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Evaluation of Mouse, Rate-Controlled Isometric Joystick, Step Keys, and Text Keys for Text Selection on a CRT

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Four devices are evaluated with respect to how rapidly they can be used to select text on a CRT display. The mouse is found to be fastest on all counts and also to have the lowest error rates. It is shown that variations in positioning time with the mouse and joystick are accounted for by Fitts's Law. In the case of the mouse, the measured Fitts's Law slope constant is close to that found in other eye-hand tasks leading to the conclusion that positioning time with this device is almost the minimal achievable. Positioning time for key devices is shown to be proportional to the number of keystrokes which must be typed.

1. Introduction

An important element in the design of the man-computer interface is the method of pointing by which the user indicates to the computer his selection of some element on the computer display. This is especially important for computer-based text-editing where the user may repeatedly use a pointing device to select the text he wishes to modify or to invoke a command from a menu displayed on the screen. The choice of pointing device may have a significant impact on the ease with which the selections can be made, and hence, since pointing typically occurs with high frequency, on the success of the entire system.

English, Englebart, and Berman (1967) measured mean pointing times and error rates for the mouse, lightpen, Grafacon tablet, and position and rate joysticks. They found the mouse to be the fastest of the devices, but did not investigate the effect of distance to target. They also gave no indication of the variability of their measures. Goodwin (1975) measured pointing times for the lightpen, lightgun, and Saunders 720 step keys. She found the light pen and lightgun equally fast and much superior to the Saunders 720 step keys. However, she used only one target size and did not investigate distance. In addition, her results also show large learning effects which are confounded with the device comparisons. Both studies were more concerned with the evaluation of devices than with the development of models from which performance could be predicted. In another line of development Fitts and others (Fitts 1954, Fitts and Peterson 1964, Fitts and Radford 1966, Knight and Dagnal 1967, Welford 1968) developed and tested the relation between distance, size of target, and hand movement time. Such a relation might potentially be used to predict pointing times for devices involving continuous hand movements; however this has not been tested directly. In particular it was not known whether Fitts's Law would hold for targets of the shape and character of text strings.

The present report examines text selection performance with four devices: the mouse, a rate-controlled isometric joystick, step keys, and text keys. The study differs from the English *et al.* and Goodwin studies in that distance, target size, and learning are all simultaneously controlled and a different set of devices is measured. Also, unlike those studies, an attempt is made to give a theoretical account of the results. In particular, performance on the continuous movement devices is tested against the predictions of Fitts's Law.

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2. Method

2.1. Subjects

Three men and two women, all undergraduates at Standford University, served as subjects in the experiment. None had ever used any of the devices previously and all had little or no experience with computers. Subjects were paid \$3·00 per hour with a \$20·00 bonus for completing the experiments. One of the five subjects was very much slower than the others and was eliminated from the experiment.

2.2. Pointing Devices

Four pointing devices were tested (see Figure 1). Two were continuous devices: the mouse and a rate-controlled isometric joystick. Two were key operated: the step keys and the text keys. The devices had been optimised informally by testing them on local users, adjusting the device parameters so as to maximise performance.

The mouse, a version of the device described in English *et al.* (1967), was a small device which sat on the table to the right of the keyboard, connected by a thin wire. On the undercarriage were two small wheels, mounted at right angles to each other. As the mouse moved over the table one wheel coded the amount of movement in the X-direction, the other the movement in the Y-direction. As the mouse moved, a cursor moved simultaneously on the CRT, two units of screen movement for each unit of mouse movement.

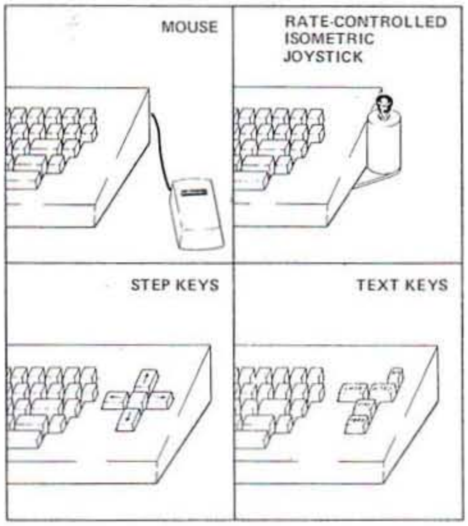

Figure 1. Pointing devices tested.

The joystick used was a small strain gauge on which had been mounted a rubber knob 1·25 cm in diameter. Applying force to the joystick in any direction did not produce noticeable movement in the joystick itself, but caused the cursor to move in the appropriate direction at a rate $=0{\cdot}0178\ (\text{force})^2$ in cm s^{-1}, where force is measured in Newtons. For forces less than about 4 Newtons, the cursor did not move at all, and the equation ceased to hold in the neighbourhood of 45 Newtons as the rate approached a ceiling of about 40 cm s^{-1}.

