus, participants had more freedom of movement at the 60° inclination even though that posture required more whole-arm movement. The participants were asked to adopt these postures of resting the arm at 20° and have it floating at the 60° inclination of the display. As viewing angle is not an independent variable in the steering law, the difference between the 20° inclination and the 60° inclination can be considered to be freedom of movement or arm posture.

Experimental design

The seven levels of the independent variable used in the experiment are in Table 1. Each of these settings was presented in random order. Each participant was required to perform a practice task and three repetitions for each setting. There were 48 conditions in the practice task and 22 experimental conditions (Table 2). The practice tasks were identical for all participants. The IDs of

Table 1. The seven experimental settings and the corresponding device.

Setting	Device setting
1	Logitech mouse with gain = 2.3
2	Logitech mouse with gain = 5.0
3	Logitech mouse with gain = 10.0
4	Logitech mouse with gain = 15.0
5	Genius pen mouse with gain = 10.0
6	Touch screen in 20° angle from horizontal (resting the right hand was compulsory)
7	Touch screen in 60° angle from horizontal (resting the right hand was not allowed)

Table 2. The length (*D*) and width (*P*) values (in mm) and the corresponding index of difficulty (ID) values used in experiment.

Condition no.	*D*	*P*	ID = (*D*/*P*)
1	100	100	1
2	80	80	1
3	120	40	3
4	150	50	3
5	120	20	6
6	150	25	6
7	120	15	8
8	160	20	8
9	225	15	15
10	150	10	15
11	200	10	20
12	300	15	20
13	250	10	25
14	300	12	25
15	225	7.5	30
16	150	5	30
17	175	5	35
18	280	8	35
19	200	5	40
20	300	7.5	40
21	225	5	45
22	270	6	45

Note. ID: index of difficulty.

practice tasks ranged from 0.25 to 50 while it was 1 to 45 in the experimental conditions. Ballistic performance was expected at ID values of 1, 3, 6, and 8. Other factors such as path angle and path shape were not investigated as most smart-device swipe movements are in a "horizontal" direction.

Procedure

Participants were asked to adjust the seat height to a comfortable position. A separate calibration was performed for Settings 6 and 7 (Table 1) to ensure that there was no parallax error. A voluntary consent form was signed followed by a verbal and written briefing about the experiment.

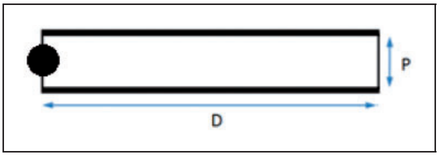

Figure 3. Steering task with path length, *D* and path width, *P*.

A sample image of the track with the measurements of *D* and *P* is shown in Figure 3. The participant was requested to click on the black circle on the left side of the image to start the experiment. If the click was within the circle, it turned green and thereafter the participant was required to steer the cursor through the path and pass the vertical boundary line on the right side as fast as possible without touching or crossing the lateral boundaries. If the cursor touched or crossed the boundary, the condition was considered to be in error and the "failed" segment of the trajectory was shown in red. These erroneous conditions were redone in a random order at the end of each repetition until all conditions were successfully completed. Participants were not allowed to lift the mouse while maneuvering. At the end of the experiment, each participant was asked to rank comfort and "ease of control" of the mouse, pen mouse, and the two settings of the touch screen on a scale of 1 to 4 (where 1 is *least comfortable/difficult to control* and 4 is *most comfortable/easiest to control*).

Analysis

The test condition information, path coordinates, and MT of each participant for each condition were saved in a file. Thereafter, MT and the number of attempts made by each participant in each condition of each repetition were extracted from the saved files. The MT was thereafter analyzed and the optimum mouse gain was determined. Additionally, error rate for each setting was calculated to determine any speed-accuracy trade-offs. Finally, user ratings were analyzed and used together with MT and error rate results to compare the devices that were tested.

Results and discussion

SPSS, Minitab, and Matlab software were used for the statistical analysis and data visualization. The MT was averaged over all three repetitions and 14 participants for each ID in each setting. The number of errors was the average number of unsuccessful attempts in each condition for each device. The user rating for each device was also averaged.

Identifying ballistic and visual control regions

The boundary between the ballistic and visual control regions can be considered to occur at an ID of around 8 to 10 (Thibbotuwawa et al., 2012a). To verify the exact value, linear regression was performed on MT versus $\sqrt{D}$ by adding points from the lowest ID value of 1. The sequential regression resulted in adjusted R^2 values as shown in Figure 4. The plot exhibits two peaks, one at ID = 3 and other at ID = 25. At low values of ID, it is ballistic control and as the difficulty increases, it becomes visual control. Adding points with ID values larger than 5 seems to result in a rapid drop in adjusted R^2. Therefore, the ballistic region can be considered to be those with ID of less than 5. As more and more points are added, the visual control dominates and R^2 starts increasing after an ID of around 10. Thus, IDs of 1 and 3 were considered to be performed ballistically and IDs larger than 15 were considered to be visually controlled with those in between being in the transition region. These limits are in agreement with Drury and Daniels (1975) as well as Thibbotuwawa et al. (2012a). The conditions with IDs 6 and 8 were excluded from further analysis, as they are most likely in the in-between region (called the transition region) of ballistic and visual control. Further study is needed to find the exact values of ID.

