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AN EVALUATION OF DISPLAY/CONTROL GAIN IN THE CONTEXT OF CONTROL-DISPLAY INTERFACE OPTIMIZATION

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(ABSTRACT)

Display/control gain is the amount of movement that occurs on a display in response to a unit amount of movement on the control. Two studies were conducted to determine the adequacy of identifying the optimum gain for an interface as a method of control-display interface optimization.

The first study examined the effects of changes in both the maximum control input and the display width on target acquisition performance with a touch tablet and a trackball. The hypothesis that an interaction between the control input and the display output would determine performance was not supported for either device. There was a main effect of the control input for the touch tablet, and significant effects of the control input and the display width for the trackball. The results also indicate that, at least for the touch tablet, gain is not a sufficient specification for performance.

The second study evaluated the effects of changes in the display amplitude, the display target width, and the control amplitude. There were significant interactions among these three factors for both touch tablet and trackball target acquisition performance. These results extend the findings of the first study with respect to the inability of gain to predict performance. In addition, the inadequacy of Fitts' Law as it applies to the given interfaces is discussed.

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INTRODUCTION

Visual displays have become a popular method of transmitting information in many workplaces. Continuous manual computer input devices such as trackballs, mice, and joysticks are frequently used to interact with the displays. An important feature of these control-display interfaces is that the input device is physically separate from the displayed output.

To optimize such interfaces, a traditional technique has been to identify the display/control (D/C) gain resulting in the best user performance. Gain may be defined as the ratio of system output to control input; that is:

$$\text{Gain} = \frac{\text{system (display) output}}{\text{control input}}. \qquad (1)$$

In the following discussion it will be assumed that the system output refers to output on a visual display. A low gain occurs when a large control input is necessary to obtain a small display cursor movement. Conversely, a high gain results when a small control input leads to a large display cursor output. Gain values may be changed by altering the display output, the control input, or both these parameters.

The practice of identifying an optimal gain as a means of optimizing an interface assumes that the composite value of gain adequately reflects the effects of the separate display and control parameters and is sufficient to predict performance. For this assumption to hold true, a necessary condition is that the method of changing gain should not affect performance. For instance, halving the control input should result in the same performance change as would a doubling of the display output because both of these changes would lead to the same numeric value of gain.

To determine whether identifying an optimal D/C gain is an adequate means of optimizing an interface, it is necessary to test this condition. That is, are changes in the control and changes in the display leading to the same numeric value of gain actually identical in terms of their effects on performance? In an attempt to answer this question, it is beneficial to consider what happens to the interface from the user's point of view when each of the three different methods is used to change gain. Remember that gain can be altered by changing display output, control input, or both. For the following discussion, assume that both control input and display output are measured in centimeters. Further, assume that the control can be displaced and that the maximum control input is 10 cm. (It should be noted that while the following discussion assumes a control that may be displaced linearly, the same concepts hold true for any zero-order control; it is the nature of the task that is critical.) If the active area of the display is also 10 cm, the gain for the interface is 1.0. To move the display cursor 5 cm, a 5-cm input is required.

The gain on the interface just described may be increased to 2.0 in three ways. First, the active area of the display may be increased to 20 cm while the maximum control input remains at 10 cm. Second, the maximum control input may be reduced to 5 cm while the display remains at 10 cm. Finally, both the display output and the control input may be modified; for example, the display size may be changed to 15 cm while the maximum control input becomes 7.5 cm.

These three different methods of changing gain are equivalent in terms of both visual input to the observer and required control movement by the observer for any given value of gain if the task is to move the display cursor the same distance on the display. For instance, when the gain was 1.0, a 5-cm display movement was achieved by a 5-cm control input. Now, when the gain is 2.0, the same 5-cm display movement must be produced by a 2.5-cm control input. This holds true regardless of which of the three methods just described was used to achieve a gain of 2.0, as is depicted in the left side of Figure 1.

In this case, the nature of the task forces the display output to remain constant across all values of gain; the only parameter free to vary, then, is the control input. Regardless of how the gain changes were achieved in the controlling hardware or software, the only change of practical significance from the point of view of the operator is that the control input has changed. Buck (1980) recognized this fact and stated that while the experimenter may modify either the control or the display, from the operator's point of view only the control input has changed, and "...the conceptual nature of the linkage between the two may in fact affect his performance, but if so it has yet to be demonstrated" (p. 580).

The validity of the necessary condition of equal effects of changes in the control and the display is irrelevant to this task because the display output never changes and it does not matter if display output affects performance differently than control input. Note that in this case the effects of gain and control input are totally confounded, and that a test of changes in gain is equivalent to a test of changes in control input.

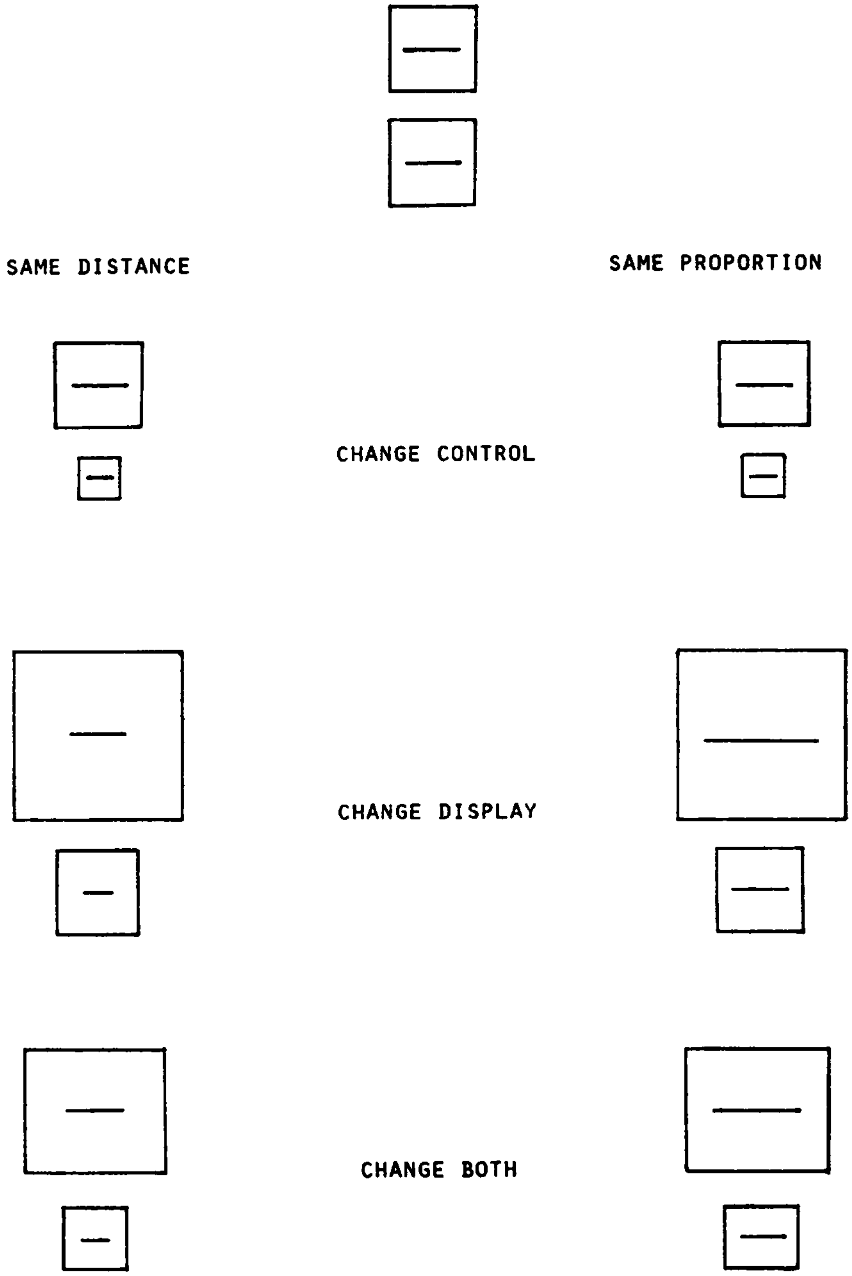


Figure 1: The Effects of Three Methods of Changing Gain.

However, if the task requires that the subject move the cursor across some proportion of the display in all gain conditions, then the method of changing gain indeed makes a difference, as is depicted in the right side of Figure 1. To illustrate this, again assume a starting display size and maximum control input of 10 cm, and an initial gain of 1.0. If the original task required subjects to move a cursor across half of the display, or 5 cm, then the control input is also 5 cm with a gain of 1.0 (for this task). As before, if the display is modified to achieve a gain of 2.0, the display must be increased to 20 cm, while the control input remains the same. If a subject is required to move the cursor across half of the new 20-cm display, or what is now a distance of 10 cm, the control input must be 5 cm; thus, the control input remains the same as it was for a gain of 1.0 while the display output changes.

Next, assume that given the original interface, the gain is changed to 2.0 through a change in the range of movement allowed on the control. In this case, the maximum control input will decrease to 5 cm while the display is still 10 cm. Now, to move the cursor halfway across the display, or 5 cm, the control input must be 2.5 cm. Thus, in this case, when the gain is changed from 1.0 to 2.0 through a change in the control, the required control input changes, while when gain was changed through a change in the display, the display output was altered.

If <u>both</u> the control and the display are altered to change gain, there is yet another result when moving the cursor across a given proportion of the display. As indicated previously, it is possible to change the gain on the standard interface to 2.0 by increasing the display size to 15 cm while simultaneously reducing the maximum control input to 7.5 cm. In this case, to move halfway across the display, or 7.5 cm, a 3.75-cm control movement is required and thus <u>both</u> the control input and the display output are altered.

