Human Performance Evaluation of a Finger-Controlled Pointing Device

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Abstract: A keyboard with an integrated isometric velocity controlled joystick, called a key joystick, was compared in learning and skilled human performance with a standard mouse in an modified version of the usual one dimensional Fitts' Law pointing task. The modified tasks included using two dimensions, i.e. motion in a plane, and dragging. Data was also collected on mode switching between typing and pointing. Skilled key joystick performance was comparable to that reported in the literature for other isometric velocity-control joysticks. The key joystick was significantly slower for pointing and dragging in both learning and skilled performance, and had more errors. At the end of the experiment the pointing task time for the key joystick was approximately 55% slower than the mouse; the dragging task time was approximately 53%. For the mode switching task, the key joystick had a significantly faster homing time, but it was not enough to compensate in overall task time for the significantly larger pointing time and non-significant difference in typing time. Both devices were shown to obey Fitts' Law for pointing and for two dimensions. This contributes to research interest in whether Fitts' Law describes motion of the finger-operated, isometric velocity controlled devices, and two-dimensional tasks. One final observation is that isometric velocity control devices are quite sensitive to the value of control equation parameters. This might account for the wide cross-experimental variance observed in their performance reported in the literature.

1. INTRODUCTION

The tremendous versatility and usefulness of pointing devices in graphical user interfaces (GUIs) has lead to their explosive popularity and market growth. This report details our evaluation of the human performance of a new pointing device, the key joystick. The key joystick embeds an isometric joystick under the 'J' key of the standard keyboard. To our knowledge this research is the first analysis of the use of the finger as the controlling body part for computer-based tasks other than key pressing.

The most common body part used for pointing device control is the hand. The mouse, the isometric hand-operated joystick, the digitizer stylus, the trackball and the light-pen are all hand operated (Card, English, & Burr, 1978; Epps, 1986; Goodwin, 1975; MacKenzie, Sellen, & Buxton, 1991). The eyes, head, knees and foot have also been used to control pointing devices (Andres & Hartung, 1989; Drury, 1975; Jagacinski & Monk, 1985; Pearson & Weiser, 1986; Pearson & Weiser, 1988). However, the mouse remains the most commonly used device.

In this report the human performance of the key joystick is compared to that of a mouse. Selection of the mouse as the basic comparison device is due not only to the abundance of experimental studies of human performance using it (Boritz, Booth, & Cowan, 1991; Card, et al., 1978; Ewing, Mehrabanzad, Scheck, Ostroff, & Shneiderman, 1986; Gillan, Holden, Adam, Rudisill, & Magee, 1990; MacKenzie, et al., 1991; Mackinlay, Card, & Robertson, 1990), but also the fact that the research data substantiates the superior efficiency of the mouse as a pointing device (Card, et al., 1978; MacKenzie, et al., 1991). Perhaps this empirically measured efficiency accounts for the mouse's market dominance. For these reasons our experiment uses the mouse as the baseline performance device. In addition, replication of the findings of other independent mouse performance experiments develops confidence in results of the present experiment and its findings concerning the key joystick.

The need to evaluate these devices in a computer-based Graphical User Interface (GUI) task environment warrants a fairly comprehensive study of learning and practiced behavior using multiple tasks. However, most of these devices have been studied only in terms of their behavior as Fitts' Law (Fitts, 1954; Fitts & Peterson, 1964) devices, that is, speed of pointing is related to the distance and size of the target object (Card, et al., 1978; Drury, 1975; Epps, 1986; Jagacinski & Monk, 1985; Kantowitz & Elvers, 1988; MacKenzie, et al., 1991; Ware & Mikaelian, 1987). In order to be able to compare the performance of the key joystick with other results from the published literature as well as remain true to the sensitivities of its real use in a real work environment, we designed a modified version of the usual one dimensional Fitts' Law pointing task. The modified task used two dimensions, i.e. motion in a plane. Data was also collected on dragging and mode switching between typing and pointing.[1] In order to replicate the types of real GUI tasks that users of these pointing devices encounter, we chose target sizes and distances which matched typical graphical objects on computer displays. We were also interested in the time it took to learn the device and the number and types of errors associated with its learning and use.

In addition to our applied research interest in comparing the performance of the key joystick to the mouse, we also had several basic research questions concerning Fitts' Law tasks:

1. Is the isometric key joystick a Fitts' Law device? Previous studies present conflicting results for isometric devices controlled by the hand. Some such as the Card et al. study (Card, et al., 1978) suggest that they are not, while others suggest that they are. (Epps, 1986; Jagacinski & Monk, 1985; Kantowitz & Elvers, 1988)
2. Does the performance of the finger demonstrate that it too is a body part that conforms to Fitts' Law? Very little study of the use of the finger for pointing control tasks has been done although devices like the key joystick are beginning to appear. In addition to the key joystick, IBM Corp. has just recently developed a miniature joystick that is located in the center of a standard keyboard between the G, T, Y and H keys and is controlled by the finger. The joystick protrudes only 2

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[1] In addition to pointing, clicking and dragging, we also note those of drawing and chording which is when a keyboard key and a pointing device button are concurrently pressed. For example, in Microsoft Word, double clicking a mouse button on a word selects it, while double clicking a mouse button with the control key on the typing keyboard depressed selects a sentence.

mm above the keys so as not to interfere with typing. Mouse buttons are replaced by keys located on either side of the keyboard's space bar. One study showed that the task of placing pegs under a microscope, which primarily involves finger movement, conforms to Fitts' Law (Langolf, Chaffin, & Foulke, 1976).

3. Can Fitts' Law be extended to two dimensions? The original Fitts task is one dimensional, i.e. the motion of the hand follows a horizontal line. Tasks with contemporary GUIs are typically two dimensional. The device is moved in a two dimensional plane corresponding to the movement of a pointer icon, the cursor, on the screen.
4. Is there a "mode" switching cognitive time for the key joystick that is comparable to "homing" time in moving the hand from keyboard to mouse? There is no literature on mode switching tasks, although estimates of homing time have been made (Card, et al., 1978; Card, Moran, & Newell, 1983). Human performance on combined typing and pointing tasks are of crucial interest to the developers of the key joystick since the keys on the keyboard are used for both pointing and typing and the system must switch between the two modes quickly and accurately. (For more details on the key joystick see section 2.2 below.) In fact the key joystick system is designed to save time for the user by eliminating the extra "homing" motions of moving the hand from keyboard to mouse and back.

The following experiment presents the subjects with these three major types of tasks: pointing, dragging, and mode switching. In each of the three different types of tasks the subject is presented with a wide variety of target sizes, angles of approach and distances. This allows collection of crucial information for comparing device and human performance as well as giving the subjects a diverse learning environment.

To support a broad study of human performance using these two devices, data was collected via videotape, computer-generated data collection and questionnaire on performance time, errors, and subjective experience during learning and practicing with the experimental devices. This presents a fairly comprehensive picture of the evolution of a learner into a competent experienced user and allows us to compare human performance on the key joystick with a standard mouse.

2. THE EXPERIMENT

2.1. Subjects

The sample consisted of 23 subjects recruited using the following method. Requests for subjects for the experiment were advertised through flyers posted around the University of Oregon campus. An additional request for subjects was also made in two classes on introductory computer science for non-majors (class size 250 students each). 36 people responded to these advertisements. The candidates were asked to fill out a form describing their computer experience. Candidates indicating that they had experience with a mouse or joystick were eliminated from further participation in the experiment.

This left a final subject pool of twenty-three individuals all of whom were undergraduates. Seven subjects were male and sixteen were female. One subject (male) was left handed, while the rest were right handed. The subjects were randomly assigned to one of the two pointing devices, with eleven subjects using the mouse and keyboard combination, while twelve subjects (including the left handed subject) used the key joystick.

Subjects were paid $5 per one hour session for their participation in the experiment.

2.2. Experimental Equipment

All experimental tasks were computer-based. The hardware used for the experiment was an IBM-PC compatible made by Austin Computers, using a 386SX CPU, operating at 16 MHz, with 4 MB of memory. The operating environment was Microsoft Windows 3.0 and Microsoft MS-DOS version 4.0. The display adapter was a Tseng 3000 VGA card. The screen was a 800 by 600 pixel, 16 color SVGA display. The point size was .28mm per pixel. Experimental materials were presented to the subjects using this display.

One pointing device was a Microsoft Mouse (FCC ID number: C3K5K5COMB). The other pointing device was a Keytronic Keyboard fitted with a key joystick made by HomeRow Inc. The operation of the keyboard is described below.

Since both devices were used for the tasks of pointing, dragging and mode switching, the following is a description of how these are accomplished on the equipment. (Note: All actions with a pointing device relate to the cursor on the computer screen. This cursor is controlled by the actions of the user on the pointing device.)

1. *Pointing* is the task of moving the cursor to a specific location on the screen. For example, in X-Windows, a user has to point to a window before that window will accept keyboard input. For the mouse pointing is accomplished by moving the device across a surface. The displacement of the mouse causes a corresponding displacement of the cursor on the screen. For the key joystick, pointing is accomplished by pressing and holding down the 'J' key on the keyboard. When the duration that the key is held down exceeds a threshold, the keyboard automatically switches from typing mode to pointing mode. This activates the joystick, which then senses the direction of lateral force on the key, and moves the cursor in the corresponding direction, the velocity of movement being controlled by the force on the joystick. If there is no lateral force on the 'J' key, the cursor does not move. When the 'J' key is released, the keyboard returns to typing mode. On many GUIs, the final selection of a location or object through the cursor is accomplished by *clicking*. On the mouse, this means pressing and quickly releasing one of the buttons on the mouse. Final selection of location on the key joystick is made by clicking the 'F' key while remaining in pointing mode, i.e. keeping the 'J' key pressed down.