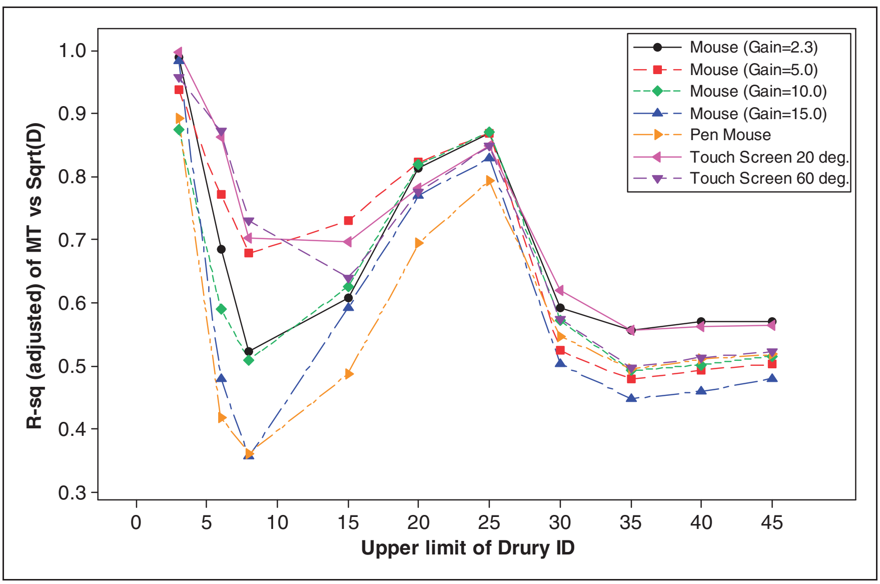

Figure 4. Plot of R^2 (MT vs. $\sqrt{\text{D}}$) with addition of points having higher IDs.
MT: movement time; ID: index of difficulty.

MT analysis

The models that govern MT are different for the two regions (equations (1) and (2)). Thus, the data were analyzed separately for each region (ballistic for IDs of 1 and 3; visual control for IDs larger than 15) for different mouse gains and device settings. All reported repeated measures analysis of variance (ANOVA) results are with the Greehouse–Geisser correction.

MT analysis for differing mouse gains. The random effects model for ballistic tasks was based on gender, gain, $\sqrt{D}$, and repetitions. Gender and repetitions were nonsignificant ($p > .05$) while the other main effects of gain and $\sqrt{D}$ were significant, $F(2.6,\ 30.6) = 27.44$, $p < .001$; $F(1.6,\ 19.7) = 77.95$, $p < .001$. The two-factor and three-factor interactions were nonsignificant ($p > .06$). The MT versus $\sqrt{D}$ relationships for each of the mouse gains are shown in equations (3)–(6) ($R^2 > .87$) and the corresponding plots are in Figure 5.

$$\text{Mouse}\,(\text{gain} = 2.3): \quad \text{MT} = -176.270 + 59.861\sqrt{D};\ \ R^2 = .991 \tag{3}$$

$$\text{Mouse}\,(\text{gain} = 5.0): \quad \text{MT} = -111.010 + 43.843\sqrt{D};\ \ R^2 = .939 \tag{4}$$

$$\text{Mouse}\,(\text{gain} = 10.0): \quad \text{MT} = -14.310 + 31.346\sqrt{D};\ \ R^2 = .875 \tag{5}$$

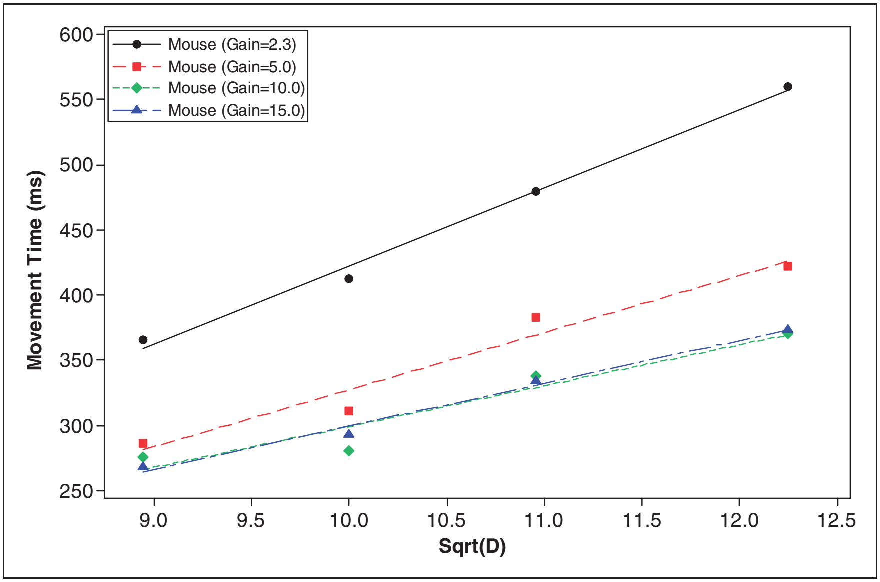

Figure 5. Relationship between MT and $\sqrt{D}$ for data in the ballistic region for various mouse gains. MT: movement time.

$$\text{Mouse (gain} = 15.0): \quad \text{MT} = -29.620 + 32.903\sqrt{D}; \ R^2 = .984 \tag{6}$$

Repeated measures ANOVA for MT of IDs 15 or larger (visual control) was also performed with factors of gender, gain, (D/P), and repetitions. Gender and repetitions were nonsignificant ($p > .05$) while gain and (D/P) were significant, $F(2.2, 26.5) = 9.23$, $p = .001$; $F(1.1, 13.3) = 81.13$, $p < .001$, main effects. The two-factor and three-factor interactions were nonsignificant ($p > .05$). The MT versus ID relationship of each mouse gain for visual control is in Figure 6 and equations (7)–(10) ($R^2 > .99$).