The step keys were the ffmiliar five key cluster found on many CRT terminals. Surrounding a central HOME key were keys to move the cursor in each of four directions. Pressing the HOME key caused the cursor to go to the upper left corner of the text. Pressing one of the horizontal keys moved the cursor 1 character (0·246 cm on the average) along the line. Pressing a vertical key moved the cursor one line (0·456 cm) up or down. Holding down one of the keys for more than 0·100 s caused it to go into a repeating mode, producing one step in the vertical direction each 0·133 s or one step in the horizontal direction each 0·067 s (3·43 cm s^{-1} vertical movement, 3·67 cm s^{-1}) horizontal movement).

The text keys were similar to keys appearing on several commercial 'word processing' terminals. Depressing the PARAGRAPH key caused the cursor to move to the beginning of the next paragraph. Depressing the LINE key caused the cursor to move downward to the same position in the next line. The WORD key moved the cursor forward one word; the CHARACTER key moved the cursor forward one character. Holding down the REVERSE key while pressing another key caused the cursor to move opposite the direction it would otherwise have moved. The text keys could also be used in a repeating mode. Holding the LINE WORD or CHARACTER keys down for longer than 0·100 s caused that key to repeat at 0·133 s per repeat for the LINE key, 0·100 s per repeat for the WORD key, or 0·067 s per repeat for the CHARACTER key. Since there were 0·456 cm $line^{-1}$, 1·320 $word^{-1}$, and 0·246 cm $character^{-1}$ movement rates were 3·43 cm s^{-1} for the LINE key, 13·20 cm s^{-1} for the WORD key, and 3·67 cm s^{-1} for the CHARACTER key.

2.3. *Procedure*

Subjects were seated in front of a computer terminal with a CRT for output, a keyboard for input, and one of the devices for pointing at targets on the screen. On each trial a page of text was displayed on the screen. Within the text a single word or phrase, the target, was highlighted by inverting the black/white values of the text and background in a rectangle surrounding the target. The subject struck the space bar of the keyboard with his right hand, then, with the same hand reached for the pointing device and directed the cursor to the target. The cursor thus positioned, the subject pressed a button 'selecting' the target as he would were he using the device in a text editor. For the mouse, the button was located on the device itself. For the other devices, the subject pressed a special key with his left hand.

2.4. *Design*

Text selections and targets were so arranged that there were five different distances from starting position to target, 1, 2, 4, 8, or 16, cm, and four different target sizes, 1, 2, 4, or 10 characters. All targets were words or groups of words. Ten different instances of each distance × target size pair were created, varying the location of the target on the display and the angle of hand movement to give a total of 200, randomly ordered, unique stimuli.

Each subject repeated the experiment with each device. The order in which subjects used the devices was randomised. At the start of each day, the subjects were given approximately twenty warm-up trials to refresh their memory of the procedure. All other trials were recorded as data. At the end of each block of twenty trials they were given feedback on the average positioning time and average number of errors for those trials. This feedback was found to be important in maintaining subjects' motivations. At the end of each 200 trials they were given a rest break of about fifteen minutes. Subjects normally accomplished 600 trials day^{-1} involving about two to three hours of work. They each used a particular device until the positioning time was no longer decreasing significantly with practice (operationally defined as when the first and last thirds of a block of the last 600 trials excluding the first 200 trials of a day did not differ significantly in positioning time at the $p<0.05$ level using a t-test). An approximation to this criterion was reached in from 1200 to 1800 trials (four to six hours) on each device. Of the 20 subject × device pairs, 15 reached this criterion, 3 performed worse in their last trials (largely because some time elapsed between sessions), and only 2 were continuing (slightly) to improve.

3. Results

3.1. *Improvement of Performance with Practice*

The learning curve which gives positioning time as a function of the amount of practice can be approximated (De Jong 1957) by

$$T_N = T_1 N^{-\alpha} \tag{1}$$

where

T_1 = estimated positioning time on the first block of trials,
T_N = estimated positioning time on the Nth block of trials,
N = trial block number, and
α = an empirically determined constant.

This form is convenient since taking the log of both sides produces an equation linear in log N,

$$\log T_N = \log T_1 - \alpha(\log N). \tag{2}$$

Thus the ease of learning for each device can be described by two numbers T_1 and α, which numbers may be conveniently determined empirically by regressing log T_N on log N. Figure 2 shows the results of plotting the data from error-free trials according to Equation 2. Each point on the graph is the average of a block N of twenty contiguous trials from which error trials have been excluded. Only the first 60 trial blocks are shown. Since some subjects reached criterion at this point, not all continued on to further trials. The values predicted by the equation are given as the straight line drawn through the points. The average target size in each block was 4·23 cm (the range of the average targest sizes for different trial blocks was 3·95 to 4·50 cm); the average distance to the target was 6·13 cm (range 5·90 to 6·42 cm).