It is evident, then, that in a task that allows both the display output and the control input to change across the range of gains, the three methods of changing gain will not produce equivalent changes in the interface for a given value of gain. Because gain is no longer confounded with control input, the parameter that is modified to produce the gain changes will determine what will change in the interface from the user's point of view. A modification in the active area of the display will be reflected in differences in display output across gains. Modifications in the maximum control input will result in changes in control input across the range of gains. Changes in both parameters will lead to changes in both the control and the display across the gains.

To summarize what has been stated thus far, the nature of the task is important in considering the effects of the different methods of changing gain and of the gain values chosen. If the task is to move a cursor the same distance with all gains, then the method of changing gain is unimportant because the same control inputs and display outputs are produced in any case. No differences in performance would be expected to result across different methods of changing gain. If, however, the task requires that the cursor move across the same proportion of the display across all gains (that is, if the display size is allowed to vary), then the method of changing gain is indeed important, because different methods lead to different required control inputs and/or display outputs. In this case we may expect to see changes in performance depending upon the method used to change gain if the effects of changing the display and the control parameters are not equivalent.

A final point should be made regarding gain and the nature of the task when both the display and the control are changed simultaneously without changing the value of gain. For example, suppose we have the same 10-cm display and control amplitudes and the corresponding gain of 1.0 assumed previously. Now, suppose both the control and the display amplitudes are enlarged by a factor of two. Five cm of movement on the control still produce 5 cm of cursor displacement; thus, the gain is still 1.0. If the task is to move a cursor the same distance on the display as changes are made in the interface, then neither the control input nor the displayed output changes; a 5-cm control input still produces the required 5-cm display output. However, if the task requires the subject to move the cursor across half the display in both cases, a 10-cm control movement is now required to produce the new 10-cm display movement. Thus, a given value of gain implies nothing about the control input and display output used to achieve that gain. Differences in the control input and the display output may lead to variations in performance even when the gain values for the interface are the same across all of the control-display set-ups.

A second point that is important to note when attempting to identify an optimal gain stems from the fact that the specific numeric value of gain is dependent upon the nature of the interface and, to some extent, the experimenter's preference in the choice of the units of measurement. System output has been defined in terms of linear units such as inches or millimeters (see, for example, Jenkins and Karr, 1954) and degrees of visual angle subtended (Gibbs and Baker, 1952; Jagacinski, Hartzell, Ward, and Bishop, 1978). Control input has been measured as number of knob turns (Jenkins and Connor, 1949), linear units (Jenkins and Karr, 1954), angular movement of the controlling limb (Gibbs, 1962), and force applied to a control device (Gibbs and Baker, 1952; Tipton and Birmingham, 1959).

The choice of units for the control input may be tied to the nature of the input device; for example, a device that is not displaced, such as a force joystick, cannot be measured in terms of units of displacement. There is some latitude, however, with devices that can be displaced; for example, the movement of a device may be measured in linear distance or as the angular movement of the controlling limb apart from the device itself.

The display units may be either linear units or degrees of visual angle, and it is typically assumed that these values are interchangeable. This assumption holds true when the display is always a given distance from the operator. If the user sits at different distances from the same display, however, linear units will not change but the subtended visual angle will. Similarly, at different distances, if the visual angle remains constant the display linear units of displacement must change, and thus the linear measurements will vary. Thus, if the user will sit at different distances from the display the assumption that these values are interchangeable cannot be valid.

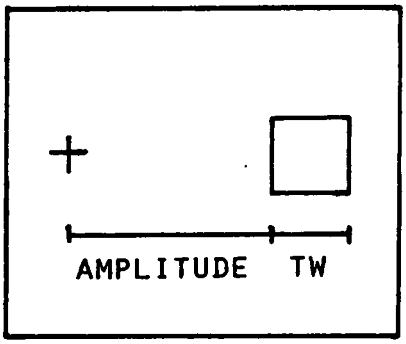
When the control and the display units are the same, gain becomes a measure of relative displacement. For example, a gain of 0.5 means that the controlled element on the display moves 50% of the distance travelled by the control. When the display and control units are different, however, gain cannot be interpreted in this manner.

It is clear from the above discussion that the numeric value of gain depends upon the units chosen. The arbitrariness of the specific numeric gain value is not a real problem for a given interface since gain values can be easily converted from one unit of measurement to another. As long as all gains for an interface are measured in the same manner, they are comparable (although it is obviously difficult, if not impossible, to compare gains across interfaces).

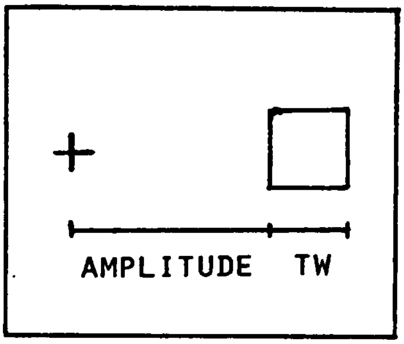
The second problem arises because upon further consideration it becomes clear that in addition to the fact that the units of measurement for the display and the control may be somewhat arbitrary, the choice of exactly what is measured in these units is also somewhat arbitrary.

Assume that the user's task involves positioning a cursor at a designated area or target on the display such as a word, a character, or a box. A distinction can then be made between: 1) the size of the active area of the display (and the corresponding distance moved by the cursor on the display from its starting position to the target area), or what will be referred to as the display amplitude, and 2) the display target width, or the size of the target on the display. Similarly, control input consists of: 1) the control movement amplitude, or the distance from the starting position to the target as measured on the control, and 2) the control target width, which is the size of the target represented on the control. These components are shown in Figure 2.

Gain can be defined in two ways, using the above distinction; either as the ratio of display amplitude to control amplitude or as the ratio of the display target width to the control target width. The difference in definition is not very important by itself since, as indicated previously, it is always possible to calculate gain according to either definition. The significance of the differences in the definitions lies in the fact that in either case only two of the four control-display components are included. Thus, the second difficulty is that the use



DISPLAY



CONTROL

Figure 2: The Four Control-Display Components.

of gain as a specification of an interface obscures the fact that at least three of these four components may be changed independently (once three are fixed, the fourth is obviously determined).

In summary, the above discussion points to two areas in which gain may be inadequate as a specification of an interface. First, it is possible that the method of changing gain may lead to empirical differences in user performance if the task allows both control input and display output to vary. That is, the three methods of changing gain may not be equivalent and thus the assumption that the composite gain value is sufficient to describe performance may be unwarranted. Second, the use of gain as the sole descriptor of an interface may hide other components of the interface that could also affect certain aspects of performance. In the following section, research concerned with D/C gain will be reviewed and evaluated in an attempt to explore these issues.

LITERATURE REVIEW

The typical paradigm used to study D/C gain is as follows: gain is varied through either a change in displayed output or the required control input, and the effect of this change on operator performance is measured. The task is usually target acquisition; that is, a displayed cursor must be positioned at a target on a screen. In early studies of gain, subjects were often required to align a pointer on a scale.

Performance is typically defined in terms of the time taken to position the cursor; the inverse value, target acquisition rate, may also be used. In addition, movement time can be divided into components such as reaction time, time to reach the target area (a measure of gross movement), time to position the cursor in the target once the target area is reached (a measure of fine adjustment), and time to confirm the acquisition. Other dependent measures are acquisition accuracy, the number of times the cursor overshoots the target, and the number of entries the cursor makes into the target prior to confirmation.

One of the earliest investigations of D/C gain was reported by Jenkins and Connor (1949). The control device was a 7-cm diameter knob. Turning the knob led to movement of a pointer on a linear scale. Gain was defined as inches of pointer movement relative to the number of knob turns made, and it was changed by modifying the amount of control movement resulting in a given pointer movement. Ten gain values from 0.22 to 33.6 were tested. Subjects were required to align the pointer at each of 10 settings on the scale using all of the gain values. The same scale was used as the display for all conditions. Thus, the task required that subjects move the pointer the same distances on the scale under all conditions.

The optimum gain in terms of total positioning time was 1.18. A U-shaped performance curve was obtained; at gains lower than 1.18, gross movement times increased, while at higher gains fine positioning times increased. The authors stated that gain affected performance more than changes in knob diameter, error tolerance, or backlash. In addition, Jenkins and Olson (1952) reported that gain was more important than either friction or inertia in determining performance. The effects of the distance from the initial pointer position to the target were not reported.

Jenkins and Olson (1952) conducted a series of studies using a lever and the same linear scale described for the previous study. In the first two experiments, several shaft-turn ratios or gains were tested. Gain was defined as inches of pointer-tip movement for one complete turn of the lever shaft. Somewhat surprisingly, the authors do not report the gain values tested, nor is an optimum value given. Gain was modified by changing the control; that is, the amount of lever movement was changed while the display was not modified. The task again required subjects to align the pointer on the scale using all of the gain values, moving the same distances on the scale in all cases.

In a third study, the authors found that a wide pointer with a wide target led to better performance in terms of total positioning time than a narrow pointer with a narrow target, regardless of the tolerance for error allowed. This finding suggests that the target width and pointer size may affect performance by themselves. The authors do not state whether varying gains were tested along with the varying error tolerances and pointer sizes.

The authors performed additional experiments using lever lengths from 10.16 to 76.2 cm, and two shaft-turn ratios, 16.3 and 33.6. A lever-tip movement to pointer movement (L/P) ratio was calculated as follows:

$$L/P = \frac{\text{lever length in cm} \times 2\pi}{\text{inches of pointer tip movement for one complete turn of shaft}} . \qquad (2)$$

L/P ratios varied between 0.75 and 11.56. The optimum L/P ratio was between 3.0 and 4.0. The authors indicate that this optimum ratio held regardless of what combination of lever length and shaft-turn ratio (the term in the denominator) was used to achieve it. The important fact was stated to be that "...the lever tip should travel three or four times as fast as the pointer" (p. 270).