$$\text{Mouse (gain} = 2.3): \quad \text{MT} = 335.270 + 65.384\left(\frac{D}{P}\right); \ R^2 = .991 \tag{7}$$

$$\text{Mouse (gain} = 5.0): \quad \text{MT} = 50.610 + 56.636\left(\frac{D}{P}\right); \ R^2 = .997 \tag{8}$$

$$\text{Mouse (gain} = 10.0): \quad \text{MT} = 79.180 + 51.260\left(\frac{D}{P}\right); \ R^2 = .994 \tag{9}$$

$$\text{Mouse (gain} = 15.0): \quad \text{MT} = -10.79 + 61.733\left(\frac{D}{P}\right); \ R^2 = .994 \tag{10}$$

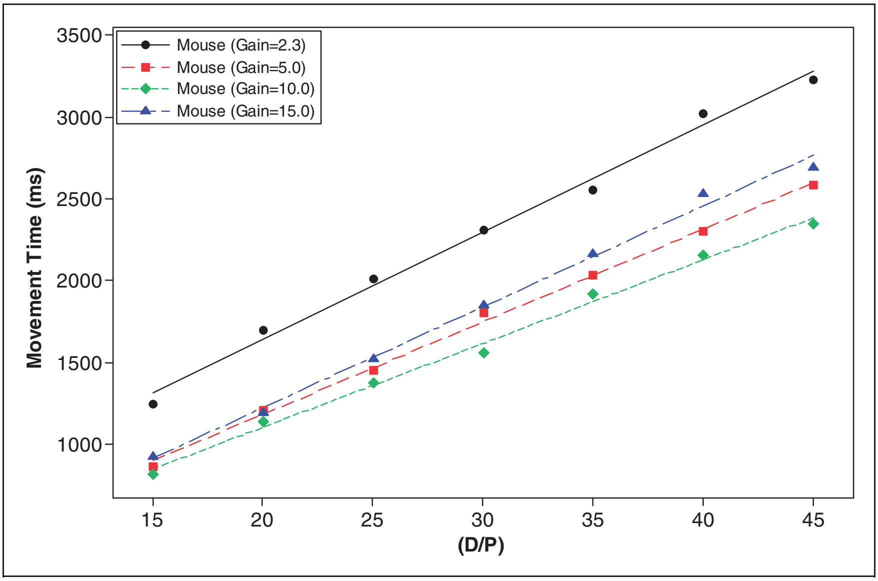

Figure 6. MT vs. (*D*/*P*) of visual control tasks for various mouse gains. MT: movement time.

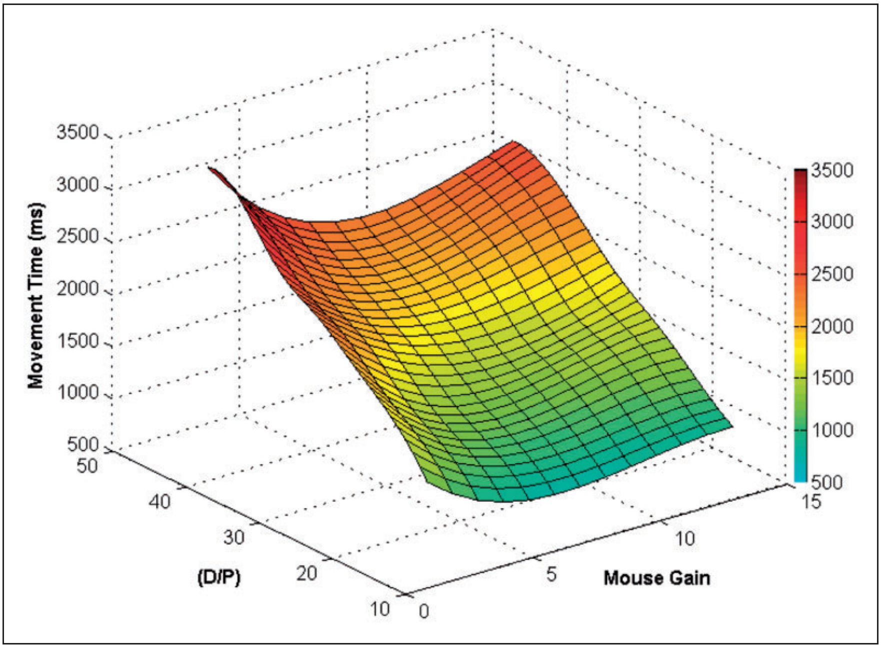

Figure 7. A spline curve for MT vs. (*D/P*) and mouse gain for data in the visual control region. MT: movement time.

It is apparent, from Figures 5 and 6, that performance in ballistic and visual control is different for the differing mouse gains. For example, the MT in visual control tasks at a mouse gain of 15 is higher than that of 10, even though the MT is comparable in ballistic tasks at these two gains. Thus, it is necessary to separate the analysis for the two types of control to get a better understanding of the control strategy.

To see the complete variation of MT with both ID and gain, a 3D-smooth spline (Figure 7) was plotted for the visual control data. MT has an inverted U-shaped variation with mouse gain. Index of performance (IP), the reciprocal of the gradient of equations (7)–(10), was calculated for visual control and the reciprocal of the gradient of equations (3)–(6) for ballistic in units of 1/s. These are the first four entries in Table 3.