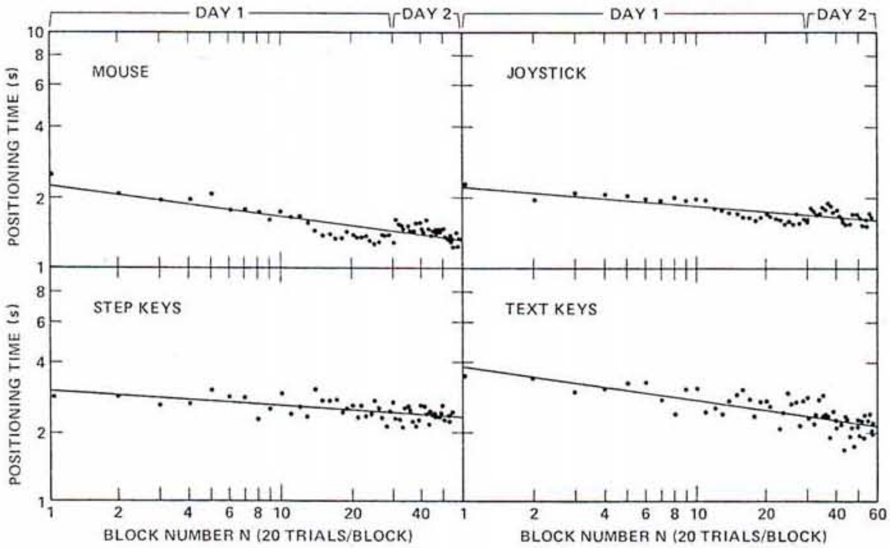

Figure 2. Learning curves for pointing devices.

The parameters T_1 and α, as determined by the regressions, are given in Table 1, along with the standard error and squared multiple correlation from the regression analysis. Practice causes more improvement in the mouse and text keys than on the other two devices. The step keys, in particular, show very little improvement with practice. Equation 2 explains 39% of the variance in the average positioning time for a block of trials for the step keys, 61% to 66% for the variance for the other devices. The fit, at least for the mouse and the joystick, is actually better than these numbers suggest. Since subjects did 30 blocks of trials on a day typically followed by a pause of a day or two before they could be rescheduled, a break in the learning curve is expected at that point and indeed such a break is quite evident for the mouse and the joystick between the 30th and 31st blocks. Fitting Equation 2 to only the first day increases the percentage of variance explained to 91% for the mouse and 83% for the joystick. In case of the step keys and text keys there is no such obvious day effect.

Table 1. Learning Curve Parameters

DEVICE	T_1 (s)	α	Learning Curve Equation[a]	s_e (s)	R^2
Mouse	2·20	0·13	$T_N = 2{\cdot}20\, N^{-0{\cdot}13}$	0·12	0·66
Joystick	2·19	0·08	$T_N = 2{\cdot}19\, N^{-0{\cdot}08}$	0·08	0·62
Step Keys	3·03	0·07	$T_N = 3{\cdot}03\, N^{-0{\cdot}07}$	0·11	0·39
Text Keys	3·86	0·15	$T_N = 3{\cdot}86\, N^{-0{\cdot}15}$	0·16	0·61

[a] N is number of trial blocks. There are 20 trials in each block.

3.2. *Overall Speed*

In order to compare the devices after learning has nearly reached asymptote (as would be the case for office workers using them daily), a sample of each subject's performance on each device was examined consisting of the last 600 trials excluding the first 200 trials of a day (in order to diminish warm-up effects). The remaining analyses will be based on this subset of the data, excluding those trials on which errors occurred. Table 2 gives the homing time, positioning time, and total time for each device averaging over all the distances and target sizes. *Homing time* was measured from the time the subject's right hand left the space bar until the cursor had begun to move. *Positioning time* was measured from when the cursor began to move until the selection button had been pressed. From the table, it can be seen that homing time increases slightly with the distance of the device from the keyboard. The longest time required is to reach the mouse, the shortest to reach the step keys. Although the text keys are near the keyboard, they take almost as long to reach as the mouse. Either it is more difficult to position the hands on the text keys or, as seems likely, subjects often spent some time planning the strategy for their move in the time between hitting the space bar to start the clock and the time when they begin pressing the keys. Further evidence for this hypothesis comes from the relatively high standard deviation observed for the homing time of the text keys. While the differences in the homing times among all device pairs except the mouse vs. the text keys are reliable statistically (at $p < 0{\cdot}05$ or better using a t–test), the differences are actually quite small. For example,while the step keys can be reached 0·15 s sooner than the mouse, they take 1·02 s longer to position. Thus the differences in the homing times are insignificant compared to the differences between the positioning times.