2. *Mode switching*. A mode switch occurs when a user changes between a pointing task and a typing task. For a mouse and keyboard combination, this is equivalent to a pointing task, homing the hand back to the keyboard, and then a typing task, or vice versa. For the key joystick, this is equivalent to entering and leaving pointing mode from typing mode.

3. *Dragging* is the task of moving an object on the screen to a target position. On the mouse this is accomplished by pointing the cursor at a target on the screen, depressing a mouse button without releasing it, and then moving the mouse. On most GUIs, the object then follows the mouse (i.e. it is 'dragged'). When the object reaches the target location, the mouse button is released. On the key joystick, dragging is performed in an analogous fashion to mouse operation except the 'F'

key is held down instead of a mouse button. An example of dragging in the Macintosh interface is the action of moving a document from one folder into another. It should be noted that there are many dragging actions in GUI use. On the Macintosh, for example, menu selection is also a dragging action, as is selecting a block of text.

2.3. Experimental Procedure

Subjects were seated in front of the computer system and provided with a chair adjustable for height and angle, as well as a foot rest. Thus they could choose as comfortable a posture as possible. At the beginning of the experiment each subject received brief instruction on use of the experimental device. The instructional period lasted approximately 5 minutes and included demonstration by the experimenter and spontaneous practice by the subject. Subjects then continued on to an experimental session of the three tasks. The session was composed of a block of pointing trials, followed by a block of mode switching trials and, finally, a block of dragging tasks. During this first session, the experimenter explained each type of task and demonstrated it. The subject then performed 10 warm-up trials which were discarded from the recorded data. The task block was then restarted, and the subject completed the assigned block. The first session of all subjects learning a device was videotaped for later analysis of learning difficulties.

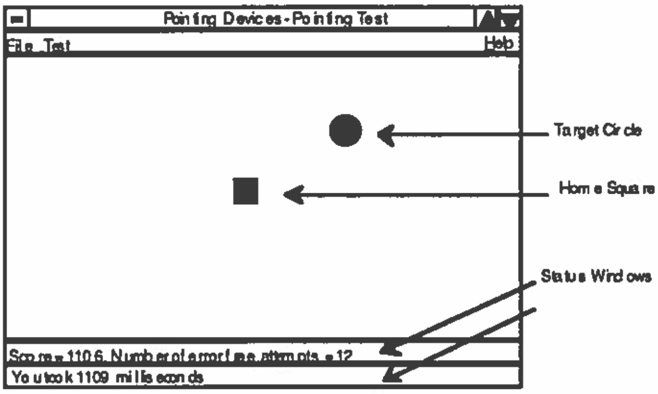
Subjects returned for more experimental sessions until a fixed number of blocks had been completed. When subjects returned to the experiment after an absence, the first ten trials of each task type were considered warm-up. The warm-up trials were discarded and the presentation restarted.

For the whole experiment subjects had an average session length of one hour, took five sessions to complete all blocks of each of the three types of tasks, and, on the average, returned for a session once a week. After completion of the entire learning experiment, subjects were interviewed using a structured questionnaire to gather more insights into their subjective experience with the device.

2.3.1. Pointing Tasks Procedure

During the pointing tasks, subjects were shown the screen depicted in Figure 1 with varying sizes and positions of targets. They were instructed to move the cursor to the home square, select it by clicking the pointing device button, then to move the cursor to the target circle and select it. They were instructed to do this as fast as possible, while maintaining accuracy. The status bars, described below, provided motivational information.

At the start of a trial, the home square was displayed in red, with the target circle in gray, on a white background. The trial started when the subject clicked in the home square. All other clicks prior to the click in the home square were ignored. When the subject clicked in the home square, it became gray, and the target circle became red. This provided subjects with feedback, to let them know that their click was successful, and that the trial had started. The subjects then clicked in the target circle, ending the trial. The time from the first click to the second click was measured.



Score = 1106, Number of error free attempts = 12

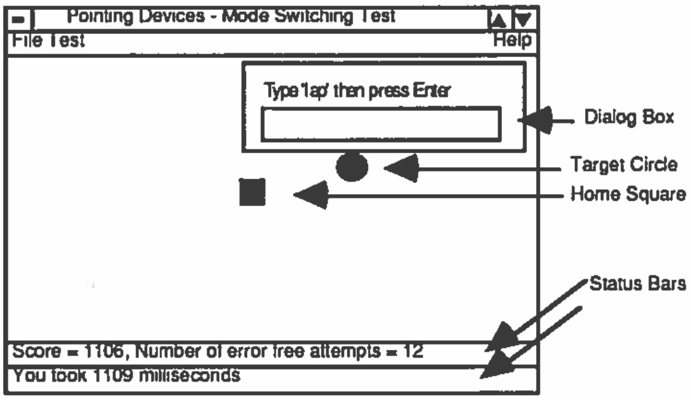
You took 1109 milliseconds

Figure 1: Pointing tasks screen

After the click in the target, the trial ended, and the home and target were redrawn. The home square was always drawn in the same place, in the center of the window. The target circle was positioned randomly as described later. The cursor was automatically positioned in the middle of the home square after the end of each trial in readiness for the beginning of a new trial. This was done to prevent subjects from performing the experiment twice. If they had had to reposition the cursor themselves, they would have made two positioning movements for each measurement we made.

There were two status bars at the bottom of the screen. The first one (the one above) displayed the 'score', which was a running average of the time taken for the last 20 trials, as well as the number of error-free trials completed. The lower status window alternated between displaying the score on the last trial, and displaying informational messages such as where the subject should click next.

When subjects missed the target and clicked outside it, the machine beeped and a message flashed in the second status window indicating that they had made an error. Subjects were then required to complete the trial.



Type 'lap' then press Enter

Score = 1106, Number of error free attempts = 12

You took 1109 milliseconds

Figure 2: Mode switching tasks screen

2.3.2. Mode Switching Tasks Procedure

For the mode switching tasks a started with a screen similar to that in the pointing experiment (see Figure 1). The subject started the trial by clicking in the home square.

The next action required was to point to the target circle and click to select it. At this point, a dialog box appeared, asking the user to type in a word, either "lap" or "fur." The subject then typed in the requested word and pressed the enter key. (See Figure 2.) The trial ended when the subject pressed the enter key.

Error trials were treated in a manner similar to the pointing experiment: subjects repeated the trial until they got both parts of the trial; selecting the target and typing in the word correct.

2.3.2. Dragging Tasks Procedure

In the dragging tasks, subjects were asked to drag the home square into the target circle. The experimental materials, presentation and data collection were identical to that of the pointing and mode switching tasks except that the size of the target circle was not varied. The trial started when the subject selected the home square. The home square then followed the cursor as long as the pointing device button was held down (i.e. dragging). (See Figure 3 for a depiction.) Upon reaching the target circle, the subject released the button and ended the trial. The data recorded was the same as in the pointing experiment. The criterion for a successful drag was that the tip of the cursor (the hot spot) should be in the target circle.[2]

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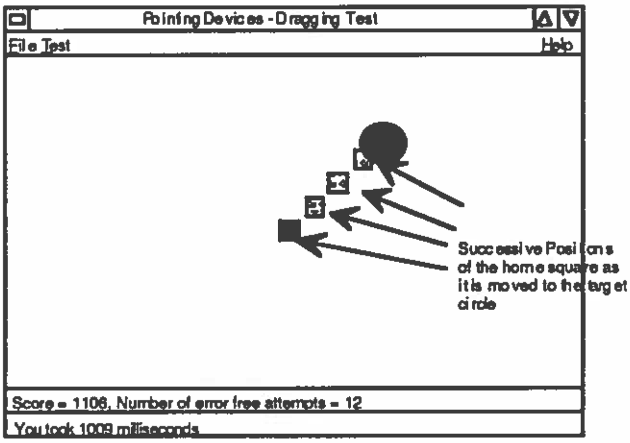
[2] While writing the code for the dragging experiment, an interesting question arose: When has an object been dragged onto another object?" For example, of the following instances, when has the light square been dragged onto the dark square?

The answer depends on the implementation of dragging. For example, one object could be considered to be dragged onto another when any part of it obscures any part of the target. The problem with this is that if there are two or more potential targets side by side, the dragged object could obscure parts of both, and it would be unclear which object was the recipient of the drag. Similar objections can be made to schemes which require some specified portion of the dragged object or the target to be covered (for example, we could require that 50% of the target should be covered, and the problem become more complicated when the sizes of the dragged object and the target are not the same). There can also be confusion about whether to consider the portion of the dragee that is overlapped, or the portion of the target overlapped. Such considerations also have an effect on how the size for Fitts' Law analyses is to be measured. For example, if we assume any degree of overlap, the size parameter in the Fitts' Law equation becomes the combined size of dragged object and target.

The problem is sidestepped in the implementation of GUIs such as the Macintosh and Microsoft Windows. The notion of a dragged object being on top of the target is determined by the position of the cursor's hotspot. This simplifies both the determination of a target hit, as well as the Fitts' Law analysis. A target hit can be determined by checking the position of the target relative to the hotspot when the mouse button is released, and the position of the dragged object can be ignored. For the Fitts' Law analysis, we just have to consider the size of the target.



Score = 1106, Number of error free attempts = 12

You took 1009 milliseconds

Figure 3: Dragging tasks screen

Errors occurred when the button was released before the cursor was in the target circle. Subjects were informed that they had made an error by a beep and a message in the lower status window, and were asked to complete the trial.

2.4 Experimental Design

This experiment consisted of a three factor repeated measures design consisting of one between subjects factor called device type (mouse vs. key joystick) and two within subject factors, task type (pointing vs. mode switching vs. dragging) and time (in blocks of trials). That is, subjects learned and used only one of the two devices but performed all three task types over a period of time.

Each subject was required to complete a total of 19 blocks of experimental trials. The total number of trials completed by each subject was 2752. Subjects performed a pointing block followed by a mode switching block followed by a dragging block.