Effect of mouse gain. A quadratic function (equation (11), Figure 8) was fitted to determine the relationship between IP and mouse gain for the first four entries in Table 3. Setting the first-order derivative of IP with respect to gain to zero, it was found that IP is maximal at a mouse gain of 12.1 for ballistic tasks and 9.1 for

Table 3. Index of performance (IP), calculated as the reciprocal of gradient for each condition.

	Inverse gradient = IP (1/s)	
Condition	Ballistic	Visual
Mouse (gain 2.3)	16.705	15.294
Mouse (gain 5.0)	22.809	17.657
Mouse (gain 10.0)	31.902	19.508
Mouse (gain 15.0)	30.392	16.199
Pen mouse	12.908	10.030
Touch screen 20°	12.677	17.318
Touch Screen 60°	20.208	22.101

IP: index of performance.

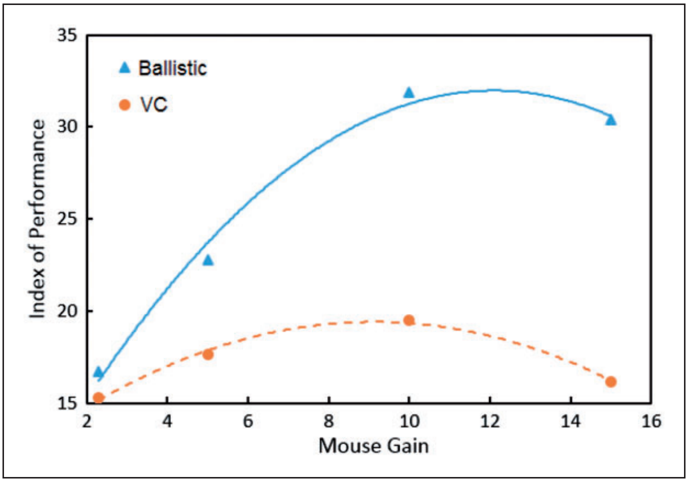

Figure 8. A second-order polynomial fit for index of performance vs. mouse gain curves for the ballistic and VC tasks. VC: visual control.

visually controlled tasks.

$$\mathrm{IP} = \begin{cases} \dfrac{1}{d} = -0.1642(\text{gain})^2 + 3.9712(\text{gain}) + 7.973; & R^2 = .99, \text{ for ballistic} \\ \dfrac{1}{b} = -0.09157(\text{gain})^2 + 1.668(\text{gain}) + 11.83; & R^2 = .97, \text{ for visual control} \end{cases} \tag{11}$$

Accot and Zhai (2001) found that a gain of 2 to 4 maximizes the IP for a graphics tablet. In this study, the mouse gain that maximizes the IP is around 9. The reasons for the difference can be twofold. First, Accot and Zhai did not separate the ballistic and visual control regions and hence their results may be confounded by the two regions. Second, it may be due to the differing type of device that was tested.

MT analysis for different devices. The gain that maximizes IP for ballistic and VC tasks is between 9 and 12 (Figure 8). Hence a mouse gain of 10 was used from the four gain levels to compare the mouse with the other device settings, i.e. pen mouse, touch screen 20°, and touch screen 60° because it is the gain closest to that yielding the highest IP for steering.

A repeated measures ANOVA of MT in ballistic tasks, based on the random effects model with the factors gender, device setting, $\sqrt{D}$, and repetitions indicated that $\sqrt{D}$ and the main effects of the device settings were significant, $F(2.2, 26.4) = 61.59$, $p < .001$; $F(1.3, 15.4) = 67.84$, $p < .001$, whereas gender and repetitions were not significant ($p > .05$). The effects of two-factor and three-factor interactions were not significant ($p > .05$) except $\sqrt{D} \times$ device setting, $F(4.0, 44.3) = 3.25$, $p = .02$. This suggests that some devices perform better over some distances, because different parts of limbs are used with different devices (Accot & Zhai, 2001; Balakrishnan & MacKenzie, 1997). The relationship between MT and $\sqrt{D}$ for the differing device settings is illustrated in Figure 9 and Equations (5) and (12)–(14).

$$\text{Pen mouse}: \quad \text{MT} = -37.200 + 77.470\sqrt{D}; \; R^2 = .892 \tag{12}$$

$$\text{Touch screen } 20^\circ: \quad \text{MT} = -454.100 + 78.884\sqrt{D}; \; R^2 = .997 \tag{13}$$

$$\text{Touch screen } 60^\circ: \quad \text{MT} = -213.640 + 49.485\sqrt{D}; \; R^2 = .957 \tag{14}$$

A repeated measures ANOVA of MT for visual controlled conditions, based on the random effects model with independent variables gender, device setting, (D/P), and repetitions was performed. The main effects (D/P) and device setting were significant, $F(1.2, 14.6) = 93.39$, $p < .001$; $F(1.8, 21.3) = 42.83$, $p < .001$. Gender and repetitions did not show any significant effect on MT ($p > .05$). Similar to ballistic tasks, all two-factor and three-factor interactions were not significant ($p > .05$) except $(D/P) \times$ device setting, $F(4.3, 52.1) = 16.62$, $p < .001$. Again, this may be due to the use of different limb parts with different devices. MT against ID is shown in Figure 10 and fitted lines are represented in equations (9) and (15)–(17). Tukey's *post hoc* analysis indicated that MT for a mouse at a gain of 10 is not significantly different ($p > .05$) to the touch screen at 60° while