Table 2. Overall Times

Device	Movement time for non-error trials (s)						Error rate	
	Homing Time		Positioning Time		Total Time			
	M	SD	M	SD	M	SD	M	SD
Mouse	0·36	0·13	1·29	0·42	1·66	0·48	5%	22%
Joystick	0·26	0·11	1·57	0·54	1·83	0·57	11%	31%
Step Keys	0·21	0·30	2·31	1·52	2·51	1·64	13%	33%
Text Keys	0·32	0·61	1·95	1·30	2·26	1·70	9%	28%

The mouse is easily the fastest device, the step keys the slowest. As a group, the continuous devices (the mouse and the joystick) are faster than the key-operated devices (the step keys and text keys). Differences between the devices are all reliable at $p \ll 0{\cdot}001$ using *t*-tests.

3.3 *Effect of Distance and Target Size*

The effect of distance on positioning time is given in Figure 3. At all distances greater than 1cm, the continuous devices are faster. The positioning time for both continuous devices seems to increase approximately with the log of the distance. The time for the step keys increases rapidly as the distance increases, while the time for the text keys increases somewhat less than as the log of the distance, owing to the existence of keys for moving relatively large distances with a single stroke. Again the mouse is the fastest device, and its advantage increases with distance.

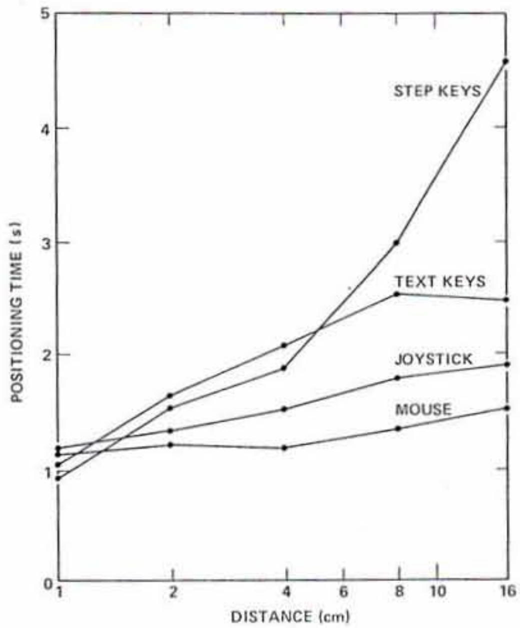

Figure 3. Effect of target distance on positioning time.

Figure 4 shows the effect of target size on positioning time. The positioning time for both the mouse and the joystick decreases with the log of the target size. The time for the text keys is independent of target size and the positioning time for the step keys also decreases roughly with the log of the target size. Again the mouse is the fastest device, and again the continuous devices as a group are faster for all target sizes.

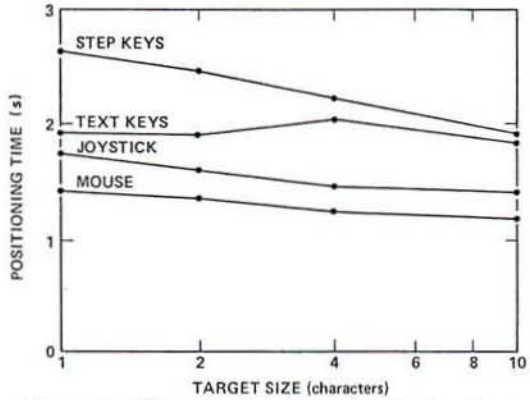

Figure 4. Effect of target size on positioning time.

3.4. *Effect of Approach Angle*

The targets in text editing are rectangles often significantly wider than they are high. Hence they might present a different problem when approached from different angles. In addition, the step keys and text keys work somewhat differently when moving horizontally than when moving vertically. To test if the direction of approach has an effect on positioning time, the target movements were classified according to whether they were vertical (0 to 22·5 degrees), diagonal (22·5 degrees to 67·5 degrees), or horizontal (67·5 degrees to 90 degrees). *Analysis of variance* shows the angle makes a significant difference in every case except for the mouse. The joystick takes slightly longer to position when the target is approached diagonally. The step keys take longer when approached horizontally than when approached vertically, a consequence probably deriving from the fact that a single keystroke would move the cursor almost twice as far vertically as horizontally. By contrast, the text keys take longer to position vertically, reflecting the presence of the WORD key. The differences induced by direction are not of great consequence, however. For the joystick it amounts to 3% of the mean positioning time; for the step keys 9% for the text keys 5%.