We can compare our 2752 task trials as a learning criterion to other published research which shows that the Card, English & Burr (1978) pointing study took subjects to 1200 trials, which they found to be a criterion such that performance between consecutive trial blocks ceased to improve by a significant difference of $p \leq .05$. MacKenzie, Sellen and Buxton (1991) reported pointing and dragging performance for a total of 800 trials also claiming that performance after the first block of 160 trials did not improve significantly ($p \leq .05$). However on the MacKenzie et al. experiment, subjects received a much less complex task environment than ours, so it was much easier to become quickly skilled. Since our experiment gave subjects 64% more practice than the Card, English & Burr study and 150% more than the MacKenzie, Sellen and Buxton study, we have confidence that these subjects are becoming skilled users by the end of our study.

2.4.1 Pointing Tasks Experimental Design

Because most of the studies of pointing relate time of performance to Fitts' Law, the subject was presented with a variety of targets which differed in target size and distance to the target. We also varied the targets by angle-of-approach to verify that both devices were fully functional in all directions. Time to perform each trial as well as percentage of errors were measured as dependent variables. Longitudinal change in performance time as a function of practice was computed to measure learning. Finally, the data was computed as a Fitts' Law equation to determine the relevant parameters.

The size, distance from home, and angle of the target circle were varied. For this experiment, there were 3 sizes (8, 16 and 32 pixels), 4 distances (31, 62, 124 to 248 pixels) and 16 angles (in 22.5 degree increments where 0.0 is directly above the home square, negative angles go counter clockwise, positive angles go clockwise), giving 192 possible combinations. In order to reduce the number of trials we randomly selected 127 of these combinations. However, for each angle there is always a width/distance combination that creates one of the Fitts' Law index of difficulty values from 1 to 32. This allows comprehensive testing of Fitts Law behavior. Table 1 shows the selected crossings:

	Width (pixels)											
	8				16				32			
	Distance (pixels)											
Angles (degrees)	31	62	124	248	31	62	124	248	31	62	124	248
-180.0	•	•	•	•		•	•	•		•		
-157.5	•		•	•		•	•	•				•
-135.0	•	•		•	•	•				•		•
-112.5		•	•	•	•	•	•	•	•	•	•	
-90.0	•	•	•	•			•	•	•		•	
-67.5	•	•		•	•	•	•		•		•	
-45.0	•	•	•	•			•	•				•
-22.5	•		•	•	•	•	•	•	•		•	•
0.0	•		•		•			•	•	•		•
22.5	•		•		•	•	•			•	•	
45.0	•			•		•			•	•	•	
67.5	•	•		•				•	•	•	•	•
90.0	•		•	•	•	•		•	•	•		•
112.5	•			•	•			•	•	•	•	•
135.0		•	•	•		•	•	•	•	•	•	
157.5	•	•		•	•	•	•		•		•	

Table 1: Width, distance, angle combinations used in the experiment

These combinations were sequenced randomly within the first block and repeated in this sequence for the remaining blocks. All subjects received identical presentations. The time at the start of the trial, the time at the end of the trial, the position of the click in the home square, the position of the click in the target circle, and the position and size of the target circle were computer-generated and saved at the end of each trial.

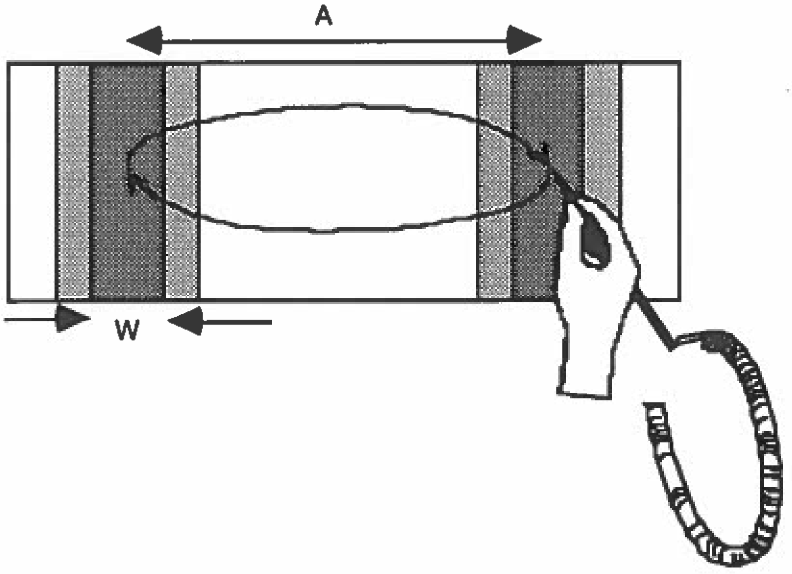


Figure 4: The original Fitts' experiment

The size of the target circle varied between 8, 16 and 32 pixels, .224 cm, .448 cm, and .896 cm respectively. These pixel sizes were chosen to approximate the sizes of objects that a person using a windowing environment would encounter, while increasing in multiples of 2 to facilitate Fitts' Law analysis. The size of an icon in Microsoft Windows is 32 pixels by 32 pixels. It is also the approximate size of a word (using 12 point Helvetica font), when approached from the side. The size of the average word when approached from the top or bottom is approximately 16 pixels. This is also the size of a character when approached from the top or bottom, and 8 pixels is approximately the width of a character when approached from the side.

Circles were chosen as targets to eliminate possible bias in Fitts' Law computation caused by the angle-of-approach. Fitts' Law computes the time to point to a target object as a function of object size which is effectively its width. Fitts' original experiment used rectangular targets where the angle-of-approach never varied (see Figure 4).

However, if the targets become rectangles, as they typically are in textual targets such as words on a computer, then the effective width of the target, depends on the angle-of-approach. (See Figure 5). If the rectangles represent words (in English and other similar languages!), then the effective width of the target depends on the angle-of-approach. W1 represents the target size if the user approaches the word from above or below. W2 represents the target size if the user approaches the word from the left or right. Finally, W3 represents the target size if the user approaches the word at an angle. Previous experimental research on computer-based pointing devices has often failed to take this into account (Card, et al., 1978; Gillan, et al., 1990), and became one bias that we wished to control.

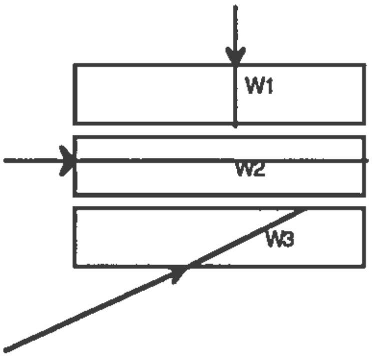


Figure 5: The effect of approach angle on the effective width of a target.

The distance between the home square and the target circle varied from 31, 62, 124 to 248 pixels, .868 cm , 1.736 cm, 3.472 cm and 6.944 respectively. These distances were chosen based on the available screen size. We wished to fit in as many distances as possible while increasing them by multiples of two.

In order to determine whether the angle-of-approach to the target made any difference, the angular position between home square and target was varied in increments of 22.5 degrees giving 16 different angular positions.

We required subjects to complete all trials error-free to ensure that they could not ignore the more difficult small targets. Although there were 127 distance, width, angle combination trials, subjects had up to a maximum of 192 trials for each block to correctly perform each combination. (In other words, subjects had up to 65 extra attempts to repeat error trials.) Data from the error trial was recorded, but ignored when calculating performance time.

2.4.2 Mode Switching Tasks Experimental Design

A significant amount of time, called homing time, is necessary for a user to move her or his hand from the keyboard to the mouse and back again. Elimination of these two instances of homing time was one of the motivations for development of the key joystick. The second task, an extension to the first, was designed to measure this time by combining a pointing action with a typing action.

The first part of this task repeated the design of the previous pointing task design. Subjects pointed to a target circle in 127 trial combinations of width, size and distance as before. However, upon selecting the target circle, a dialog box appeared asked the subject to type in one of two words, either “lap” or “fur.” Subjects were randomly assigned one of the words initially and then repeated that word for all trials within a block. The next block for the subject presented the alternate word. The rationale behind this protocol is as follows. Since we wanted to measure the physical time of homing for the mouse, i.e. the time between the end of selecting the target and the initiation of typing, we did not want it inflated with “thinking” time caused by response to a random presentation of either word.

The words “fur” and “lap” were chosen with the placement of the key joystick in mind. The joystick uses both index fingers to activate normal mouse functions, one to press the ‘J’ key to move the cursor, and one to click (the mouse “button”) using the ‘F’ key. When a person is touch typing, the word 'lap' does not require the use of the index fingers, while the word 'fur' requires exclusive use of the index fingers. We assumed that subjects using the key joystick would find it harder to type “fur”. They would first use the ‘J’ and ‘F’ keys to point and click in the target. Immediately after this, they would have to release the keys to start typing, and then they would have to use those fingers again, this time to type. Similarly they would find it easier to type “lap”. This would counterbalance the difficulty for key joystick users giving us a better average performance.

Four time points were recorded during a trial: (a) the time at which the subject clicked in the home square, (b) clicked in the target circle, (c) started typing, and (d) pressed enter to signal the termination of typing. Because of the sequence of physical actions within a trial, mouse homing time is measured as the duration between times (b) and (c), or the time it takes to move the hand from the mouse to the keyboard.

Error trials were treated in a manner similar to the pointing experiment: subjects repeated the trial until they both selected the target and typed in the word correctly. For this experiment, errors were recorded and classified in three possible categories: the subject selected a point outside the target, the subject typed the word incorrectly, or the subject made both errors. As in the pointing experiment, only error-free trials were used for computing performance time.

2.4.3 Dragging Tasks Experimental Design

The third experiment was designed to determine performance on dragging. The size of the target circle was not varied because at the time we conceived the experiment we had not thought of dragging as a Fitts’ Law task and therefore subject to the same size-distance interaction. We therefore fully crossed 4 distances with 16 angles giving 64 trials rather than 127 in the previous tasks. The home square and the target circle for all trials were 32 pixels in diameter which is the size of an icon, a common target for dragging operations.