Jenkins and Karr (1954) extended the concept of D/C gain to a two-dimensional input device, the joystick. The display was a 30.5-cm aluminum disc used to simulate an oscilloscope. The L/P ratio just described was calculated using lever lengths from 30.5 to 76.2 cm. The value used in the denominator of the L/P ratio was modified by changing the amount of control movement that resulted in the maximum display response. The same display was used in all conditions.

All subjects were tested with all L/P ratios. The task was to align the cursor at one of nine possible settings on the disc, and the cursor moved the same distances on the display in all conditions. L/P ratios between 1.0 and 3.9 were tested. A ratio of 2.5 (that is, the tip of the joystick moves 2.5 times faster than the cursor) was found to be optimal in terms of positioning time, variability, and mis-settings.

Gibbs (1962) investigated the effects of both time lags and gain for positional and velocity systems. The control was a joystick and the subject's task was to move a spot of light 2.25 cm along a line on a CRT; this distance was the same in all conditions. Three joysticks were tested; a 9-cm joystick was used with the thumb, a 12-cm joystick was used with the hand, and a 32.5-cm joystick was used as a forearm control. Display lags ranged from zero to 2.0 seconds for both positional and velocity systems. For both the positional and velocity systems, gain was changed by varying the movement of the cursor on the display relative to a constant joystick deflection. All subjects performed the task using all combinations of gain, lag, and joystick length.

For the positional system, displacement of the joystick led to a proportional linear displacement of the spot of light on the display. Six gains from 0.15 to 0.90 were used; gain was defined as the visual angle of spot movement on the display relative to the angular movement of the joystick and limb about their respective "mechanical and anatomical pivots." For this system, there was a significant Gain x Lag interaction, such that the optimal gain depended upon the lag. With no lag in the system, the lowest gain of 0.15 resulted in the best performance in terms of total time to target, and there was an increasing monotonic relationship between gain and total time to target. As lag was introduced, U-shaped curves were found, with the optimal gain occurring at 0.3 for a 0.08-s lag, and at 0.5 for lags from 0.20 to 2.0 s. The same pattern of results occurred for all three limbs, with the hand control resulting in the best overall performance. The effect of gain varied depending upon the limb used; for example, the thumb was more affected by a change in gain than was either the arm or the hand.

In a second experiment, Gibbs used a velocity control in which gain was defined as radians of visual angle subtended by the cursor movement on the display per second relative to one radian of joystick movement. Seven different rates of cursor movement on the display were used to provide gains from 0.4 to 4.0 s^{-1}. The results indicated U-shaped curves for all lags and the three different limbs. Under all conditions of lag, a gain of 1.5 s^{-1} was the best of all values tested for the three limbs. However, although a gain of 1.3 s^{-1} was not tested, Gibbs states that this value is optimal if the data are used to predict performance.

Gibbs' (1962) work indicates that positional and velocity systems using the same control and display provide different results in terms of optimal gains and that lags affect the optimal gains found for positional systems. The limb used for control movements may also influence the results in positional systems. In addition, Gibbs makes three observations. First, he states that there is no mathematical formula for determining the optimal gain for a system a priori; that is, gain is simply an independent variable that may be defined in several ways and empirically related to several aspects of user performance. Second, Gibbs also states that had an increase in accuracy rather than a decrease in movement time been the desired criterion, the optimal gain obtained would tend to decrease. Thus, optimal gain may also be affected by the criterion used to measure task performance.

Third, for the positional system, the optimal gain for each limb required approximately the same angular limb movement but different joystick movements. Thus, Gibbs suggests that it is the similarity of the angular movement of the limb and not of the joystick movement that is critical in comparing gains for controls using different limbs. He states that angular measures of limb movements were a more generalizable measure of the control input for the positional system than linear joystick movements would have been. This appears to be the opposite of what Jenkins and Olson (1952) reported. As indicated previously, in a study using levers of different lengths to move a pointer on a display, Jenkins and Olson stated that it was the number of centimeters traversed by the hand as it turned the lever that was significant in determining performance, and not the number of turns of the lever. Presumably, the number of turns of the lever is more analagous to an angular measure of limb movement.

Hammerton (1962) examined the effects of D/C gain on a velocity control system similar to that of Gibbs (1962). Using an 8.89-cm joystick, subjects were required to move a spot of light 2.25 cm on a CRT. This distance did not change across conditions. Gain was defined in the same manner as Gibbs (1962) defined it for the velocity control; that is, as the ratio of the angular velocity of the cursor in radians per second to the angular displacement of the joystick in radians. While Gibbs (1962) varied gain through a change in cursor speed on the display, Hammerton modified gain by changing the control; that is, the maximum amount of joystick deflection was changed while the maximum speed of the spot on the display was not altered. The gains tested varied from 0.78 to 8.68 s^{-1}, and all subjects were tested using all gains.

Hammerton hypothesized that the U-shaped curves reported by other researchers such as Gibbs were due to the method used to change gain. Specifically, Gibbs had altered the maximum possible cursor velocity in his velocity system. Hammerton suggested that if the maximum possible cursor velocity is always the same while the maximum possible control movement is varied (in this case the amount of joystick deflection), then gross movement or acquisition time would not be affected if a short-travel joystick was used. Because gross movement is responsible for increases in movement times at low gains, Hammerton hypothesized that "...the curves relating gain to performance time should be level over low and moderate gains, only rising with high gains because of difficulty in settling on the target" (p. 540).

Hammerton did not find a U-shaped curve such as that reported by Gibbs for the velocity system. Rather, movement times for the low gains were similar while movement times increased at higher gains. Hammerton interpreted these results as supporting his hypothesis that a change in gain made by changing joystick rather than cursor movement does not affect gross movement or acquisition time while fine adjustment or settling time is still affected by an increase in gain.

There are several problems with Hammerton's study and his interpretation of the results. First, it is unclear why he did not expect a change in joystick movement and therefore required limb movement to affect gross movement times, even if a short-travel joystick was used. Second, he did not separate his dependent measure, total time, into what he called acquisition and settling time; thus, it is not possible to determine the validity of his hypothesis.

Third, although Hammerton stated that he changed gain by using five joystick deflections, he also crossed these values with five maximum cursor velocities, thereby obtaining 25 different conditions, or "...five values of gain on five separate curves of equal velocity" (p. 540). Thus, Hammerton did include conditions with differing cursor velocities for a given joystick displacement, but he did not compare conditions having the same gain achieved through the two different methods. Differences between the two methods of gain are only inferred by comparisons with Gibbs' (1962) data. These comparisons are tenuous since Hammerton did not include gains lower than 0.78 s^{-1} in his study, and Gibbs used gains as low as 0.4 s^{-1}. It may be the case that a decrement in performance would have been evidenced if gains lower than 0.78 s^{-1} were used.

A final point is that Hammerton did not report an optimum gain value, although he stated that a high maximum cursor velocity with a low gain provides the best performance (note that the definition of gain would require a large amount of joystick deflection to obtain this gain). From the graphed data, the optimum gain appears to be in the area of 1.0 to 1.5 s^{-1}, a value comparable to the optimum gain of 1.3 s^{-1} predicted by Gibbs. Gibbs (1962) reported that in a previous study he had changed gain by modifying joystick length while keeping cursor speed constant. He stated that the optimal gains found in both studies were similar; however, he did not report on the similarities among the rest of the curves relating gain to performance. It is possible that Hammerton's results are due to differences in the control-display interfaces and the gain values used in his study and not to the differences in the method of changing gain.

Gain has also been studied in relation to force-operated controls. Tipton and Birmingham (1959) varied gain using a force-operated lever. The amount of force required to obtain maximum cursor displacement varied from 1 oz to 8 lb (128 oz). The authors stated that the control sensitivity was varied to produce eight values ranging from 1 to 128. Thus, although not explicitly stated, gain was apparently defined in terms of the amount of force required on the control for a given amount of cursor movement. Gain was thus modified by changing the amount of force required on the control; lower gains required greater amounts of force to be applied to the control to achieve a given amount of cursor movement on the display. Subjects performed a compensatory tracking task; the reference input was a sine wave. The same reference input was used for all gains. All subjects were tested on all gains. The dependent measure used was average integrated error, measured in what the researchers refer to as arbitrary units.

The results indicated that error increased slightly for gains greater than 16; optimal performance occurred for the lower gains of 1 through 8. The authors stated, however, that although these differences are significant, the actual variation in performance was small (a factor of 2.5), indicating that operators are capable of adjusting their performance to compensate for changes in gain (which had changed by a factor of 128).

Arnaut and Greenstein (in press) varied the D/C gain of a positional system using a touch tablet as the input device. The task required subjects to move a cursor a random distance on the display to position the cursor within a target. Across gains the average distance the cursor moved on the display remained the same. Three different target sizes were used. Gain was defined as the ratio of linear cursor movement on the display to the linear movement of the subject's finger on the control. Gain was modified by changing the amount of movement required on the touch tablet while the display was not changed. All subjects were tested using all gains.

Five gains from 0.875 to 2.5 were tested in one experiment. Gains of 0.875 and 1.0 were optimal in terms of target acquisition rate, number of entries into the target prior to confirmation, and error rate. The effect of target size was significant; smaller targets were not acquired as easily as large targets. There was also a significant Gain x Target Size interaction such that performance with the smaller targets was more affected by a change in gains than was performance with the large targets.

In a second experiment performed to more closely examine lower gains, five gains ranging from 0.61 to 1.4 were tested. Performance in terms of target acquisition rate and error rate was best for gains of 0.8 and 1.0. This result suggests that with gains lower than 0.8 there was little improvement in fine positioning ability while gross movement time increased. Above 1.0 a reduction in fine adjustment ability led to a decrement in performance.

The studies that have been reviewed are among the few designed to investigate the impact of gain on operator performance. To summarize, four points may be made. First, the effects of gain vary depending on the particular control-display interface and on differences within that interface. In particular, such variables as display lag, the order of the control system (i.e., whether a positional or velocity control is used), the limb used to make the control movements, and the target size all affect performance.