3.5. *Errors*

Of the four devices tested, the mouse had the lowest overall error rate, 5%; the step keys had the highest, 13%. The differences are reliable at $p<0\cdot05$ or better using *t*-tests. There is only a very slight increase in error rate with distance. However, there is a decrease in error rate with target size for every device except the text keys (Figure 5).

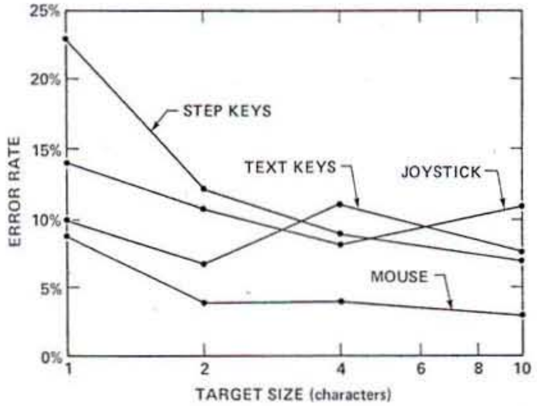

Figure 5. Effect of target size on error rate.

This finding replicates the result of Fitts and Radford (1966). In an investigation of self-initiated, discrete, pointing movements using a stylus, there was a similar marked reduction in errors as the target increased in size, but only a slight increase in error rate as the distance to the target increased.

4. Discussion

While these empirical results are of direct use in selecting a pointing device, it would obviously be of greater benefit if a theoretical account of the results could be made. For one thing, the need for some experiments might be obviated; for another, ways of improving pointing performance might be suggested. Fortunately, a first-order account for the devices of this experiment is not hard to give.

4.1. *Mouse*

The time to make a hand movement can be described by a version of Fitt's Law (Welford 1968),

$$T_{\text{pos}} = K_0 + K \log_2 (D/S + 0{\cdot}5) \text{ s} \tag{3}$$

where

T_{pos} = Positioning time,

D = Distance to the target,

S = Size of the target,

and

K_0, K = constants.

Here the constant K_0 includes within it the time for the hand initially to adjust its grasp on the mouse and the time to make the selection with the selection button. A constant of $K \simeq 0{\cdot}1 \text{ s bit}^{-1}$ (10 bits s^{-1}) appears in a large number of studies on movement. This number is a measure of the information processing capacity of the eye-hand coordinate system. For single, discrete, subject-paced movements, the constant is a little less than $0{\cdot}1 \text{ s bit}^{-1}$. Fitts and Radford (1966) get a value of $0{\cdot}078 \text{ s bit}^{-1}$ (12·8 bit s^{-1}, recomputed from their Figure 1, Experiment 1, for the experimental condition where accuracy is stressed). Pierce and Karlin (1957) get maximum rates of $0{\cdot}085 \text{ s bit}^{-1}$ (11·7 bits s^{-1}) in a pointing experiment. For continous movement, repetitive, experimenter-paced tasks, such as alternately touching two targets with a stylus or pursuit tracking, the constant is slightly above $0{\cdot}1 \text{ s bit}^{-1}$. Elkind and Sprague (1961) get maximum rates of $0{\cdot}135 \text{ s bit}^{-1}$ (7·4 bits s^{-1}) for a pursuit tracking task. Fitts's original dotting experiment as replotted by Welford (1968, p. 148) gives a K of 0·120 bit^{-1} as does Welford's own study using the actual distance between the dots, the same measure of distance used in this study.

Fitts's Law predicts that plotting positioning time as a function of $\log_2 (D/S + 0{\cdot}5)$ should give a straight line. As the solid line in Figure 6 shows, this prediction is confirmed. Furthermore, the slope of the line K should be in the neighborhood of 0·1 sec/bit. Again the prediction is confirmed. The equation for the line in Figure 6 as determined by regression analysis is

$$T_{\text{pos}} = 1{\cdot}03 + 0{\cdot}096 \log_2 (D/S + 0{\cdot}5) \text{ s} \tag{4}$$

The equation has a standard error of 0·07 s and explains 83% of the variance of the means for each condition. This is roughly comparable to the percentage of variance explained by Fitts and Radford. The slope of 0·096 bit s^{-1} is in the 0·1 bit s^{-1} range found in other studies. Since the standard error of estimate for K is 0·008 bit s^{-1}, the mouse would seem to be close to, but slightly slowerrthan, the optimal rate of around 0·08 bit s^{-1} observed for the stylus and for finger pointing.