3. RESULTS

3.1. Effect of learning on performance time

Learning can be characterized as the improvement of performance time when repeating a task. Table 2 shows the differences in mean trial time for each block of tasks varied by task type.

Mean Trial Time (ms) by Block Number (within task type)

		1	2	3	4	5	6	7
Point	MOUSE	1473	1301	1208	1126	1117	1105	1111
	Key Joystick	2687	2056	1888	1879	1796	1729	1723
	KJ:M	+82%	+58%	+56%	+67%	+61%	+56%	+55%
Mode Switch	MOUSE	3112	2569	2464	2361	2283		
	Key Joystick	4002	3340	3118	2870	2662		
	KJ:M	ns	ns	ns	ns	ns		
Drag	MOUSE	1214	1088	1016	1012	982	955	928
	Key Joystick	1928	1744	1632	1516	1496	1432	1417
	KJ:M	+59%	+60%	+61%	+50%	+52%	+50%	+53%

Note: all differences between devices are significant at $p \leq .05$; ns is not significant.

Table 2: Change in mean trial time as a result of practice

As one can see, the time to perform a trial decreases with practice for all tasks. It also differs between the two devices. For pointing tasks, on the first block the average trial for the key joystick takes 82% more time than the mouse, but by the seventh block, the key joystick takes only 55% more. This suggests that key joystick users are improving at a faster rate. There is also a difference between tasks in that the advantage for mouse users was not as great in the mode switching tasks. There is a faster mean task time on dragging tasks than pointing tasks because the size of the target did not vary from 32 pixels (.896 cm) which was the largest target. According to Fitts' law, positioning time should be fastest on the largest targets. Since smaller targets were included in the pointing tasks, the overall mean time is greater. The mode switching tasks are longer not only because they include all the pointing tasks, but also an extra typing step.

A repeated measures analysis of variance with one between subjects factor (device) and two within factors (task and time) was performed to verify whether the apparent distinction between the two devices was statistically significant. There is a main effect of device ($F_{1,20}=26.54$, $p<.0001$); performance also differed by tasks ($F_{2,40}=297.01$, $p<.0001$); as well as time ($F_{3,60}=44.5$, $p<.0001$). There was no significant difference in task-by-device. The lack of significant difference for task-by-device can be seen in Figure 6. The means for dragging and pointing tasks are very close to one another and given the variance do not show significant difference by task. There is an effect of task-by-time-by-device ($F_{6,120}=2.27$, $p<.05$)

Analyzing each type of task separately shows that for pointing tasks there is a main effect by device ($F_{1,17}=37.8$, $p<.0001$), time ($F_{6,102}=33.9$, $p<.0001$), and an interaction effect of time and device ($F_{6,102}=6.234$, $p<.0001$). We find a similar result for dragging with main effect by device ($F_{1,17}=71.7$, $p<.0001$), time ($F_{6,102}=16.5$, $p<.0001$), and an interaction effect of time and device ($F_{6,102}=2.3$, $p<.05$). For mode switching the results are slightly mixed. There is a main effect by device ($F_{1,20}=10.7$, $p<.005$), time ($F_{4,80}=19.7$, $p<.0001$), but no interaction effect of time and device.

The decrease in performance time as a result of repetition can be quantified as the Power Law of Practice (Card, Moran & Newell, 1983). The time T_n to perform a task on the nth trial follows a power law. That is, with practice, performance time decreases as a function of the following equation:

$$T_n = T_1 n^{-a}$$

or, alternately, the log of the time to do a task on the nth trial is equal to the log of the time to do it on the first trial minus a constant, a, times the trial number.

$$\log T_n = \log T_1 - a \log n$$

This equation can be plotted as the log of the mean trial time for subjects (y axis) vs. the log of the trial block number (x axis) and will yield a straight line if the data is well-behaved. Figure 6 displays the data for the experiment for all three task types with the log of the mean trial time for subjects (y axis) plotted vs. the log of the block number (x axis). The resulting plot shows an excellent fit to a straight line. The regression equations for these data are shown in Table 3.

3.2. Practiced Performance Time

At the end of the experimental sessions, we are able to assess the relative difference in performance speed by examining the last block of a task type. A Bonferroni *t* test was applied to determine if significant improvement, i.e. learning, was still occurring by these last blocks of tasks. For all three task types significant improvement ($p \leq .05$) in performance time did not occur after the third block of each type of task. We safely can conclude that data analyzed from the last four blocks of each task type is that of well-practiced performance.

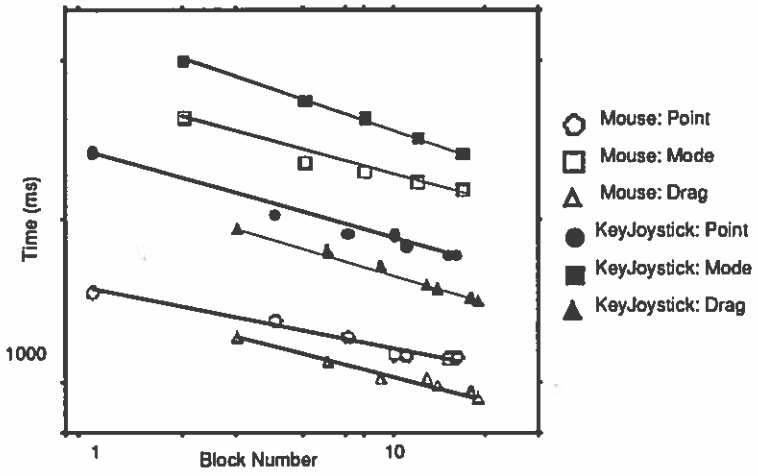


Figure 6: Change in mean trial time as a result of practice.

	Regression Equation	Correlation		
Mouse Pointing	log1483ms -.11log(n)	$r^2 = .975$	$F_{1,5}=196.41$	$p = .0001$
Key Joystick Pointing	log2636ms -.158log(n)	$r^2 = .981$	$F_{1,5}=254.10$	$p = .0001$
Mouse Mode Switch	log3350ms -.143log(n)	$r^2 = .958$	$F_{1,3}=68.38$	$p = .0037$
Key Joystick Mode	log4560ms -.187log(n)	$r^2 = .998$	$F_{1,3}=1220.62$	$p = .0001$
Mouse Dragging	log 1393ms -.134log(n)	$r^2 = .972$	$F_{1,5}=171.96$	$p = .0001$
Key Joystick Dragging	log 2344 ms -.169log(n)	$r^2 = .996$	$F_{1,5}=1266.36$	$p = .0001$

Table 3: Computation of regression equations as a result of practice.

Practiced means for pointing times were 1123 ms for the mouse and 1779 ms for the key joystick; means for mode switching (point + home + type) were 2357 ms for the mouse and 2823 ms for the key joystick; means for dragging were 966 for the mouse and 1407 for the key joystick. Figure 7 plots these task time means by device. There was a significant main effect for device ($F_{1,20}=27.0$, $p < .0001$) with the mouse faster than the key joystick. Likewise, there was a difference in performance time by task ($F_{2,40}= 498.1$, $p <.0001$) with dragging faster than pointing which was faster than mode switching. This is not a very interesting effect in that these three tasks are quite dissimilar from one another. Unlike pointing and mode switching dragging did not vary the size of the target. Similarly mode switching was slowest because of the multiple sub tasks of point, home and type. There was also a task by device interaction ($F_{2,40}=3.2$, $p < .05$). These are all within the acceptable level and thus we will accept the hypothesis that the users of the mouse and the users of the key joystick do differ significantly in performance.

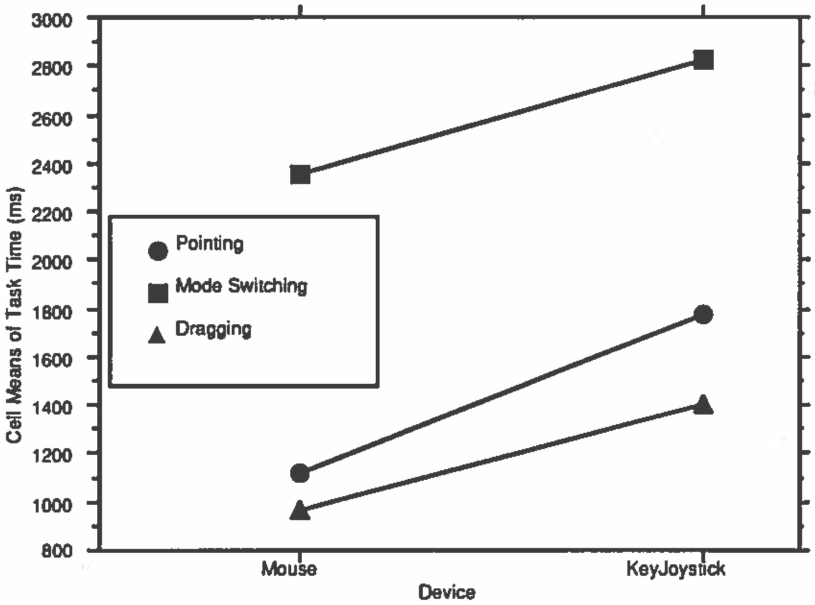


Figure 7: Interaction Plot of Device * Tasks

As we saw in Table 2, by the end of the experiment the key joystick users are 55% slower in pointing tasks, 17% slower in mode switching tasks, and 52% slower in dragging. These data suggest that key joystick does save performance time by reducing homing time, but is slower as a pointing device both for basic pointing and for dragging.

We did further analysis of the mode switching tasks on the savings due to homing time reduction. Figure 8 displays an interaction plot of device by mode switching sub tasks.