A second point is that some studies have indicated a U-shaped relationship between gain and performance, while others have shown a primarily monotonic relationship. It is unclear whether this difference is due to the range of gains tested or to differences among the controls used.

Third, no consistent method has been used to change gains. Some researchers have varied the amount of control input required to achieve a given amount of display output; other researchers have modified cursor displacement while leaving the range of control input constant. However, all of the studies discussed so far required that subjects move a cursor or pointer the same distance on the display under all conditions of gain. As indicated previously, for such a task the method of changing gain is irrelevant in a positional control system because the same control input is required regardless of how gain is changed. Because changes in gain and changes in control input have been confounded, it is unclear from these studies whether the different methods of changing gain differentially affect performance.

A fourth point is that different researchers have used different dependent measures. It is possible that changes in gain do not affect all aspects of performance in the same manner. For example, Hammerton (1962) suggested that gross and fine positioning may be differentially affected by the two methods of changing gain. However, his study did not allow this hypothesis to be adequately tested. Therefore, not only should more than one aspect of performance be measured when studying D/C gain, a measure such as time to reach the target should be broken down into more fine-grained components such as gross and fine positioning time.

There is some research that attempts to sort out the effects of the different ways of changing a control-display interface. Buck (1980) has suggested that gain is not the critical factor in determining performance. Buck recognized that in previous studies changes in gain always required changes in the amount of movement on the input device while the display was held constant. Defining gain as the ratio of display target width to control target width, Buck hypothesized that the change in control target widths in earlier studies led to the poorer performance seen with an increase in gain. He further stated that if the task required a change in the display target width instead of control target width, there would be no change in performance.

To test this hypothesis, Buck (1980) conducted a study in which subjects were required to use a joystick to position a 2-mm cursor at a 1.5-mm target on an oscilloscope. Two levels of control target width and two levels of display target width were combined to provide four conditions. Different subjects were tested under each condition. In terms of the current distinctions made between tasks, subjects were required to move the cursor across the same proportion of the display in all cases, but not the same distance. Thus, in two conditions, control input was constant and the display output changed, while in the other two conditions the opposite occurred. Three levels of gain resulted from the four combinations of control and display target widths (0.525, 1.05, and 2.10). Three dependent measures were used: total movement time, adjustment or gross movement time, and overshoot or fine adjustment time.

Buck changed display amplitude and display target width simultaneously, as well as confounding changes in control amplitude and control target width. Therefore, although Buck states that the effects of the control were due to the changes in control target width, the control amplitude had also changed, so it is not possible to identify any effect beyond that of a general main effect of control input. The same is true for the display effect. For total movement time, neither the control nor the display main effect was significant, but there was a significant Control x Display interaction. Adjustment or gross movement time was affected only by control input. Overshoot or fine positioning time was affected by both the control and display, but there was no significant interaction between these variables.

Buck states that the results indicate that gain had no significant effect on performance. There are several problems with the interpretation of these results. First, no analysis of gain was presented. Thus, it is unclear whether gain actually affected movement times. Looking at the mean values of the groups, movement time showed a decrease when going from a gain of 0.525 to a gain of 1.05, and then an increase for a gain of 2.10. It is possible that these differences were statistically significant. Additional values of control input, display output, and the resulting gain would aid in clarifying both the effects of gain and the effects of control input and display output.

Other problems with this study make the results questionable. The cursor was bigger than the targets, and may have obscured them during positioning. The size of the target always appeared the same on the display; display target width was changed by changing the criterion for a correct entry into the target, but subjects were not informed of the criterion, nor did the size of the target reflect the change (that is, the target was always 1.5 mm).

While not designed to specifically test Buck's hypothesis, a study by Arnaut and Greenstein (in press) permitted an examination of the effects of control and display target width. If gain is defined to be the ratio of display target width to control target width, then control target width is equal to the ratio of display target width to gain. Thus, by looking at various combinations of gain and target sizes, they were able to identify several conditions with the same effective control target width but different display target widths. They reported that these conditions had significantly different target acquisition rates, a composite measure of gross and fine positioning. If Buck's hypothesis were correct, there should be no differences among these groups. The number of entries into the target prior to confirmation of the target acquisition, however, did not differ across those groups with the same control target width, suggesting that display target width did not affect this measure of fine positioning.

Buck's results show a somewhat different pattern; fine positioning time was affected by both the control and display, while gross positioning was affected only by the control. The results concerning the different methods of changing gain are thus unclear, with Buck's hypothesis regarding the importance of control target width receiving minimal support.

Using a somewhat different approach, Parng (1986) separated the effects of control target width, control amplitude, and display target width. Using a touch tablet, he had subjects perform a Fitts' tapping task with control amplitudes of 24, 48, and 96 mm, control target widths of 4 and 8 mm, and display target widths of 4 and 9 mm. Control and display target widths were between-subjects factors, and movement amplitude was a within-subjects factor. The task was to lift a stylus from the right side of the tablet, place it at the left side of the tablet, and then carry out any necessary fine adjustment on the tablet to position the cursor in the target. Using the ratio of display target width to control target width as a definition of gain, Parng had four gain values: 0.5, 1.0, 1.125, and 2.25.

The results show a significant effect of Control Amplitude and a significant Control Amplitude x Control Target Width interaction for gross movement. There were significant main effects of Control Target Width and Control Amplitude for fine adjustment, along with a Control Target Width x Display Target Width interaction. For total movement time, there were significant main effects of Control and Display Target Widths and Control Amplitude. Parng states that gain does not systematically affect performance.

There are three problems with Parng's work in relating it to the effect of gain on performance. First, like Buck, Parng did not include conditions in which the same gain was achieved through different control-display combinations. Therefore, neither researcher directly addressed the absence of an effect of gain on performance, although they both state that gain did not systematically affect performance. Therefore, the usefulness of gain as a specification for an interface has yet to be evaluated empirically.

A second problem is Parng's definition of gain as the ratio of control target width to display target width. This definition may be adequate for the task used in Parng's study since no continuous movement on the tablet was made until the subject touched down in the area of the target.

However, many input devices, such as the mouse, joystick, and trackball, require that some gross movement be made using the device and not simply by making a ballistic movement in the air. It might be expected that the ratio of control target width to display target width may not sufficiently explain gross movement since the area of the target would not yet have been reached during gross movement.

A third problem is that changing the control target width and the movement amplitude separately constitutes a rather artificial situation and is not what typically happens when gain is modified. Parng's task was designed to test certain hypotheses regarding Fitts' Law, and the tapping task used is not typical to situations where D/C gain is an issue. Conventional changes in gain made by altering the control input would cause a simultaneous increase or decrease in both the control amplitude and the control target width. It is more likely that the total active area of the display (or the display amplitude) and the display target width would be changed separately; that is, bigger or smaller targets would be presented on the same display. For example, Arnaut and Greenstein (in press) and Epps, Snyder, and Muto (1986) presented targets of different sizes on the same display for a target acquisition task.

Because of these limitations, Parng's (1986) results are limited in their ability to answer questions concerning gain for tasks with continuous movement on an input device. In addition, like Buck's (1980) research, they do not systematically rule out the effect of gain on performance, although both authors state that they do.

The purpose of the present research was to test the adequacy of gain as a specification for an interface, especially as used in interface optimization. The possibility that changes in the control input and the display output of an interface may have different effects on user performance is important because optimization of the interface would then depend on more than the ratio of system output to control input. In addition, it is possible that the use of gain may obscure the effects of other factors important to performance. In such a case it might become necessary to optimize two or more of the the four components of the control and the display instead of simply changing one to change a gain value.

RESEARCH OBJECTIVES AND HYPOTHESES

An initial experiment investigates the effects of both separate and simultaneous changes in the display output and the control input of an interface. The purpose of this study is to determine whether the composite gain value sufficiently describes performance, or whether changes in the control and the display affect performance in different ways. The task requires subjects to move a cursor across a given proportion of the display so that changes in both factors could be assessed. No attempt was made to differentiate between the target width and amplitude components of the control and the display in the first study; as the control and display amplitudes increased, the associated target widths increased proportionately. Therefore, for the first experiment, the display and control effects are assumed to be due to overall changes in the display output and the control input. In keeping with this assumption, for the first experiment the control and display variables are referred to as control input and display output or width, respectively.

There are four possible hypotheses regarding the cause of performance differences resulting from changes in control input and display output. The first hypothesis is that a change in display output alone causes a change in performance. However, as indicated previously, most researchers have changed gain by changing only the control input. The differences in performance that resulted indicate that changes in the control input do affect performance, and thus it is unlikely that display output alone is responsible for performance differences.

A second hypothesis is that control input alone is responsible for performance. This is essentially the explanation proposed by Buck (1980), although he specifically stated (but did not test) that control target width determined performance. Buck reported that display output affected overshoot (or fine adjustment) time. Additionally, Arnaut and Greenstein's (in press) results suggest that display target width affects target acquisition rate and Parng (1986) found a Control Target Width x Display Target Width interaction for fine adjustment. Thus, since there is some evidence to indicate that changes in the display can lead to performance differences, considering control input alone may be insufficient.

The third hypothesis is that gain, a value that takes both display output and control input into account, is responsible for performance differences. This assumption was made in all of the studies reviewed previously except those performed by Buck (1980) and Parng (1986). However, the use of gain as an explanation for performance has several problems. As indicated previously, it is possible to obtain the same numeric gain for an interface by simultaneously enlarging or reducing control and display widths by the same factor. Clearly, it is possible to enlarge the control input to such an extent that it is physically impossible to make the required input in a given period of time. A display could be made so small that users have difficulty viewing the output, or it may be made so large that users must move their heads to scan it. In these cases performance is likely to differ even though the numeric value of gain has not changed.

It may be argued that such extreme changes in controls or displays result in an interface so different from the original that they are not comparable. However, note that any change in gain necessarily leads to some difference in the interface whether it be in the control, the display, or both. At what point have the controls and the displays changed enough to warrant being called different?