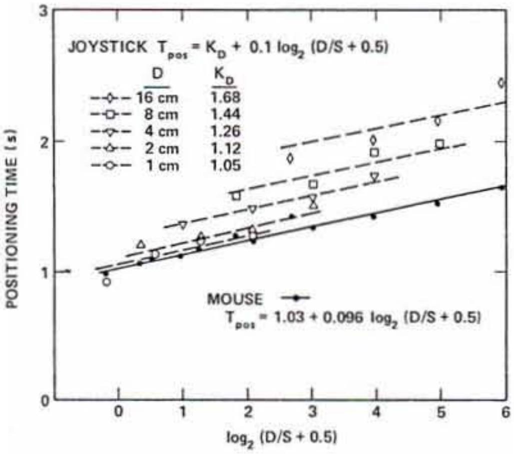

Figure 6. Positioning time for continuous devices as a function of Fitts's index of difficulty $\log_2(D/S+0{\cdot}5)$.

The values for positioning time obtained in this experiment are apparently in good agreement with those obtained by English *et al.* Making the assumption that their CRT characters were about the same width as ours and assuming an intermediate target distance of about 8 cm, Equation 4 (plus the addition of the 0·36 s homing time from Table 2) predicts 1·87 s for 1 character targets (English *et al.* reported 1·93 s) and 1·66 s for 'word' targets of 5 characters (English *et al.* reported 1·68 s).

4.2. *Joystick*

Although it is a rate-controlled device instead of a position device, we might wonder if the joystick follows Fitts's Law. Plotting the average time per positioning for each distance × size cell of the experiment according to Equation 3 shows that there is an approximate fit to

$$T_{\text{pos}} = 0{\cdot}99 + 0{\cdot}220 \log_2 (D/S + 0{\cdot}5). \tag{5}$$

Equation 5 has a standard error of 0·13 s and explains 89% of the variance of the means. The size of the slope K shows that information is being processed at only half the speed as with the mouse and significantly below the maximum rate. Closer examination gives some insight into the difficulty. The points for the joystick in Figure 6 actually form a series of parallel lines, one for each distance, each with a slope of around 0·1 bit s^{-1}. Setting K to 0·1 bit s^{-1}, we can therefore write as an alternative model

$$T_{\text{pos}} = K_D + 0{\cdot}1 \log_2 (D/S + 0{\cdot}5).$$

K_D is the intercept for distance D. From the figure, K_D is about 1·05 s for $D = 1$ cm, 1·12 s for 2 cm, 1·26 s for 4 cm, 1·44 s for 8 cm, and 1·68 s for 16 cm. For this model the standard error of the fit is reduced to 0·07 s, the same as for the mouse. (Since the slope was not determined by the regression, a comparable R^2 cannot be computed.) Thus the tested joystick can be thought of as a Fitts's Law device with a slope twice that for hand movememts; or it can be thought of as a Fitts's Law device with the expected slope, but having an intercept which increases with distance. The problem with this joystick is probably related to the non-linearity in the control (Poulton 1974, Craik and Vince 1963). It should be noted that for the 1 cm distance (where the effect of non-linearity is slight) the positioning time is virtually the same as for the mouse. Thus the possibility of designing a joystick with performance characteristics comparable to the mouse is by no means excluded.

4.3. *Step Keys*

As a first approximation one might expect the time to use the step keys to be governed by the number of keystrokes which must be used to move the cursor to the target. Since the keys can only move the cursor vertically or horizontally, the number of keystrokes is $D_x/0{\cdot}456+D_y/0{\cdot}246$, where D_x and D_y are the horizontal and vertical components of distance to the target; 0·456 cm is the size of a vertical step and 0·246 cm is the size of a horizontal step. Hence positioning time should be

$$T_{\text{pos}}=K_0+C(D_x/0{\cdot}456+D_y/0{\cdot}246). \tag{6}$$

This equation with $K_0=1{\cdot}20$ s and $C=0{\cdot}052$ s keystroke^{-1} has a standard error of 0·54 s and explains 84% of the variance of the means.

Since the tapping rate is around 0·15 s keystroke^{-1}, C is much too fast to be identified with the pressing of a key. It is also too fast to be identified with the 0·067 s keystroke^{-1} automatic repetition mode. Figure 7 shows positioning time plotted against the predicted number of keystrokes. The long solid line is Equation 6 with the above parameters. The figure shows that positioning time is linear with the number of keystrokes until the predicted number of keystrokes becomes large (that is, the distance to the target is long). In these cases the user often has the opportunity to reduce positioning time by using the HOME key. Fitting Equation 6 to the first part of the graph ($D_x/0{\cdot}456+D_y/0{\cdot}246<40$) gives

$$T_{\text{pos}}=0{\cdot}98+0{\cdot}074\,(D_x/0{\cdot}456+D_y/0{\cdot}246).$$

The equation, indicated as a short solid line on the figure, has a standard error of 0·18 s and explains 95% of the variance in the means. The reasonable slope of 0·074 s keystroke^{-1} shows that the 0·067 s keystroke^{-1} automatic repetition feature was heavily used.