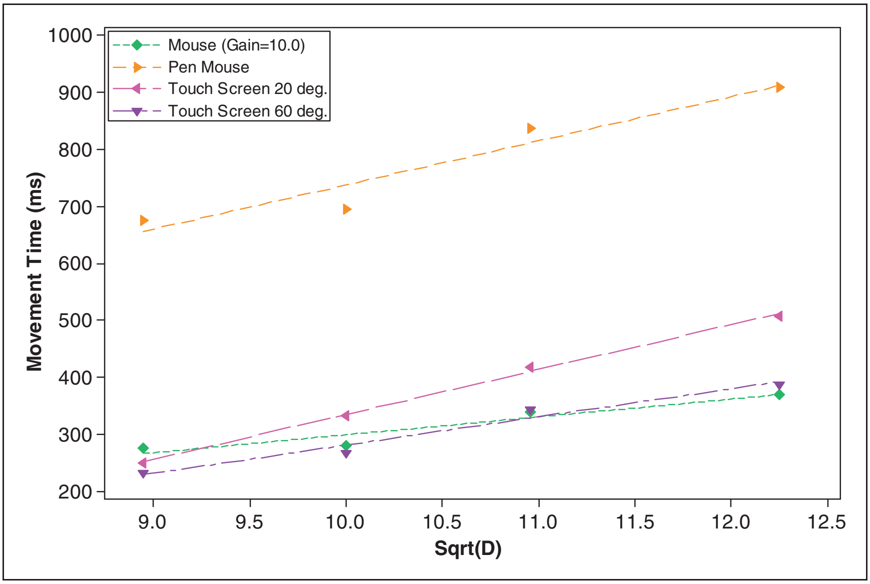

Figure 9. MT vs. $\sqrt{D}$ for differing devices. All data are in the ballistic region.
MT: movement time.

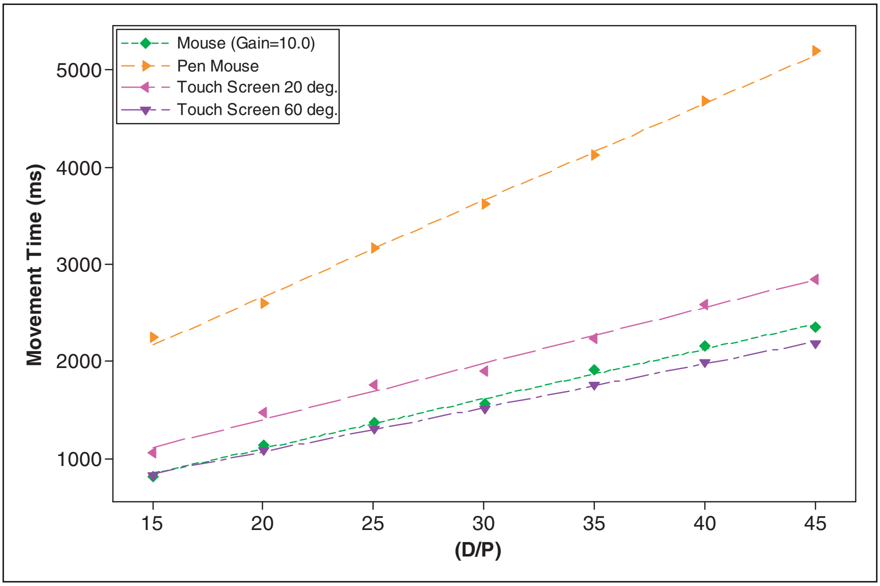

Figure 10. MT vs. (*D*/*P*) in visual control region for differing devices.
MT: movement time.

all others were significantly different from each other ($p < .001$).

$$\text{Pen mouse}: \quad \mathrm{MT} = 672.130 + 99.700\left(\frac{D}{P}\right); \; R^2 = .997 \tag{15}$$

$$\text{Touch screen } 20^\circ: \quad \mathrm{MT} = 248.780 + 57.744\left(\frac{D}{P}\right); \; R^2 = .990 \tag{16}$$

$$\text{Touch screen } 60^\circ: \quad \mathrm{MT} = 168.24 + 45.246\left(\frac{D}{P}\right); \; R^2 = .998 \tag{17}$$

The variance of the IP for points in Figure 9 (var = 81.43) is significantly higher than that of points in Figure 10 (var = 26.91). As IP indicates the sensitivity of a device to the difficulty level of a given task, it may be concluded that the variation of this sensitivity is more pronounced in the ballistic region. Hence, analysis of the two regions should be done separately.

MT comparison of devices. MT comparisons between any two devices are plotted in Figure 11. There is a strong ($R^2 > .98$) relationship in MT between each pair of devices for visual control conditions (equations (18)–(23). When the arm is resting on the table, it is constrained, and the MT is approximately 30% higher than when using the touch screen at 60° for visual control conditions (equation (18)). That is, a free-floating arm results in faster movement relative to a constrained arm even though the former may be more fatiguing in the longer term.

$$\mathrm{MT}_{\text{touch screen } 20^\circ} = 1.297 \times \mathrm{MT}_{\text{touch screen } 60^\circ}; \; R^2 = .994 \tag{18}$$

$$\mathrm{MT}_{\text{touch screen } 20^\circ} = 1.216 \times \mathrm{MT}_{\text{mouse(gain=10.0)}}; \; R^2 = .987 \tag{19}$$

$$\mathrm{MT}_{\text{touch screen } 20^\circ} = 0.543 \times \mathrm{MT}_{\text{pen mouse}}; \; R^2 = .983 \tag{20}$$

$$\mathrm{MT}_{\text{pen mouse}} = 2.385 \times \mathrm{MT}_{\text{touch screen } 60^\circ}; \; R^2 = .986 \tag{21}$$

$$\mathrm{MT}_{\text{pen mouse}} = 2.235 \times \mathrm{MT}_{\text{mouse(gain=10.0)}}; \; R^2 = .963 \tag{22}$$

$$\mathrm{MT}_{\text{mouse(gain=10.0)}} = 1.066 \times \mathrm{MT}_{\text{touch screen } 60^\circ}; \; R^2 = .994 \tag{23}$$

Equation (23) clearly shows that a free-floating arm has a lower MT than one in which the mouse has an optimal gain. This implies that a touch screen without any gain is faster than using a mouse that is set close to its optimal gain.