An important point relating to this third hypothesis is that *gain per se has never been tested*. If gain determines performance, then performance should not differ regardless of how a given gain is achieved. However, no researcher has demonstrated this; rather, *different* gains have been compared to determine how performance changes. And in fact, the differences in gains that have been tested have actually amounted to differences in control input. Thus, gain alone has never been demonstrated to be responsible for changes in performance. Additionally, the arbitrary nature of both the choice of what to measure on the interface and what units to measure it in complicate any interpretation of the effects of gain. Finally, the fact that the separate effects of the control and the display become less important than their combined ratio when using gain to describe an interface argues against the use of gain as the best predictor of performance.

Because of these problems, a fourth hypothesis is adopted in the present research. That is, control input and display output interact to produce changes in performance. This hypothesis is not the same as saying that the ratio of these factors determines performance. A significant Control x Display interaction would suggest that not only may both the control and the display parameters affect performance, but that the effects of a change in control input are dependent upon the level of display output and vice versa. By definition, gain implies independence between these factors, and that their effects are uniform across the gains tested.

Two studies were conducted. The first study tested the hypothesis just presented. The second study was designed to explore further the effects of display amplitude, display target width, and control amplitude.

EXPERIMENT 1 METHOD

The purpose of this study was to vary independently the control input and display output of two interfaces to assess the effects of these changes on performance. The hypothesis to be tested was that for each interface an interaction between changes in the control and the display would be reponsible for variations in performance.

There were three independent variables: control input, display output, and input device. A mixed-factor design was used: input device was a between-subjects factor, and control input and display output were within-subjects factors.

Independent Variables

Input device. Ohlson (1978) categorized input devices into four classifications based upon two dimensions. These dimensions are: direct versus indirect devices, and graphical versus tactile devices. C-D gain is only relevant for indirect devices in which the display is not also the control. Both an indirect graphical device, the touch tablet, and an indirect tactile device, the trackball, were used in this study. The touch tablet and trackball are both examples of a class of input devices known as locators (Foley and Wallace, 1974); that is, they both provide input regarding position or orientation. Thus, the devices themselves may be used for similar tasks. Each was used to provide positional input only due to the frequency of use of this type of system as reported in the literature and in real-world applications. A similar pattern of results for the two input devices would suggest that there may indeed be common effects of changes in control inputs even if the input device differs. A difference in the results, however, would indicate that the nature of the control may be important in optimizing the interface.

A touch tablet may be used with either relative or absolute cursor control. With relative mode, when the user places a finger anywhere on the tablet, the cursor remains where it is on the display. Movement of the finger leads to a corresponding cursor movement relative to this initial cursor location. With absolute mode, when the user places a finger anywhere on the tablet, the cursor moves to a place on the display corresponding to the position of the finger on the tablet. Cursor position is continually referenced to the finger position. Arnaut and Greenstein (in press) and

Epps et al. (1986) report that absolute mode resulted in better performance than relative mode for target acquisition tasks; Ellingstad, Parng, Gehlen, Swierenga, and Auflick (1985) report similar results for a character deletion task. However, relative mode was used because it requires a certain amount of gross movement on the tablet to move the cursor from its current position on the display. Since there is evidence that changes in the interface may affect gross movement and fine adjustment times differently (Arnaut and Greenstein, in press; Buck, 1980), it is important to measure gross movements.

Control input. There were five levels of control input for each input device. For the touch tablet, the control input was defined as the distance the finger must move across the tablet to move the cursor across the entire display. These values were: 50, 75, 100, 125, and 150 mm. The levels were chosen to correspond to the active display areas that were presented.

For the trackball, the control input referred to the distance a point on the circumference of the trackball must travel to move the cursor across the entire display. The five levels chosen were: 50, 100, 150, 200, and 250 mm. For each input device the same numerical value of gain was obtained in several display-width/control-input combinations so that the effect of gain could be assessed if the hypothesized control-display interaction was not significant for that device.

Display width. There were five display widths: 50, 75, 100, 125, and 150 mm. These values were chosen based on hardware limitations; due to the size of the display, 170 mm is the largest square that can be displayed. This size was used for training. The other values were chosen to represent a large range of active display areas.

Unlike Buck's work, in the present study the sizes of the target and of the cursor on the display changed proportionally when the display output increased so that subjects were aware of the changed conditions. As the display width changed, the corresponding target sizes were 5, 7.5, 10, 12.5, and 15 mm; the cursor sizes were 2.5, 3.75, 5, 6.25, and 7.5 mm. Figure 3 presents an example of the display; the actual display was light on a dark background.

The cursor was always moved across the same proportion of the display width (four-fifths), but the distance changed as the display width changed. The five cursor movement distances corresponding to the five display widths were: 40, 60, 80, 100, and 120 mm (these distances are measured from the initial cursor position to the target center).

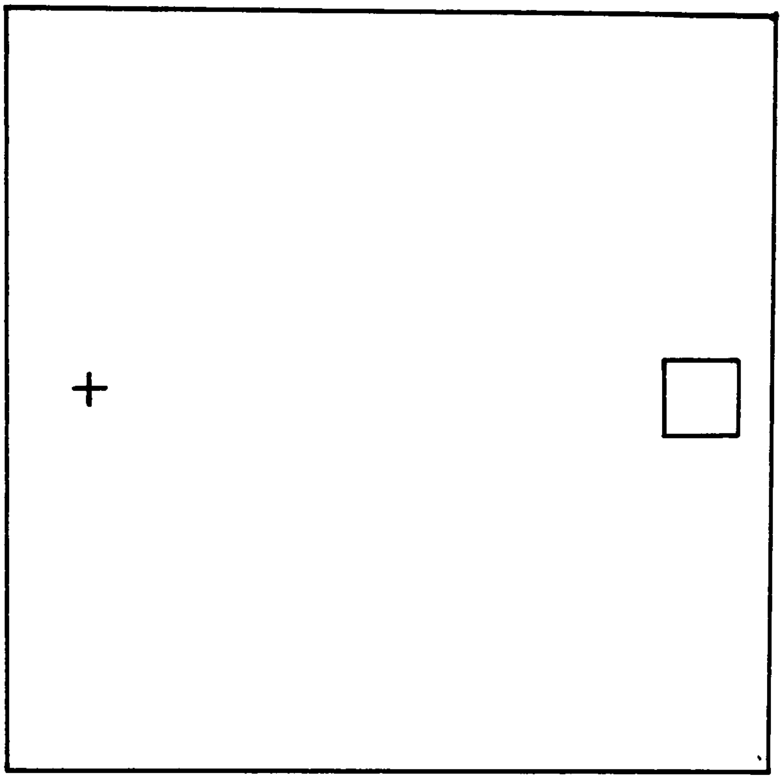


Figure 3: Example of the Experimental Display (100 mm).

Table 1 summarizes the display widths, target sizes, cursor sizes, and cursor movement distances for each level of display output.

When the display was enlarged, the number of positions the display cursor could take was identical to the number for the smallest display (130 and 60 for the X- and Y-axes, respectively). Thus, when the targets were enlarged proportionately as the display size increased, the number of cursor locations inside the target did not change, ruling out this factor as a possible explanation for performance differences.

Apparatus

Input devices. The touch tablet was a 279.4-mm square Elographics E-233 finger-sensitive touch tablet. The tablet was housed in a 660- x 432-mm plexiglas frame; the back of the frame was raised 66 mm, inclining the tablet at a 9-deg angle. With relative mode the size of the tablet is not necessarily tied to the level of control input; however, the active area of the tablet changed in the present study as the control width changed. An overlay was placed over the tablet indicating the current size, both to provide a visual cue for the change in input and to allow subjects to make one continuous hand movement to move the cursor across the

TABLE 1

Summary of Display Output Dimensions

(All values are in mm)

Display Width	Target Size	Cursor Size	Cursor Movement Distance
50	5.0	2.5	40
75	7.5	3.75	60
100	10.0	5.0	80
125	12.5	6.25	100
150	15.0	7.5	120

display in all conditions. Each overlay was 20 mm longer and wider than the active area of the tablet so that there was always a 10-mm margin around the active area of the tablet that did not respond to any input. Thus, the subjects could not use the edges of the overlay as tactile cues to start or stop the cursor movement.

The second input device was a Measurement Systems 621 low-profile trackball. The diameter of the trackball was 40 mm. The trackball was placed in a 205- x 240-mm housing, the back of which was raised 66 mm, placing the top surface at a 16-deg angle.

Both input devices were used on a table 765 mm high. The subjects were allowed to use either hand to operate each device. The tablet was placed directly in front of the subject, and the trackball was positioned according to each subject's preference and then taped in place. An IBM-PC keyboard was used with the trackball to confirm a target acquisition; the keyboard was also positioned according to preference.

Display. The task was presented on a 317.5-mm IBM PC 5153 color display with 640 x 200 pixel resolution. The display was in an adjustable metal frame. The front of the frame was raised 45 mm. Subjects were seated so that their eyes were from 610 to 762 mm from the screen. The five display sizes were indicated by a white square centered on the black display. The target was a white square, and the cursor was a white cross hair. The smallest displayed item was the 2.5-mm cursor in the 50-mm display condition. At 610 mm, the cursor subtended 14.1 min of visual angle, and at 762 mm it subtended 11.3 min.

Additional equipment. An IBM PC-XT personal computer supporting IBM Pascal and Halo Graphics software was used to present the task and to collect performance data. After each trial began, the time and the X and Y cursor coordinates were sampled approximately every 0.05 s and recorded in a data file. An acquisition was considered correct if the center of the cursor was inside the target; the accuracy of the response was determined while the experiment was in progress. Acquisition time measures were calculated from the recorded data after the experimental session was complete.

Subjects

Twenty male students ranging in age from 19 to 32 volunteered to participate in the study. They were paid $5 per hour and a bonus for completing the study. All subjects had at least 20/29 near acuity as measured by a Bausch and Lomb Orthorater.