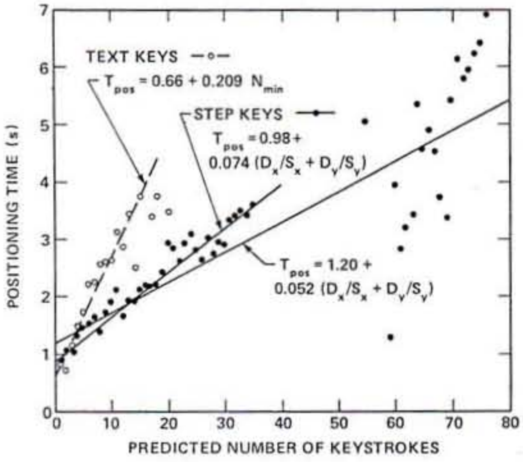

Figure 7. Positioning time for key devices as a function of predicted number of keystrokes.

4.4. *Text Keys*

The text keys present the user on most trials with a choice of methods to reach the target. For example, he might press the PARAGRAPH key repeatedly until the cursor has moved to the paragraph containing the target paragraph. He could then press the LINE key repeatedly until it is on the target line, then use the WORD key to bring it over to the target. Or he might use the PARAGRAPH key to bring it over to the target,then holding, the REVERSE key down, use the LINE key to back up to the line after the target line. And finally, using REVERSE and WORD, back up until he hits the target. In fact, there are 26 different methods for moving the cursor to the target, although only a subset will be possible in a given situation. The fastest method will depend on where the target is located relative to the starting position and the boundaries of surronding lines and paragraphs.

A reasonable hypothesis would be that positioning time is proportional to the number of keystrokes and that for well practiced subjects the number of keystrokes will be minimum necessary. To test this hypothesis each trial was analysed to determine the minimum number of keystrokes $N_{\min}$ necessary to hit the target. The average positioning time as a function of $N_{\min}$ is plotted as the open circles in Figure 7. A least squares fit gives

$$T_{\mathrm{pos}} = 0{\cdot}66 + 0{\cdot}209\ N_{\mathrm{min.}}$$

The standard is 0·24 s and the equation explains 89% of the variance of the means. The keystroke rate of 0·209 s keystroke^{-1} is very reasonable, being approximately equal to the typing rate for random words (Devoe 1967). Evidently, the automatic repetition mode was little used. Examination of some statistics on the minimum numbers of keystrokes for each trial shows there was little need for it. For one thing, an average of only six keystrokes was necessary for the text keys to locate a target word. Ten or fewer keystrokes were sufficient for over 90% of the targets. For another, these keystrokes were distributed across several keys, further limiting opportunities to use the repetition mode. The PARAGRAPH key was needed on 48% on the trials, the LINE key on 85%, the word key on 83%, and the REVERSE key on 81%.

4.5. *Comparison of Devices*

Table 3 summarises the models, the standard of the fit, and the percentage of variance between the means explained by the model.

Table 3. Summary of Models for Positioning Time (T_{pos})

Device	Model (times in s)	s_e	R^2
Mouse	$T_{\mathrm{pos}} = 1{\cdot}03 + 0{\cdot}096 \log_2 (D/S + 0{\cdot}5)$	0·07	0·83
Joystick	$T_{\mathrm{pos}} = 0{\cdot}99 + 0{\cdot}220 \log_2 (D/S + 0{\cdot}5)$[a]	0·13	0·89
	$T_{\mathrm{pos}} = K_d + 0{\cdot}1 \log_2 (D/S + 0{\cdot}5)$[b]	0·07	—
Step Keys	$T_{\mathrm{pos}} = 1{\cdot}20 + 0{\cdot}052 (D_x/S_x + D_y/S_y)$[c]	0·54	0·84
	$T_{\mathrm{pos}} = 0{\cdot}98 + 0{\cdot}074 (D_x/S_x + D_y/S_y)$[d]	0·18	0·95
Text Keys ,	$T_{\mathrm{pos}} = 0{\cdot}66 + 0{\cdot}209\ N_{\min}$	0·24	0·89

[a] Least squares fit to all data points.

[d] Fit for number of keystrokes $(D_x/S_x + D_y/S_y) < 40$,

[c] Least squares fit to all data points.

[b] Fitting a separate line with slope 0·1 bit s^{-1} for each distance.

where HOME key unlikely to be used.