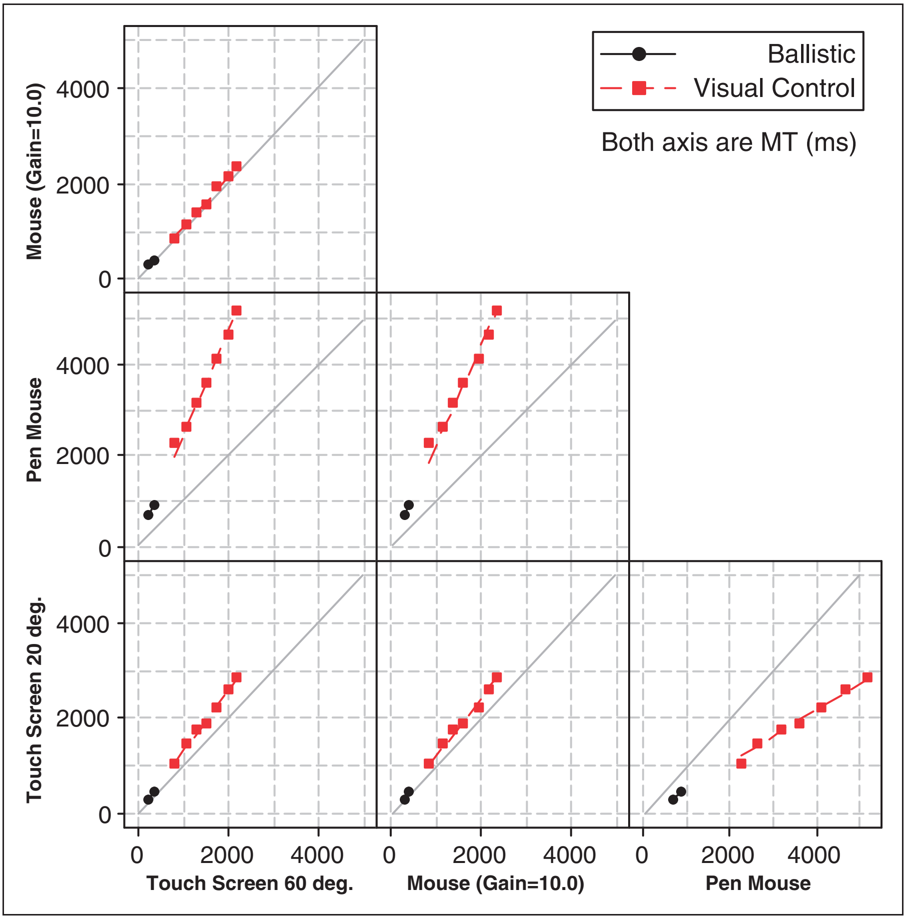

Figure 11. Movement time comparison among devices. Each point in each graph represents MT in ms for a given ID. MT: movement time; ID: index of difficulty.

Cockburn, Ahlström, and Gutwin (2012) found that MT for pointing in touch screens is higher than that of mouse, with the converse holding true for open-space dragging tasks similar to Fitts's task. Unfortunately, Cockburn et al. did not mention the mouse gain they used as the gain has a large effect on MT (Buck, 1980; Casiez et al., 2008). MT is just one user metric. To gain a broader understanding, error and user ratings were analyzed as well.

Errors

The number of incorrect attempts was counted as errors. Repeated measures ANOVA of errors for the model gender, device setting, repetitions, and ID

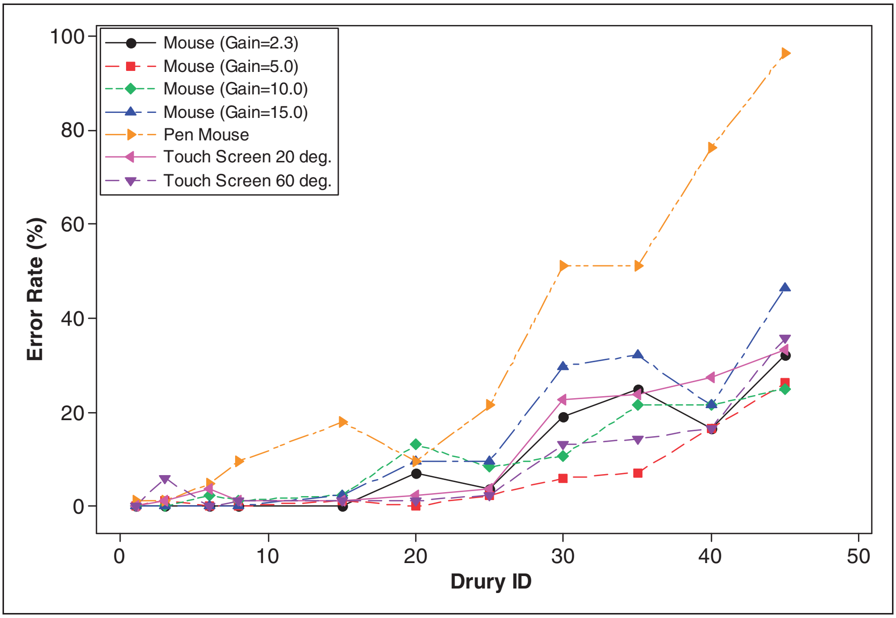

Figure 12. Error rate (%) for each setting against IDs. ID: index of difficulty.

indicated that gender and repetitions were not significant ($p > .05$) while device setting and ID were significant, $F(3.1,\ 37.0) = 24.16$, $p < .001$; $F(2.4,\ 29.2) = 32.76$, $p < .001$. All two-factor and three-factor interactions were not significant ($p > .05$) except device setting × ID, $F(5.5,\ 66.4) = 3.69$, $p = .004$. In general, there is an increasing trend of error rate with increasing ID, with near zero errors in the ballistic region (Figure 12).