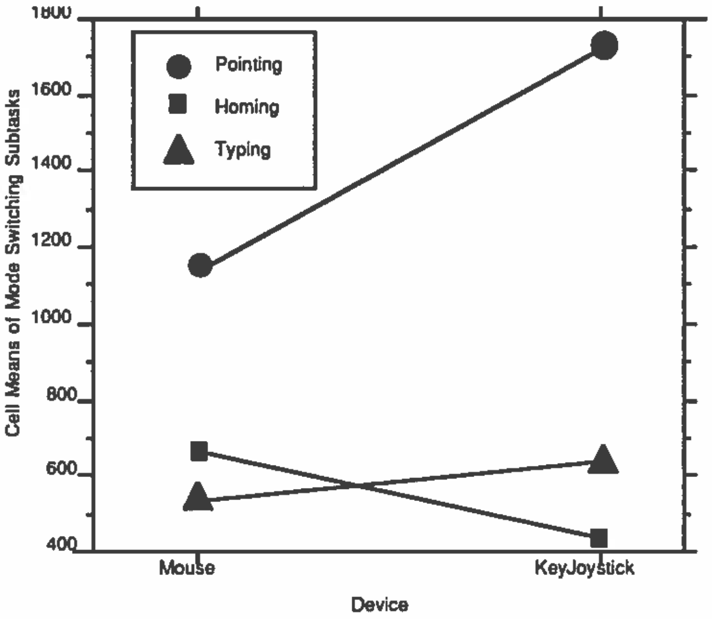


Figure 8: Interaction Plot of Device * Mode Switching Sub tasks

An analysis of variance of just the mode switching task data is shown in Table 4. There is a main effect by device (F 1,20 = 8.0, p < .01), and also an effect by sub tasks (F 2,40 = 236.7, p < .0001). The major cause of this sub task effect is that the mouse greatly outpaces the joystick in pointing (F 1,20 = 38.3, p < .0001). This effect occurs despite the fact that there is no significant difference in typing time and a significant difference in homing time in favor of the key joystick (F 1,20 = 19.2, p < .0003). Faster homing on the key joystick saves approximately 229 ms but the difference in pointing speed between mouse and key joystick is 588 ms.

	Mean Trial Time (ms) for Mode Switching Sub-Tasks		
	Pointing	**Homing**	**Typing**
Mouse	1158	667	531
Key Joystick	1746	438	639
KJ:Mouse	+51%*	-34%*	not significant

*significant at p ≤ .001

Table 4: Mean times for sub-tasks on mode switching final block

3.3. Fitts' Law analysis

Fitts' Law is a model of human performance for computer-based pointing and dragging tasks. The law predicts that the time to acquire a target is logarithmically related to the distance (between the starting position and the target) divided by the target width or, using the Welford formulation (Welford, 1968):

$$Time_{position} = a + b\log_2(\frac{Distance}{Width} + 0.5)$$

The log term is called the index of difficulty, and a and b are both constants. In plain English, it takes longer to point farther away and to smaller targets.

To test whether the key joystick could be characterized as a Fitts' Law device, we analyzed the final task block for pointing tasks to determine the effect of target distance, target width and angle-of-approach on pointing time.

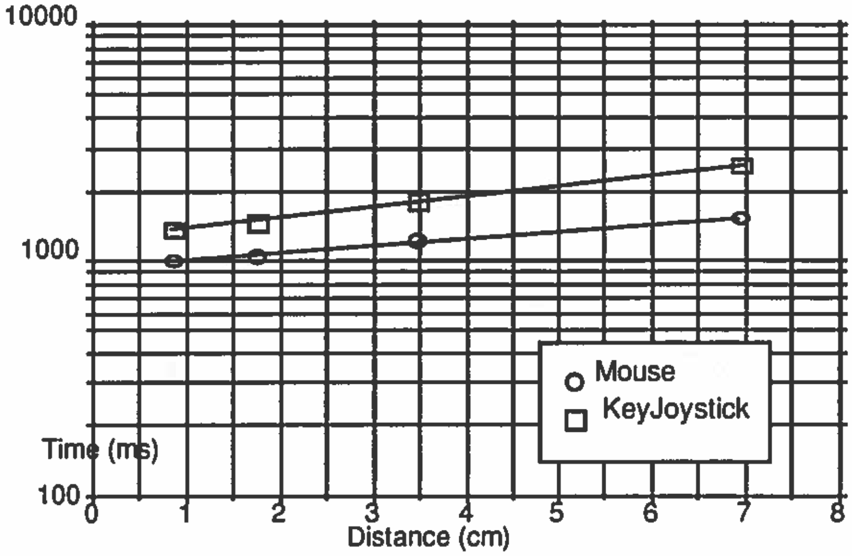


Figure 9: Fitts' Law distance analysis for pointing tasks

Figure 9 shows that pointing time increases as target distance increases as we would expect for a Fitts' Law analysis.

Figure 10 demonstrates the opposite effect: that pointing time decreases as target width increases—again, a well-behaved Fitts' Law result.

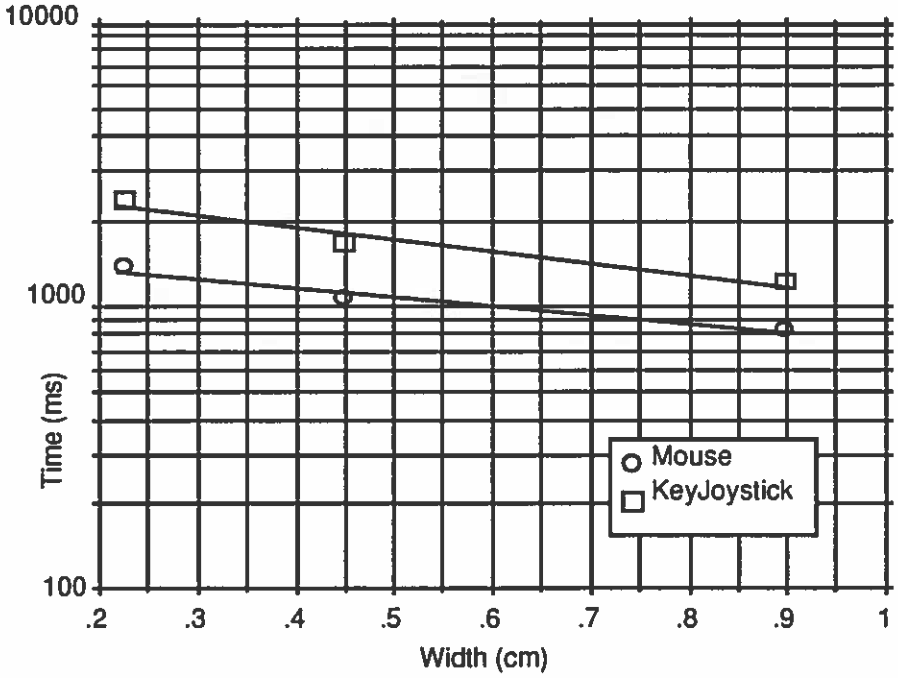


Figure 10: Fitts' Law width analysis for pointing tasks

For our final analysis of these two devices using Fitts' Law, we plot in Figure 11 pointing time as a function of the index of difficulty: $\log_2(\text{Distance} / \text{Width} + 0.5)$. The data fits very nicely using a linear regression technique to straight lines. The line for the key joystick is 467.8 ms + 506.50 (ID); for the mouse it is 479.89ms + 240.92 (ID). For the key joystick r^2 is .987 ($p \leq .0001$) and for the mouse r^2 is .992 ($p \leq .0001$) which we would expect if the devices are Fitts' Law pointing devices.

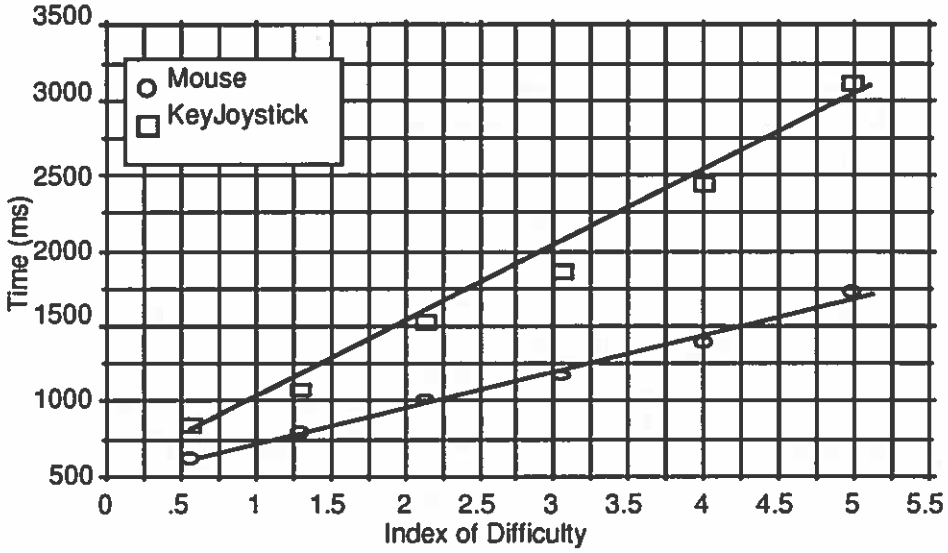


Figure 11: Fitts' Law index of difficulty analysis for pointing tasks

3.4 Error rate

Although all of the data on performance time analysis reported above represents error-free trials, data was collected during the course of this experiment on the number of trials in which the subjects failed to complete the task. In computer-based pointing devices, these error rates usually reflect the ability of the subjects to accurately control the pointing device and/or perform the correct action sequences of cursor movement and button pressing for pointing, dragging and context switching between typing and pointing.

Figures 12, 13 and 14 show the changes in error rate during the experiment for the pointing tasks, mode switching tasks and dragging tasks respectively.