The match of the Fitts's Law slope to the roughly $K \simeq 0{\cdot}1$ s bit^{-1} constant observed in other hand movement and manual control studies means that positioning time is apparently limited by central information processing capacities of the eye-hand guidance system (*cf.* Welford 1968, Glencross 1977). Taking $K = 0{\cdot}08$ s bit^{-1} as the most likely minimum value for a similar movement task, and $K_0 = 1$ s as a typical value observed in this experiment, it would seem unlikely that a continuous movement device could be developed whose positioning time is less than $1 + 0{\cdot}08 \log_2 (D/S + 0{\cdot}5)$ s (unless it can somehow reduce the information which must be centrally processed), although something might be done to reduce the value of K_0. If this is true, then an optimal device would be expected to be no more than about 5% faster than the mouse in the extreme case of 1 character targets 16 cm distant ($1 + 0{\cdot}095 \log_2 (16/1 + 0{\cdot}5) = 1{\cdot}38$ s *vs.* $1 + 0{\cdot}08 \log_2(16/1 + 0{\cdot}5) = 1{\cdot}32$ s). Typical differences would be much less. By comparison in this same case, the joystick (in this experiment) is 83% slower than the optimal device, the text keys 107% slower, and the step keys 239% slower. Even if K_0 were zero, the mouse would still be only 23% slower than the minimum. While devices might be built which improve on the mouse's homing time, error rate, or ability for fine movement, it is unlikely their positioning times will be significantly faster.

This maximum information processing capacity probably explains the lack of any significant difference in positioning time between the lightpen and the lightgun in Goodwin's experiment. Both are probably Fitts's Law devices, so both can be expected to have the same maximum $0{\cdot}1$ s bit^{-1} rate as the mouse (if they are optimised with respect to control/display ratio and any other relevent variables).

In interpreting these results, highly favourable to the mouse, some qualifications are in order. Of the four devices, the mouse is clearly the most 'compatible' for this task (*cf.* Poulton 1974, Chapter 16), meaning less mental translation is needed to map intended motion of the cursor into motor movement of the hands than for the other devices. Thus it would be expected to be easier to use, put lower cognitive load on the user, and have lower error rates. There are, however, linits to its compatibility. Inexperienced users are often bewildered about what to do when they run the mouse into the side of the keyboard trying to move the cursor across the screen. They need to be told that their mice can simply be picked up and deposited at a more convenient place on the table without affecting the cursor. Even experienced users are surprised at the results when they hold their mice backwards or sideways.

The greatest difficulty with the mouse for text-editing occurs with small targets. Punctuation marks such as a period are considerably smaller than an average character. The error rate for the mouse, which was already up to 9% for one character targets, would be even higher for these sorts of targets.

5. Summary and Conclusion

Of the four devices tested the mouse is clearly the superior device for text selection on a CRT:

1. The positioning time of the mouse is significantly faster than that of the other devices. This is true overall and at every distance and size combination save for single character targets.
2. The error rate of the mouse is significantly lower than that of the other devices.
3. The rate of movement of the mouse is nearly maximal with respect to the information processing capabilities of the eye-hand guidance system.

As a group the continuous movement devices are superior in both speed and error-rate.

For the continuous movement devices, positioning time is given by Fitts's Law. For the key devices it is proportional to the number of keystrokes.

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Quatre dispositifs ont été évalués en fonction de la rapidité de leur utilisation pour une sélection de textes sur l'écran d'un oscilloscope. La balladeuse s'est avérée être la plus rapide et la plus précise. On a montré que les variations dans les temps de positionnement avec la balladeuse et le levier de commande pouvaient être expliquées par la loi de Fitts. Dans le cas de la balladeuse, la pente de la droite de Fitts est proche de celle qui a été trouvée dans d'autres tâches de coordination oeil—main, ce qui semble indiquer que le temps de positionnement avec ce dispositif, est le plus court possible. Les temps de positionnement avec des touches est proportionnel au nombre de frappes nécessaires.

Es wurden vier Einrichtungen untersucht, um festzustellen, wie schnell Textstellen auf einem CRT-Display ausgewählt werden können. Die Einrichtung 'mouse' konnte in allen Fällen als die schnellste bei gleichzeitig geringster Fehlerhäufigkeit ermittelt werden. Die Ergebnisse machen deutlich, daß die Variationen der Positionierungszeiten bei den Einrichtungen 'mouse' und 'joystick' dem Gesetz nach Fitts entsprechen. Bei den Untersuchungen mit 'mouse' entsprach die gemessene Funktionskonstante des Fitt-Gesetzes den Konstanten, die bei anderen Auge-Hand-Tätigkeiten gefunden wurden. Diese Tatsache führt zu dem Schluß, daß bei dieser Einrichtung die minimal möglichen Positionierungszeiten erreicht werden. Die Positionierungszeit für Tasteneinrichtungen ist nach den Ergebnissen proportional zur Anzahl notwendiger Tastungen.

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