Usability ratings

The subjective ratings are shown in Figure 13. The one-way ANOVA of comfort rating for differing devices indicated statistical significance, $F(3,\ 52) = 12.47$, $p < .001$. Tukey's *post hoc* tests indicated that mouse, pen mouse, and touch screen 20° can be categorized into one group and touch screen 60° (free hand) into another group.

Device was a significant factor, $F(3,\ 52) = 31.76$, $p < .001$, for ease of control. Tukey's *post hoc* tests showed that ease of control ratings for the two touch screen angles can be grouped together while mouse and pen mouse are two separate groups. This implies that resting the hand has no significant effect on ease of control.

A comparison between error rate and IP is shown in Figure 14. Performance and user ratings for all settings are tabulated in Table 4. Even though the pen

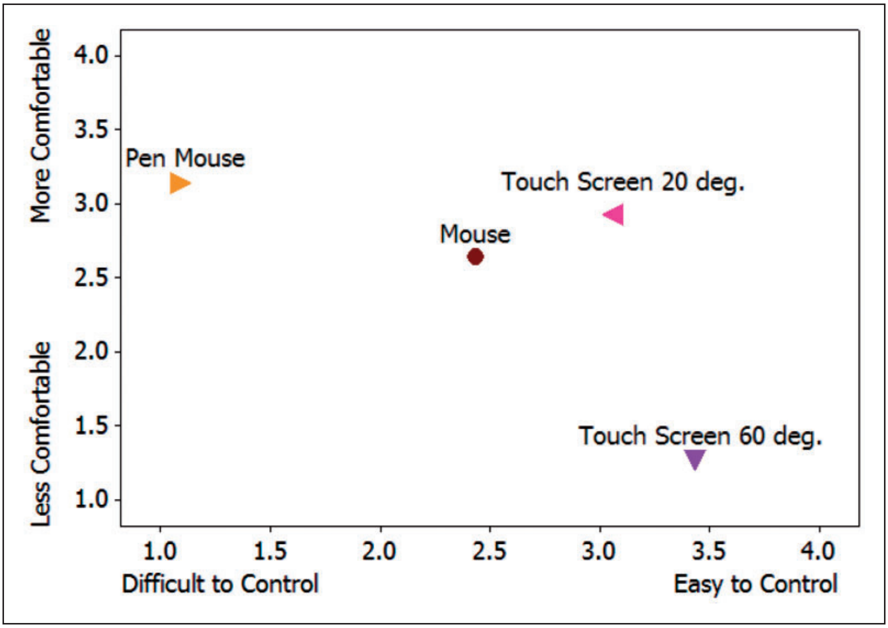

Figure 13. Mean user ratings.

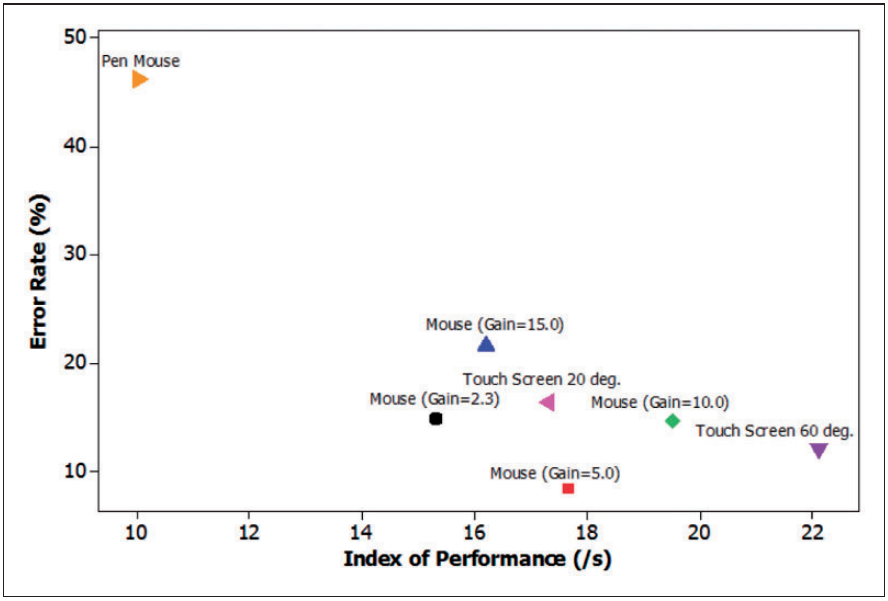

Figure 14. Mean error rate versus index of performance for visual control tasks.

Table 4. Index of performance, error rate, and user ratings in each condition.