Subjects were asked about previous experience with the input device to which they had been assigned. Of those subjects using the tablet, five had never used one before; only one had more than two hours of experience with a tablet, and he had not used a tablet in the last year. Of those subjects using the trackball, three had never used one before; seven had used them in video game applications, with the estimates of total use ranging from 1 to 40 hours.

Task

The subject used the designated control device to move the display cursor into the target. The display cursor appeared at one of four possible starting positions (left, right, top, or bottom) at the initiation of the trial, and the target was at the opposite side of the display. The purpose of changing target position was to ensure that subjects could not predict the direction of movement for a given trial.

Two short tones sounded to indicate the start of the trial, and the subject could then initiate a control movement. When the subject was satisfied that the center of the cursor was inside the target, he removed his hand from the input device and confirmed the acquisition with his other hand. On the touch tablet, a 280- x 38-mm area at the bottom of the tablet was reserved for confirmation. For the trackball, the subject pressed the space bar on the keyboard to confirm the acquisition. If the acquisition was correct, a high-frequency tone sounded; if the acquisition was incorrect, a low-frequency tone sounded. Two seconds after confirmation, a new trial begain.

Procedure

Ten subjects were assigned to use the touch tablet, and the other 10 used the trackball. Pretests indicated a potential for transfer effects across control inputs. Thus, testing for each subject took place over five consecutive days with a different control input used on each day. In addition, the order of the control inputs was counterbalanced across the 10 subjects for each input device. Subjects were tested at approximately the same time each day.

On each of the five test days, subjects were tested on all five display sizes. The order of the display sizes was partially counterbalanced across test days.

On the first day, subjects signed the informed consent form (Appendix A). Subjects next read the instructions for the assigned input device (Appendix B). If the subject had any questions, they were answered at this time. Next, subjects performed 80 training trials using a 170-mm display with 17-mm targets. A 170-mm touch tablet and a 300-mm trackball movement were used for training.

During and after the training trials, the subjects were again given an opportunity to ask questions. The first set of experimental trials then began. For each of the five display sizes, 80 trials were given, 20 for each movement direction. The order of presentation of the four movement directions was randomized within the constraint that both the first 40 and the last 40 trials in the block each had 10 trials in each movement direction.

Subjects were allowed to take a break after any of the trial blocks. The entire experiment required approximately two and a half to four hours per subject. On the last day, subjects were asked to rank both the display sizes and the control inputs in order of preference using the questionnaires shown in Appendix C.

EXPERIMENT 1 RESULTS

The dependent measures used were gross movement time, fine adjustment time, total movement time, the percentage of responses resulting in errors, and subjective rankings. Gross movements were measured as the time from the initial touch on the tablet or the initial trackball movement to the first entry of the cursor into the target. This measure thus excludes reaction time. Fine adjustment was measured as the time from the initial target entry to the final lift-off of the finger from the tablet or the last trackball movement. Thus, this measure did not include the time taken to confirm the target acquisition. Total movement time was the time from initial movement on the tablet or trackball to the final movement on the tablet or the trackball.

All responses were included in the analyses, regardless of whether they had been correct or not. This may have caused some fine adjustment times to be zero, if the cursor had not entered the target at least once before confirmation. However, because there were so few errors, and because some fine adjustment times were zero for correct responses (when the cursor entered the target and the subject confirmed the response before the clock changed), the inclusion of responses in error was not considered to present a problem. In addition, there is no reason to expect gross or total movement times to have been systematically affected by whether or not the response was in error.

The results for the touch tablet and the trackball were analyzed separately for two reasons. First, it was desired only to determine if the same pattern of changes in response to the same type of changes in the interfaces occurred, and not to make direct quantitative comparisons between the two input devices. Second, the control input levels and types of movements for the two devices are not directly comparable, and thus the control input factor varies in nature across the devices.

Performance Stability

The target acquisitions were grouped into eight blocks of 10 target acquisitions for each input device. Comparisons indicated that the last four blocks (the last 40 trials) did not differ significantly ($p > 0.05$) for any of the dependent measures. Thus, it appears that performance stabilized after 40 target acquisitions, and only the last 40 trials were used for subsequent analysis.

Touch Tablet

The hypothesis to be tested is that the interaction between the control input and the display output would produce significant variations in performance. To test this hypothesis, an analysis of variance was performed on each of the dependent measures. The Control x Display interaction is not significant for any of the dependent measures (see Tables 2, 3, 4, and 5). Thus, the hypothesis that the control input and the display output would interact to determine performance is not supported.

There was a significant ($p < 0.05$) main effect of control input on all the dependent measures with the exception of errors. The display width did not significantly affect any aspect of performance, although the display effect for the fine adjustment times approached statistical significance. Thus, it appears that control input was the primary determinant of the time taken to acquire targets with the touch tablet.

Post-hoc Bonferroni t-tests indicated that the effect of the control input differed across the dependent measures. As can be seen in Figure 4 and Table 6, for the gross movement times the largest tablet size was significantly worse than any other tablet size. The other tablet sizes did not differ significantly. Thus, large tablets (e.g., 150 mm) increase gross movement time.

TABLE 2

ANOVA Summary Table for Touch Tablet Gross Movement Times (Experiment 1)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	9	305509.31		
<u>Within</u>				
Control (C)	4	327312.98	10.01	0.0001
C x Sub	36	32689.81		
Display (D)	4	12816.48	1.43	0.2449
D x Sub	36	8981.85		
C x D	16	11558.02	1.22	0.1376
C x D x Sub	144	9485.32		
Total	249			

TABLE 3

ANOVA Summary Table for Touch Tablet Fine Adjustment Times (Experiment 1)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	9	434871.97		
<u>Within</u>				
Control (C)	4	774128.28	10.66	0.0001
C x Sub	36	72610.09		
Display (D)	4	25842.18	2.53	0.0561
D x Sub	36	10148.62		
C x D	16	7929.28	0.62	0.8656
C x D x Sub	144	12831.70		
Total	249			

TABLE 4

ANOVA Summary Table for Touch Tablet Total Movement Times (Experiment 1)

Source	df	MS	*F*	*p*
Between				
Subjects (Sub)	9	886431.69		
Within				
Control (C)	4	834198.98	6.37	0.0006
C x Sub	36	130955.35		
Display (D)	4	52753.57	2.16	0.0931
D x Sub	36	24403.34		
C x D	16	22059.81	0.82	0.6597
C x D x Sub	144	26854.62		
Total	249			

TABLE 5

ANOVA Summary Table for Touch Tablet Errors (Experiment 1)

Source	df	MS	*F*	*p*
Between				
Subjects (Sub)	9	17.66		
Within				
Control (C)	4	13.85	1.37	0.2645
C x Sub	36	10.13		
Display (D)	4	0.54	0.30	0.8786
D x Sub	36	1.82		
C x D	16	1.80	0.72	0.7713
C x D x Sub	144	2.51		
Total	249			

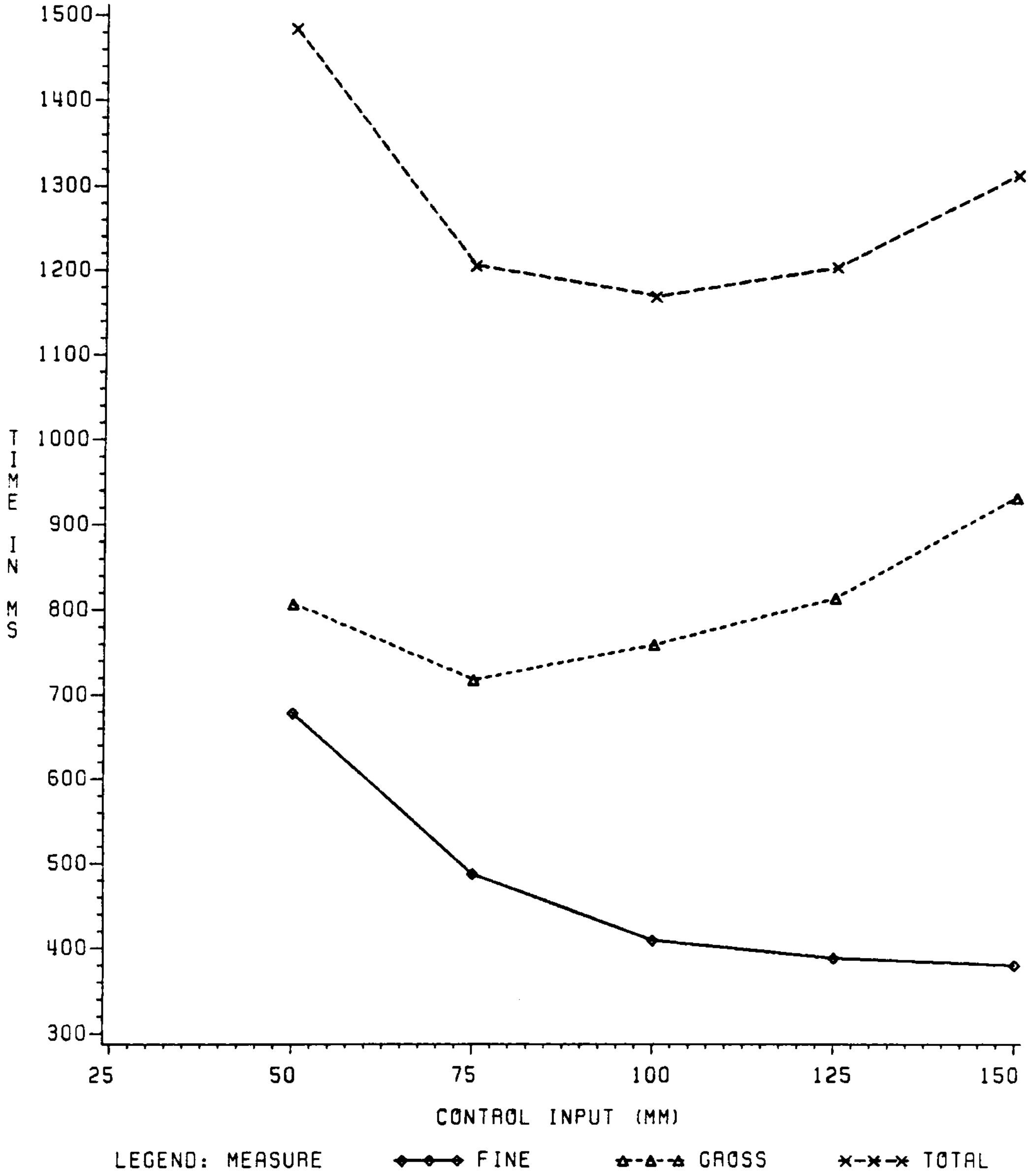


Figure 4: Effect of Control Input on Touch Tablet Acquisition Times.