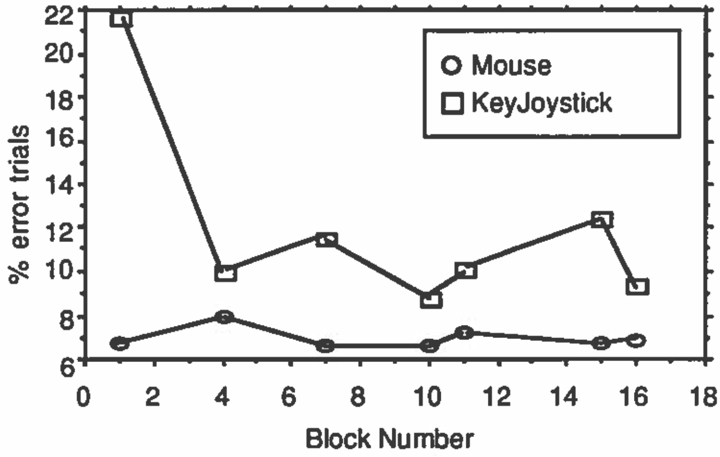


Figure 12: Pointing tasks percentage of error trials

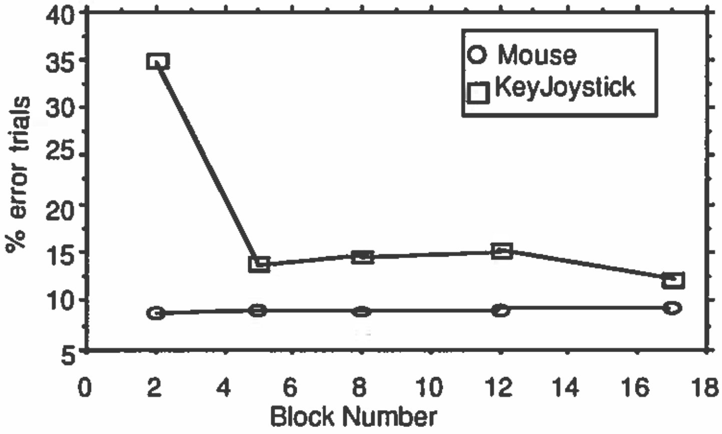


Figure 13: Mode Switching tasks percentage of error trials

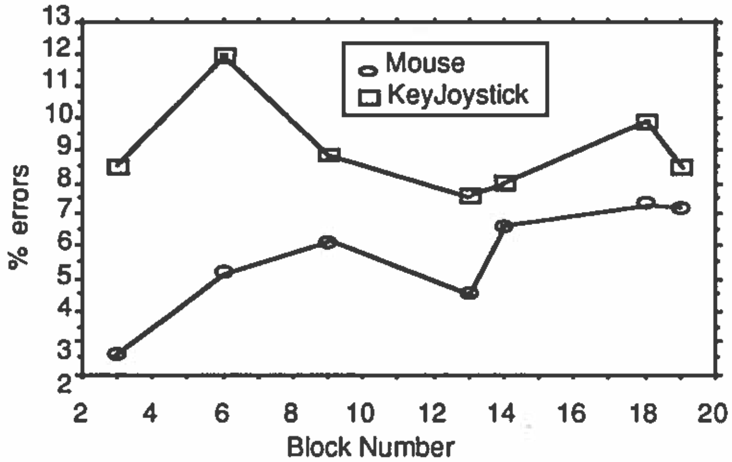


Figure 14: Dragging tasks percentage of error trials

Table 5 shows the overall changes in error rate for the two devices. Although the key joystick had consistently higher error rates for all tasks and for all blocks, only the first block during initial learning is significant.

Pointing errors occurred when subjects clicked outside the target circle once the trail had begun. (Recall that all mouse-events prior to the first click in the home square, which started the trial, were ignored.) For pointing tasks a repeated measures analysis of variance shows a main effect by device ($F_{1,\ 17}=4.278$, $p<.05$); and by time ($F_{6,102}=5.44$, $p<.0001$) and by device by time ($F_{6,102}=5.44$, $p<.0001$). However, looking at each block, the only significant difference is in the first block: Mouse error rate mean= 6.8%, key joystick mean= 21.6%, ($F_{1,20}=11.4$, $p \leq .003$).

		Mean error rate by Block Number (within task type)			
		1	2	3	Practiced
Point	MOUSE	6.8	7.9	6.6	6.9
	KEY JOYSTICK	21.6	10.0	11.5	10.3
	KJ:M	+218%	ns	ns	ns
Mode Switch	MOUSE	18.7	9.1	8.9	8.8
	KEY JOYSTICK	34.8	13.8	14.5	13.0
	KJ:M	+86%	ns	ns	ns
Drag	MOUSE	2.6	5.2	6.0	3.7
	KEY JOYSTICK	8.5	11.9	8.9	6.2
	KJ:M	+227%	+129%	ns	ns

ns: not significant

Table 5: Change in error rate as a result of practice

For the mode switching tasks a repeated measures analysis of variance shows a main effect by device ($F_{1,\ 20}=5.89$, $p<.03$); and by time ($F_{4,80}=16.46$, $p<.0001$) and by device by time ($F_{4,80}=3.1$, $p<.05$). However again, only the first block shows a significant difference between devices: Mouse mean= 8.7%, key joystick : mean= 17.1% ($F_{1,20}=5.1$, $p \leq .03$). Mode switching errors include both pointing errors, typing errors, or a combination of both. For key joystick users, the key joystick's failure to switch correctly to typing mode also caused mode switching errors.

For the dragging tasks the repeated measures showed no significant differences, although on an individual block level, the first block showed a significant difference: Mouse mean= 2.0%, key joystick mean= 9.1%, ($F_{1,20}=17.4$, $p \leq .0005$). The second block also showed a significant difference: Mouse mean= 4.4%, key joystick mean= 11.4%, ($F_{1,20}=15.4$, $p \leq .0002$). Most dragging errors are "dropping" errors when the user fails to sustain the button depression during the movement of the cursor. There are overall fewer errors on dragging tasks because the size of the target did not vary from 32 pixels (.896 cm) which was the largest target and, thus, according to Fitts' law should be the fastest of the targets to which to move.

For the practiced tasks, there is a main effect by device ($F_{1,20}=6.36$, $p<.03$) with a mean of 6.6% for the mouse and 9.8% for the key joystick; and by task ($F_{2,40}=16.17$, $p<.0001$) with a mean of 10.9% for mode switching, 8.6% for pointing and 5.0% for dragging. A contrast analysis with means comparisons showed that all three tasks were significantly different from each other, $p \leq .05$. There was no significant effect difference in error rate for the interaction of device by task.

4. DISCUSSION

4.1 Learning to use the two devices

The results of this experiment suggest that the key joystick is more difficult to learn to control and use than the mouse, but that the key joystick can be mastered, with motivated and concentrated practice, to become as usable as the mouse. Key joystick users were much slower and had more errors in all three tasks throughout the period of this experimental study. Although key joystick users were learning faster, i.e. they have a "steeper" slope on their learning, they were not able to equalize the difference between the two devices. By the end of six hours of concentrated practice, key joystick users were still 55% slower for pointing and dragging times. The lack of control and difficulty in use that key joystick users experience during early learning is reflected in the much higher error rates (more than three times those for the mouse) for the initial sessions for all tasks. Key joystick users however soon gain better control and have non-significant differences in error rate for the remaining sessions. For further insights into the problems that key joystick learners had, see Section 4.2 and Appendix 1 of this report.

This picture leads to a practical question, how skilled were the users at the end of our experiment and does this have anything to do with the real world? Or, bluntly, how confident can we be about the results of this experiment? By the time subjects completed all five sessions, they had performed at least 2752 task trials with the selected device. This is approximately 438 tasks per hour (taking 4.5 hours out of the five hours as time on task). We can suggest that they are very practiced by this point, although not yet experts. Although we have no data to prove it, we assume that in a naturalistic setting, for example word processing an office document, users would probably perform at least 2 pointing operations per minute giving about 120 tasks per hour. Thus we guess that our concentrated experimental environment would be equivalent to about 23 hours of naturalistic practice. Concentrated, repetitive practice such as in this experiment creates faster overall learning because the time between task executions is not as subject to the effect of forgetting.

We also believe that though these experiments used a classical Fitts task, these tasks were modified to reproduce the environment of the computer user thus establishing greater ecological validity. For example, we extended the tasks to two dimensions and included tasks for dragging and mode switching in addition to pointing. We also used target sizes which conform to common display sizes such as text characters and icons.

4.2 Practiced performance

The results we have found allow us to make some comparisons to other published data on computer-based pointing devices which were not studied in this experiment. Table 6 lists the ranking of devices by pointing speed for skilled users within three studies: Card et al. (1978), MacKenzie et al. (1991), and Douglas & Mithal (this report).

		Pointing		Dragging		homing to K/b	homing from k/b
Study	Device	Time (ms)	Error Rate	Time (ms)	Error Rate	Time (ms)	Time (ms)
Card*	Mouse	1290	5%				360
	Joystick	1570	11%				260
	Text Keys	1950	9%	n/a			320
	Step Keys	2310	13%				210
Mac**	Tablet	665	4.0%	802	13.6%		
	Mouse	674	3.5%	916	10.8%		
	Trackball	1101	3.9%	1284	17.3%		
Doug**	Mouse	1111	6.9%	953	4.5%	672	
	Key Joystick	1723	9.4%	1451	5.8%	408**	

*Card et al. (1978); MacKenzie et al. (1991); Douglas & Mithal (this report)
**homing time for key joystick is mode switching the keyboard

Table 6: Comparison of different devices

The key joystick falls in the middle of performance. The tablet is the top performer as we would expect since it most directly translates finger, hand and arm control. The mouse is the next top performer in all three studies for both pointing and dragging. If we examine the proportional difference between the mouse and the other devices, the key joystick seems to fall in the middle of the devices along with the trackball, and standard joystick. However, MacKenzie (1992) argues that it is impossible to compare absolute speed of pointing across studies and suggests instead using the ratios of the Fitts' law index of performance, which is 1/slope of the regression line.