Setting	IP (s^{-1})	Error rate (%)	User rating	
			Comfort	Ease of control
Mouse (gain 2.3)	15.294	14.796	2.643	2.429
Mouse (gain 5.0)	17.657	8.503		
Mouse (gain 10.0)	19.508	14.626		
Mouse (gain 15.0)	16.199	21.599		
Pen mouse	10.030	46.259	3.143	1.071
Touch screen 20°	17.318	16.327	2.929	3.071
Touch screen 60°	22.101	12.075	1.286	3.429

IP: index of performance.

mouse is comfortable because of its *pen-like* shape, its poor usability is shown by the lowest IP, highest error rate, and low controllability. Touch screen has the highest IP and ease of control. Error rates in touch screen are comparable to minimum error rates of the mouse. Comfort is lowered when the arm is free. However, in real-life situations, it is unlikely that a user will have a continuous set of tasks where no breaks can be taken. Hence, the lower comfort rating is not that much of a concern.

A principal component analysis was performed for data in Table 4. The first two components (equations (24) and (25)) explain 81.9% and 12.9% of the total variance, respectively (Eigenvalues were 3.28 and 0.52).

$$PC_1 = -0.537(\text{IP}) + 0.486(\text{error rate}) + 0.449(\text{comfort}) - 0.524(\text{ease of control}) \tag{24}$$

$$PC_2 = 0.002(\text{IP}) - 0.595(\text{error rate}) + 0.794(\text{comfort}) + 0.126(\text{ease of control}) \tag{25}$$

Based on the bi-plot given in Figure 15 and the correlation matrix given in Table 5, ease of control and IP have a high correlation. For present-day interfaces, ease of control and IP have a negative correlation with error rate and comfort. A high ease of control level can be associated with a low error rate but a high ease of control level will have a lower comfort indicating that more work is needed on the design of appropriate pointing devices for various tasks.

To summarize, the efficacies of four pointing devices (a computer mouse, a pen-shaped computer mouse, and a touch screen at two inclinations) were determined as MT and accuracy for a set of computer-based steering tasks. The gain that maximizes the IP in a computer mouse, for steering tasks,

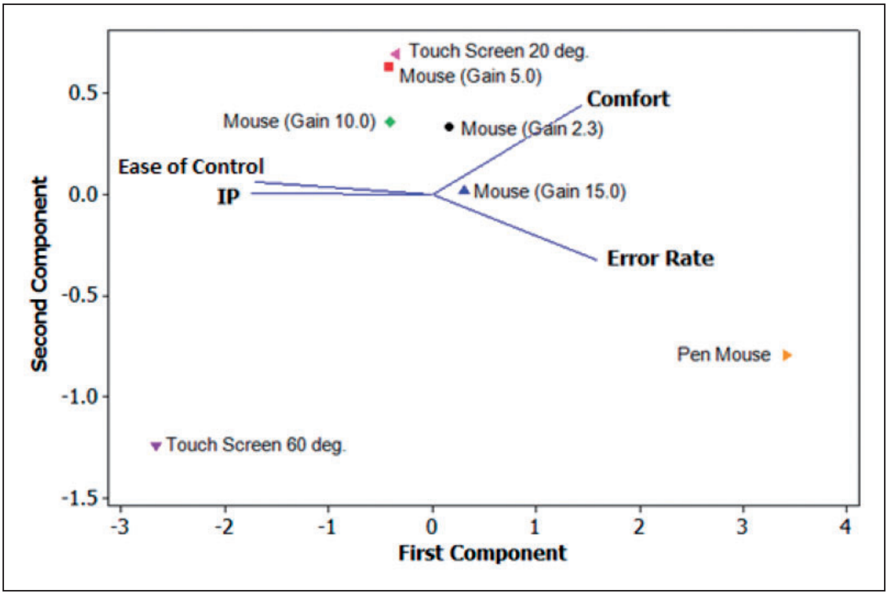

Figure 15. Bi-plot for principal component analysis.

Table 5. Intercorrelation matrix among variables.

	Index of performance	Error rate	Comfort
Error rate	$R = -.84$, $p = .02$		
Comfort	$R = -.77$, $p = .04$	$R = .50$, $p = .26$	
Ease of control	$R = .89$, $p = .007$	$R = -.82$, $p = .02$	$R = -.70$, $p = .08$

is around 9 for visual control tasks and 12 for ballistic tasks. The touch screen at a 60° inclination had a MT similar to the mouse at a gain of 10, and hence it is not surprising that touch interfaces are gaining popularity for easier and faster performance. Resting the limb increases MT, and it has no advantage in terms of an increase in ease of control level.

When error rate, comfort, and ease of control are considered in addition to MT, the selection between a mouse and a touch screen depends on the task difficulty. Thus, each device has its own advantages and disadvantages. Hence, the optimal input device should be chosen based on what is needed and how it needs to be used. For example, if error rate is a vital factor in a particular application, then it is advisable to avoid using the pen mouse. Choosing a device is a trade-off between performance and comfort and there is a strong need to develop devices that can perform best in all metrics. Nevertheless, as differing factors dominate the various devices that are available, it may be possible to have an option in GUIs to use a preconfigured setting on the most appropriate device for any given application, even though it may not be optimal.

In this study, only horizontal paths were evaluated. Performance may vary depending on the angle of the path and the shape of the path (Accot & Zhai, 2001; Thibbotuwawa et al., 2012b) Also, people are used to touch screens on small-sized devices such as phones and tablets. In this experiment, a full sized touch screen monitor was used. Even though the operation was straightforward, the participants may not have been able to perform at their best performance on the large touch screen. So there is a possibility that performance on a touch screen can be much better than what was found in the experiment. Furthermore, this experiment was rather well-controlled. Hence, it is necessary to also evaluate the ecological validity when a person interacts with real-world computer applications.

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