TABLE 6

Comparison of Touch Tablet Gross Movement Times for the Control Inputs

Control Input (mm)	Mean Time (ms)	Grouping*
150	932.9	A
125	813.9	B
50	806.9	B
100	759.1	B
75	717.5	B

* Means with different letters are significantly different ($p < 0.05$).

As shown in Figure 4 and Table 7, the opposite result was found for fine adjustment time. Here the smallest (50-mm) tablet provided the worst performance with no significant differences among the other tablet sizes. For total movement time, the smallest and largest tablets (50 and 150 mm) led to poorer performance (see Table 8) while the other sizes were not significantly different from one another. Thus, as can be seen in Figure 4, the total movement time suggests a compromise between the gross movement time and fine adjustment time results; that is, both extreme tablet sizes lead to an increase in total movement times.

Gain. The clear effect of the control input on the dependent measures combined with the absence of any effect of display output suggests that gain alone cannot be a determinant of touch tablet performance. For example, consider the superiority of the large tablet for fine positioning. An interface consisting of a 150-mm tablet with a 150-mm display would be expected to lead to better fine positioning than a 50-mm tablet with a 50-mm display based on the present results, even though both interfaces have a gain of 1.0, since the display width did not affect performance.

While this argument follows logically from the results, the first study was designed so that the same numerical

TABLE 7

Comparison of Touch Tablet Fine Adjustment Times for the Control Inputs

Control Input (mm)	Mean Time (ms)	Grouping*
50	678.0	A
75	487.4	B
100	409.3	B
125	388.7	B
150	380.2	B

* Means with different letters are significantly different ($p < 0.05$).

TABLE 8

Comparison of Touch Tablet Total Movement Times for the Control Inputs

Control Input (mm)	Mean Time (ms)	Grouping*
50	1485.1	A
150	1314.5	A B
125	1205.2	B
75	1204.0	B
100	1169.5	B

* Means with different letters are significantly different ($p < 0.05$).

values of gain were obtained for several control-display combinations. Thus, it was possible to test for statistical differences between conditions having the same gain obtained in different ways. Post-hoc F- and t-tests were performed. Table 9 shows the common gain values and the control-display combinations that produced these gains. The mean gross movement time, fine adjustment time, total movement time, and percentage of responses in error are shown.

As can be seen in Table 9, there were differences between the dependent measures for most (constant) gain values. There were significant differences in gross movement times for gains of 0.5 ($t = 2.93$, $p = 0.0168$), 0.67 ($t = 3.72$, $p = 0.0048$), 1.0 ($F = 9.83$, $p = 0.0001$), and 2.0 ($t = 2.29$, $p = 0.0480$). For fine adjustment, gains of 0.67, 1.0, and 1.5 indicated significant differences ($t = 3.72$, $p = 0.0042$, $F = 4.95$, $p = 0.0028$, and $t = 2.58$, $p = 0.0298$, respectively). For total movement time, there were significant differences for gains of 1.0 ($F = 4.54$, $p = 0.0045$), 1.5 ($t = 2.44$, $p = 0.0371$) and 2.0 ($t = 2.53$, $p = 0.0323$). No significant differences were found in the percent error measure.

Subjective rankings. Table 10 shows the rank sums for the subjective rankings of the touch tablet and display sizes. The subjects were requested to rank the tablet and display sizes from one to five so that the most preferred

TABLE 9

Means for Touch Tablet Control-Display Combinations with the Same Gain Values

Gain	Display Width (mm)	Control Input (mm)	Gross Time (ms)	Fine Time (ms)	Total Time (ms)	Errors (%)
0.5	50	100	795.0	414.3	1211.5	1.00
	75	150	975.4	381.8	1357.2	0.75
0.67	50	75	758.0	497.3	1256.8	1.25
	100	150	938.2	387.0	1327.7	1.50
1.0	50	50	804.4	664.7	1469.9	2.25
	75	75	712.4	485.3	1197.8	0.75
	100	100	730.3	400.5	1130.8	0.75
	125	125	834.6	380.6	1219.5	1.50
	150	150	923.2	391.5	1314.7	1.25
1.5	75	50	795.5	749.9	1545.4	2.00
	150	100	740.7	421.5	1164.0	0.75
2.0	100	50	858.0	681.2	1539.2	1.50
	150	75	704.1	523.7	1227.8	0.25

Underlined values for the same gain differ significantly ($p < 0.05$).

tablet or display was given a rank of one. Thus, a low rank sum indicates that the value was preferred.

A Friedman test for rank sums indicated significant differences among tablet sizes for the rankings ($p < 0.001$). Post-hoc distribution-free multiple comparisons (Hollander and Wolfe, 1973) indicated that the subjects liked the 100-mm tablet best, and they ranked it significantly higher than the two least preferred tablet sizes, the 50- and 150-mm tablets ($p < 0.05$). The next most preferred tablet, 125 mm, also differed significantly from the least-liked 50-mm tablet ($p <0.05$).

A Friedman rank sum test also indicated significant differences for the ranks of the display sizes used with the tablet ($p < 0.001$). The 100-mm display was preferred, followed by the 125-mm display. Both of these displays were ranked significantly higher than the least-liked 50-mm display ($p < 0.05$).

Trackball

As indicated in Tables 11, 12, 13, and 14, none of the dependent measures indicated a significant Control x Display interaction, although the error measure came close (p = 0.059). As was the case for the touch tablet, there was a significant main effect of the control input for gross

TABLE 10

Rank Sums for the Touch Tablet

Control Input (mm)	Rank Sum	Grouping*
50	44.0	A
150	41.0	A B
75	27.0	A B C
125	24.0	B C
100	14.0	C

Display Width (mm)	Rank Sum	Grouping*
50	48.0	A
75	33.0	A B
150	33.0	A B
125	20.0	B
100	16.0	B

* Means with different letters are significantly different ($p < 0.05$).

movement times (see Table 11). No other effects were significant for gross movement. The least sensitive input (that is, the one in which the trackball had to be moved the greatest distance, 250 mm) led to significantly poorer performance than did the other inputs with the exception of the 200-mm input, as seen in Figure 5 and Table 15. The more sensitive the input, the better was the performance in terms of gross movement time.

There was no significant control effect on fine adjustment time. However, as seen in Table 12, the effect of display width was significant for this dependent measure. Post-hoc Bonferroni t-tests indicated that the two largest displays led to significantly better performance than the smallest display (see Figure 6 and Table 16).

For the total movement time, both the control and the display main effects were significant (see Table 13). As shown in Figure 5 and Table 17, the lower sensitivities (200 and 250 mm) led to the poorest performance, and the three most sensitive control inputs led to shorter total movement times. Figure 6 and Table 18 indicate the differences among the display widths for the total movement time. The smaller displays (50 to 100 mm) provided the worst performance while the larger displays provided the better performance.

TABLE 11

ANOVA Summary Table for Trackball Gross Movement Times (Experiment 1)

Source	df	MS	*F*	*p*
Between				
Subjects (Sub)	9	126422.10		
Within				
Control (C)	4	184055.88	8.84	0.0001
C x Sub	36	20830.67		
Display (D)	4	3707.58	1.62	0.1901
D x Sub	36	2287.15		
C x D	16	3306.78	1.32	0.1900
C x D x Sub	144	2496.98		
Total	249			

TABLE 12

ANOVA Summary Table for Trackball Fine Adjustment Times (Experiment 1)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	9	38907.43		
<u>Within</u>				
Control (C)	4	6428.80	1.00	0.4194
C x Sub	36	6973.13		
Display (D)	4	10571.61	7.52	0.0002
D x Sub	36	1406.59		
C x D	16	2528.99	1.34	0.1785
C x D x Sub	144	1881.25		
Total	249			

TABLE 13

ANOVA Summary Table for Trackball Total Movement Times (Experiment 1)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	9	214652.14		
<u>Within</u>				
Control (C)	4	252888.13	11.02	0.0001
C x Sub	36	22955.16		
Display (D)	4	23572.76	7.29	0.0003
D x Sub	36	3232.74		
C x D	16	5780.05	1.46	0.1214
C x D x Sub	144	3950.78		
Total	249			

TABLE 14

ANOVA Summary Table for Trackball Errors (Experiment 1)

Source	df	MS	*F*	*p*
Between				
Subjects (Sub)	9	47.96		
Within				
Control (C)	4	34.15	4.85	0.0031
C x Sub	36	7.04		
Display (D)	4	6.40	1.60	0.1966
D x Sub	36	4.01		
C x D	16	9.10	1.67	0.0585
C x D x Sub	144	5.45		
Total	249			