Table 7 ranks the devices, as suggested by MacKenzie (1992), by the ratios within each study of the index of performance from fastest to slowest using the mouse as the base comparison. The Text Keys and Step Keys are not Fitts' law devices and cannot be ranked in this way. What we see from these ratios is still a confusing picture of relative performance: The tablet appears to be the fastest device followed by the mouse followed by the joystick, except for the performance of the trackball which in the Epps study outperforms the mouse, but in the MacKenzie study is reversed. The only legitimate statistical way to handle these rankings is to test the agreement between independent rankings using a non-parametric test such as Kendall's coefficient of concordance (Siegel, 1956). Unfortunately we can't use that test or any other because all of these studies fail to test enough devices. In other words, experimental replication is critical to the formation of an understanding of these results.

Study	Device	Index of Performance (IP) in bits / sec	Ratio of IP within study compared to mouse	Ranking based on IP ratio within study
Card*	Mouse	10.4	1	1
	Isometric Joystick	4.5	2.31 (mouse / joystick)	2
Epps*	Mouse	2.6	1	2
	Isometric Joystick	1.2	2.17 (mouse / joystick)	3
	Trackball	2.9	.89 (mouse / trackball)	1
Mac*	Mouse	4.5	1	2
	Trackball	3.3	1.36 (mouse / trackball)	3
	Tablet	4.9	.92 (mouse/tablet)	1
Doug *	Mouse	4.17	1	1
	Key Joystick (Isometric)	2.06	2.02 (mouse / key joystick)	2

*Card et al. (1978); Epps (1986); MacKenzie et al. (1991); Douglas & Mithal (1992, this report)

Table 7: Ranking by index of performance ratios for different devices

For the dragging task the key joystick appears to be slower than the trackball and mouse (the joystick has not been tested) but had fewer problems of control than the trackball (see Table 6). The error rates for these devices differ, but it is our opinion that that is not significant due to the results of our study.

4.3 Mode switching

The preceding analysis of key joystick performance has allowed us to also test whether the reduction of homing time in a separate physical device such as the mouse allows the key joystick system an advantage in performance. This was one of the inspirations behind the key joystick invention. Keyboard mode switching time in the case of key joystick was found to be significantly less than homing time to the keyboard for the mouse. However, the saving of homing time cannot be less than the homing time of the mouse subtracted by the greater of the time it takes the keyboard to mode switch and the time it takes users to mode switch. If this is a small number (i.e. mode switching time is close to homing time), then the overall speed will be determined by the speed of the pointing devices. And this is exactly what we found. Mouse users still have such an advantage in speed of pointing that a savings in homing time has little effect.

It is important to point out though that if the task mix is such that there is a lot of mode switching between typing and pointing, the savings of homing time can be important to the user, if for only for a subjective feeling that physical movement is reduced. This clearly will reduce overall fatigue. For very experienced touch typists, it may be subjectively preferable to never remove the fingers from the keyboard. At this time, we do not know what the mix of typing, pointing and mode switching is in the natural task environment.

GUI file manipulation requires little typing, and therefore little mode switching, where we would expect the mouse to be faster. But GUI word processing requires lots of typing, and therefore lots of mode switching, where the key joystick would have an edge for simple pointing movements. What we do not know is what is the average time spent in these tasks or how the particular device is used in context, and what the makeup of pointing tasks would be.

For example, we could hypothesize that key joystick users will revert to typing mode after all pointing actions which are followed by a pause longer than about a 5 second duration. This would happen even if the next action was also a pointing action. There are several reasons for this. One is because the user would not find it natural to maintain a contracted muscle position pressing down on the key for a long period without experiencing fatigue. (Several of our key joystick subjects complained of fatigue from using the device during our experiments. This was not the case for the mouse subjects.) Secondly many typists have experienced repeating key functions on typing keyboards and have been taught to immediately release the key press. The issue here is not that users don't press down on a key for a long period, e.g. mouse button during a drag, but that the context switching required of the key joystick is an additional mental effort that can lead to errors if executed incorrectly. Therefore the user opts for safety even though he or she may have to revert again to the same mode of pointing.

It is also useful to compare the results from this experiment with the classic experiment by Card, English and Burr (1978) who in a somewhat informal way measured the time it takes for the user to home *away* from the keyboard to the mouse or other device. (In our study it is the time to home *to* the keyboard.) Table 4 shows 360 ms for the mouse in the Card et al. study. It has often been assumed that these two homing times are the same, e.g. the Keystroke Model (Card, Moran & Newell, 1983), and have both been referred to as homing time. This assumption is, however, an assumption and can be challenged by the data generated in this experiment. Fitts' Law itself indicates otherwise. In both movements, the distance is the same. In the first movement however, the target is the mouse, which is fairly large. In the second movement, the target is a key on the keyboard, which is small in comparison to the mouse. It should therefore take significantly longer to home *to* the keyboard than to home away from it to the mouse. What our study does not determine is both times since we originally designed it under the assumption that both times were equivalent. Such a study should be conducted.

It is important to point out that in techniques such as the one used by the key joystick, it is not possible to eliminate all the homing time. This is because the keyboard has to wait a finite amount of time after the 'J' key is depressed before going into pointing mode. For example, consider the situation where a user is typing, then decides to point. The keyboard will have to wait for some time before switching into pointing mode in case the user was just typing a 'J'. In an article examining keyboard design, Kinkead noted that the average time for a keystroke is 155 (Kinkead, 1975). If we take this to be the minimum time that the key joystick must wait after the 'J' key is depressed before going into pointing mode, then the maximum savings in mode switching time would be

$$MaxTimeSaved = MouseModeSwitchTime - MinimumKeyJoystickModeSwitchTime$$

Assuming that the mode switch time for going from the keyboard to the mouse that was measured by Card (Card, et al., 1978) is applicable for our study, the maximum time that can be saved in a mode switch from typing to pointing would be

$$MaxTimeSaved = 360 - 155 \approx 200ms$$

Similarly, for going from pointing to typing, and using the data from our experiment,

$$MaxTimeSaved = 675 - 155 \approx 500ms$$

Therefore, if task involves a mode switch from typing to pointing, some sequence of pointing tasks, and then a modes witch back to pointing, then the key joystick will save time when it takes no more than 700 milliseconds longer than the mouse for the pointing task.

In general, we can say that pointing tasks are made up of

n modeswitches-to-pointing + m points + n modeswitches-out-of-pointing

(this is because each mode switch into pointing requires a matching mode switch out of pointing regardless of how many (0 or more) pointing tasks there are).

So we can say that the key joystick will save time when the ratio

$$\frac{\text{total mouse pointing time}}{\text{total keyjoystick pointing time}} = \frac{n(360+672)+1100m}{n(155+155)+1723m} > 1$$

or

$$n(360+672)+1100m > n(155+155)+1723m$$

$$720n > 600m$$

$$120n > 100m$$

Now, if we assume that n>1 only when there is some sort of error, and that in the case of the practiced expert, n will be 1, then we have

$1.2 > m$ (approximately)

as the condition when the key joystick will be faster than the mouse, assuming the maximum saving in speed. As m is a positive integer greater than zero, for all cases where a task takes 2 or more pointing actions, the mouse will be faster than the key joystick assuming the index of performance for the two devices as measured by our experiment.

The previous discussion of homing times versus mode switching suggests that when homing to a separate pointing device is compared to mode switching on a single device there is a potential for mental effort that is beyond that required for simply executing the action. Nowhere is this more obvious than in the error rates for mode switching on the key joystick.

It is helpful to understand mode switching errors in terms of a transition diagram describing the states that the system goes through during pointing, dragging and mode switching.

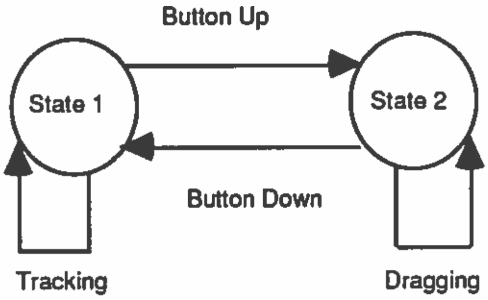


Figure 15: Buxton's State transition diagram for tracking and dragging.

Buxton (Buxton, 1990) suggests the state transition diagram shown in Figure 15 as a model for describing pointing and dragging with a device such as a mouse or trackball. In our attempt to use this model for our experimental design, we found it inadequate, and substituted it with the more elaborate diagram found in Figure 18.

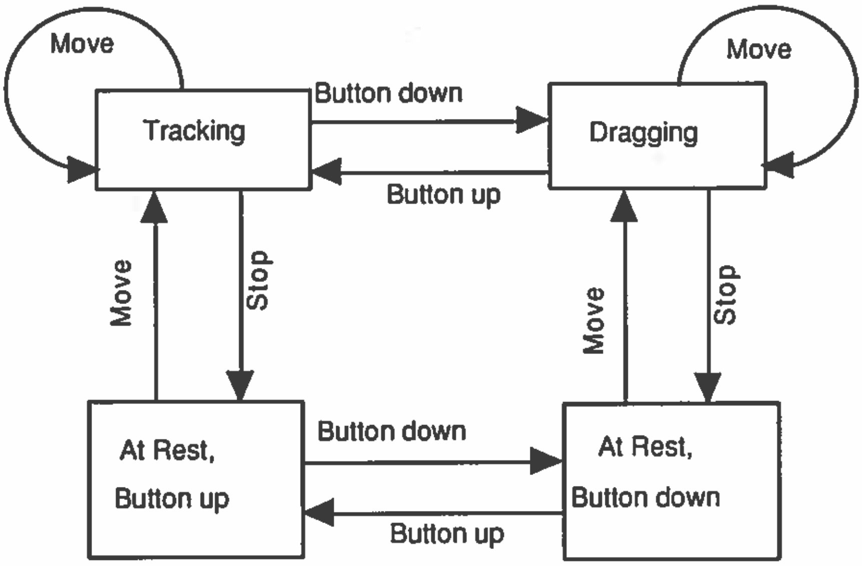
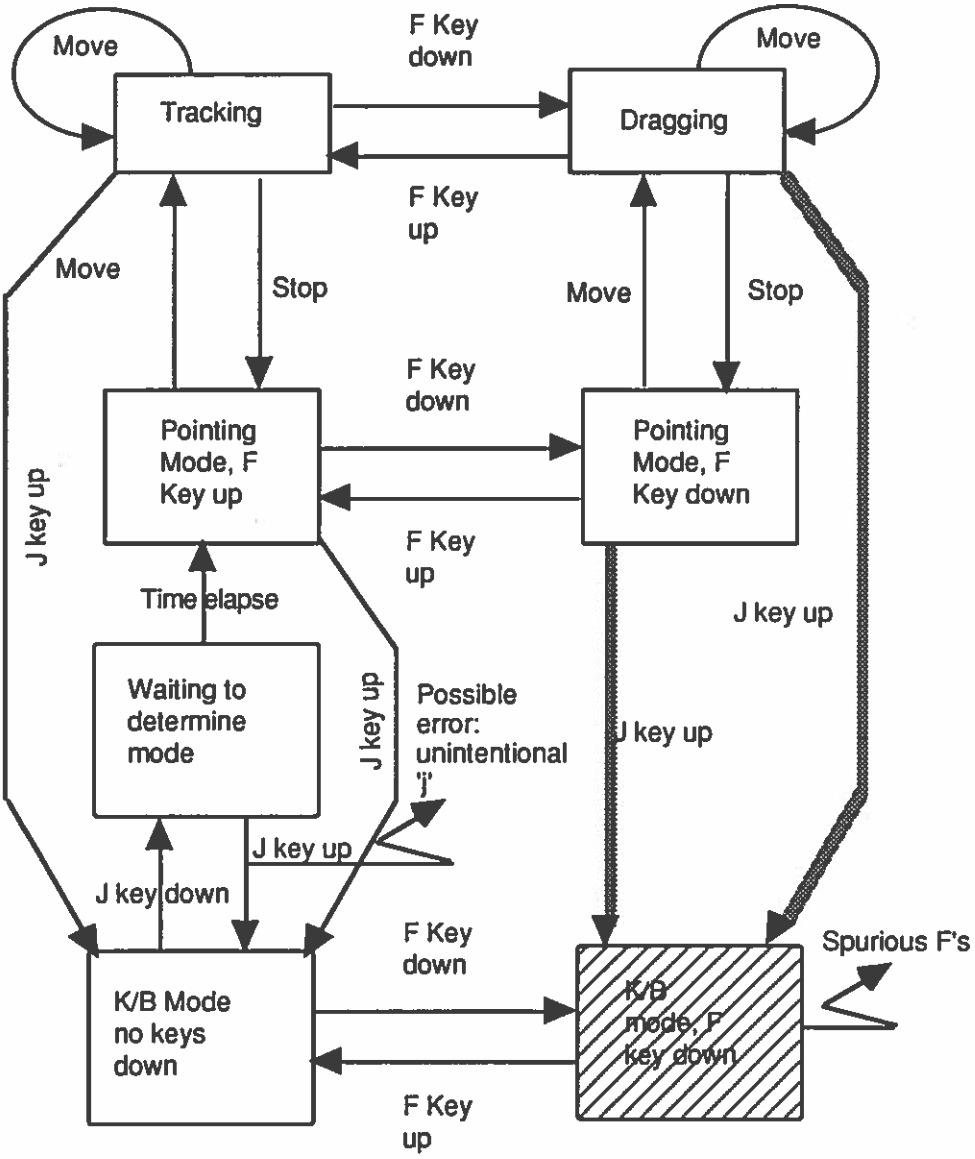


Figure 16: Modified State transition diagram for tracking and dragging with mouse or trackball.

The state transition diagram in Figure 16 is closer to representing the state of the system than Buxton's diagram. It is also more useful for the programmer trying to implement code for dragging.

While this state transition diagram is sufficient for separate pointing devices like mice and trackballs, it is inadequate for the key joystick because the key joystick needs additional states to represent the states of the keys on the keyboard. The state transition diagram for the key joystick is shown in Figure 17.



Gray arcs represent error transitions, where the keyboard sends out a sequence of spurious 'f's. Note that as long as the keyboard is in the shaded state, it is outputting a stream of spurious f's.

Figure 17: State transition diagram for the key joystick.

Figure 17 is useful for understanding how errors occurred on the key joystick. Mode switching errors occurred when the subjects did not correctly switch the keyboard between pointing and typing modes. For example, if they pressed the 'j' key and released it before the keyboard went into pointing mode, a 'j' would be sent to the computer. This situation is marked in Figure 17 as "Possible error: unintentional 'j'". On a number of occasions, the subjects apparently pressed and released the 'j' key a number of times, causing more than one 'j' to appear. A similar mode switch error occurred if the subject pressed the 'f' key when the keyboard was not in pointing mode, resulting in an 'f' appearing. We call these *switching errors*.

A second kind of error was caused by the subject placing their hands on the wrong set of keys. As a result, when they tried to press down on the 'j' key, a sequence of 'h's or 'k's would appear. This we call a *hand positioning error*.

A third type of error occurred when, during a click action or during dragging, the subject pressed the 'f' key, and released the 'j' key prior to releasing the 'f' key. This would cause a sequence of 'f's to appear. This is shown in figure 19 by the shaded state box. We call this a *state recognition error*, based on the rationale given below.

Note that while there is no way of knowing whether the first two kinds of errors are intentional or not, the third kind of errors can be prevented within the driver software for the key joystick by preventing the transmission of characters to the computer from the time that the keyboard goes into pointing mode till the time that all keys are released.

5. CONCLUSION

The key joystick is a Fitts' Law device, providing us with at least one example of a finger-operated, isometric joystick that follows Fitts' Law. Our studies also showed that Fitts' Law holds in situations where the target lies in a two-dimensional plane.

While the finger used in this manner followed Fitts' Law, we were somewhat surprised by the low index of performance we obtained. In their 1976 study Langolf et al. obtained an index of performance of 38 bits/second for the finger and 23 when the hand flexed and extended about the wrist (Langolf, et al., 1976), which is approximately what happens with a mouse. The answer to this possibly lies in studies by Kantowitz and Jagacinski. Both studies (Jagacinski, Repperger, Ward, & Moran, 1980; Kantowitz & Elvers, 1988), indicate that velocity controlled devices are slower than the corresponding position controlled device.

We believe that a second reason lies in the device being isometric. Langolf et al. studied movement in non-isometric conditions. There is no motivation to believe that results from the non-isometric situation will carry across to the isometric situation. We feel that if the key joystick had not been an isometric device, it might have performed better. Note that this reasoning contradicts that by Kantowitz and Elvers (Kantowitz & Elvers, 1988), who felt that "there are several advantages gained by substituting isometric [] controllers. Isometric controllers are simpler because limb displacement, and hence muscle strength remains constant." While the fact that strength remains constant might make it more easy to analyze the task, constant limb displacement and muscle strength may not be conducive to added control, and we suspect exactly the opposite.

The homing time we obtained was greater than that obtained by Card et al (Card, et al., 1978). Their value was 360 milliseconds for movement from keyboard to mouse, while ours was 672 milliseconds from mouse to keyboard. This finding is consistent with Fitts' Law, and raises doubts about the assumption in the Keystroke Level Model (Card, et al., 1983; Card, P., & Newell, 1980) that the movement times between mouse and keyboard are equal.

The study showed that over a wide range of tasks, the mouse is faster and has fewer errors than the key joystick both during learning as well as during practiced performance. We also conclude that it is an improvement over text and step keys. Where the issues get murky is in comparing the key joystick to other joysticks and the trackball. There are also several possible things which can be done to improve the key joystick performance for users: optimizing the parameters in the control equations, providing motivated practice environments before they try to work on real problems in the real world, and possibly changing the physical positioning and physical operation of the key to joystick interface.

MacKenzie (Mackenzie, 1992) suggests the Index of Performance (IP = 1 / slope of Fitts' Law regression line) as the most critical value in determining the performance of a pointing device. Our study bears this out. In addition, we feel that mode switching or homing time has little effect on the overall pointing speed, and that IP is still a better indicator of pointing performance than mode switching time. In other words, in order to make a device fast, it is more fruitful to concentrate on the pointing speed than on the mode switching speed.

A number of questions remain that need to be addressed. What is the effect of angle on movement speed. Card et al's study suggested an effect because of angle, but they did not correct for angle of approach. In two separate studies, Boritz and Jagacinski (Boritz, et al., 1991; Jagacinski & Monk, 1985) indicated an effect due to angle, but did not study its effect in terms of the Fitts' Law equation. We would also like to know more about the relation to Fitts' Law to dragging in two dimensions. Our follow-up study addresses these two concerns.

Additional research needs to be done on the efficacy of isometric controllers versus non-isometric controllers. Non-isometric controllers provide some feedback to users by way of limb position, which is absent in the case of isometric controllers. This may contribute to reduced performance. On the other hand, isometric controllers offer advantages such as very small space requirements, and the lack of moving parts. Because the key joystick can be added to a standard keyboard, it is ideally suited for inclusion in laptop and notebook computers. It would therefore be advantageous to know exactly what the implications are of replacing a non-isometric device with an isometric device.

A number of studies have indicated that velocity control is less effective than position control. It would be interesting to see what would happen if the control algorithm for the key joystick were replaced with one for position control. How does that affect the problem?

Finally, the problem that the manufacturers of the key joystick would most like to see answered is the question of how the parameters of the controlling software should be set for optimal performance.

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