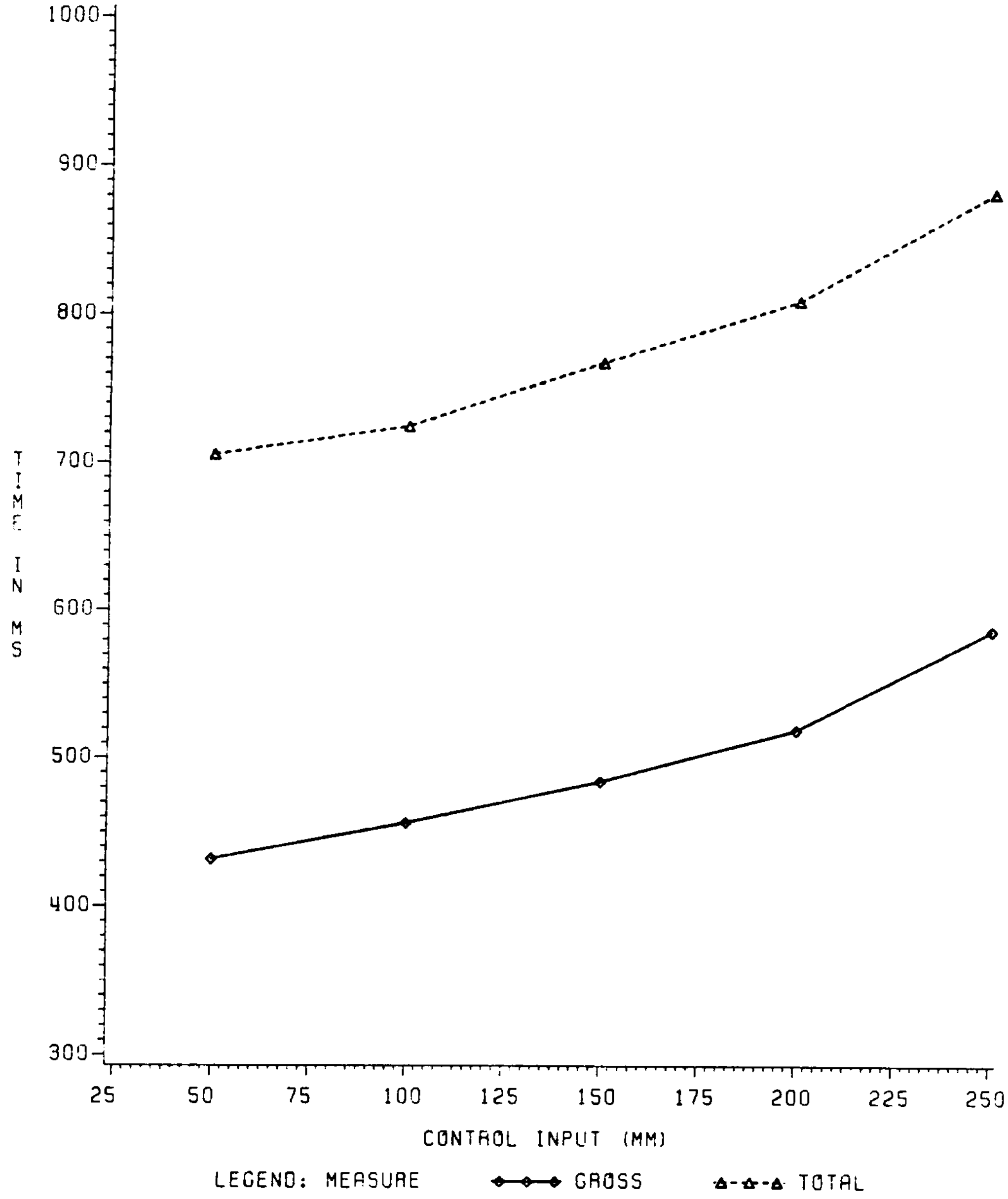


Figure 5: Effect of Control Input on Trackball Gross and Total Movement Times.

TABLE 15

Comparison of Trackball Gross Movement Times for the Control Inputs

Control Input (mm)	Mean Time (ms)	Grouping*
250	586.9	A
200	519.0	A B
150	483.6	B C
100	455.9	B C
50	431.4	C

* Means with different letters are significantly different ($p < 0.05$).

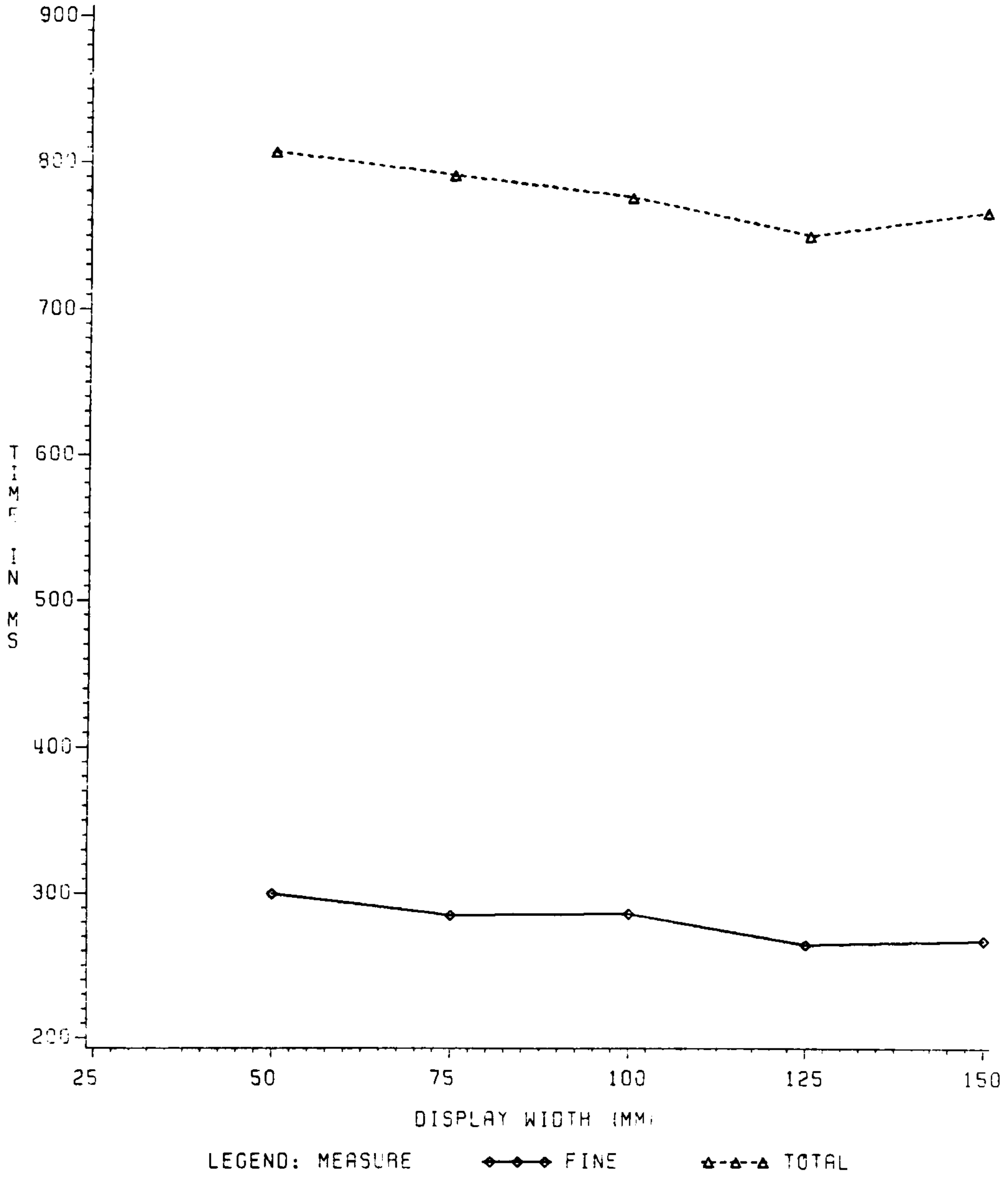


Figure 6: Effect of Display Width on Trackball Fine Adjustment and Total Movement Times.

TABLE 16

Comparison of Trackball Fine Adjustment Times for the Display Widths

Display Width (mm)	Mean Time (ms)	Grouping*
50	299.4	A
100	285.6	A B
75	284.6	A B
150	267.1	B
125	264.2	B

* Means with different letters are significantly different ($p < 0.05$).

TABLE 17

Comparison of Trackball Total Movement Times for the Control Inputs

Control Input (mm)	Mean Time (ms)	Grouping*
250	882.8	A
200	809.6	A B
150	767.8	B C
100	724.4	B C
50	705.3	C

* Means with different letters are significantly different ($p < 0.05$).

TABLE 18

Comparison of Trackball Total Movement Times for the Display Widths

Display Width (mm)	Mean Time (ms)	Grouping*
50	806.5	A
75	790.9	A B
100	775.8	A B C
150	766.4	B C
125	750.2	C

* Means with different letters are significantly different ($p < 0.05$).

For errors, only the main effect of the control input was significant. The mean percentage of responses in error for the five levels of trackball input are shown in Figure 7 and Table 19. The most sensitive input (50 mm) led to the most errors, while the less sensitive inputs showed fewer errors in target acquisition. This result indicates that while the time taken to acquire targets improves with increased trackball sensitivity, performance in terms of errors deteriorates. However, even in the worst condition (50 mm), only 3.2 % of the responses were in error.

Gain. Since no significant Control x Display interaction was found for the trackball, comparisons were made between conditions with the same gain obtained through two or more control-display combinations. Table 20 shows the mean values of the four dependent measures for these conditions. For a gain of 1.0, F-tests indicate significant differences among the three conditions for gross movement time (F = 6.84, p = 0.0062) and total movement time (F = 4.92, p = 0.0197), but not for fine adjustment time or errors (F = 0.11, p = 0.8955, and F = 0.04, p = 0.9646).

For a gain of 0.5, only gross movement time shows significant differences between conditions (F = 4.96, p = 0.0072). Fine adjustment time, total movement time, and errors show no significant effects (F = 2.17, p = 0.1144, F

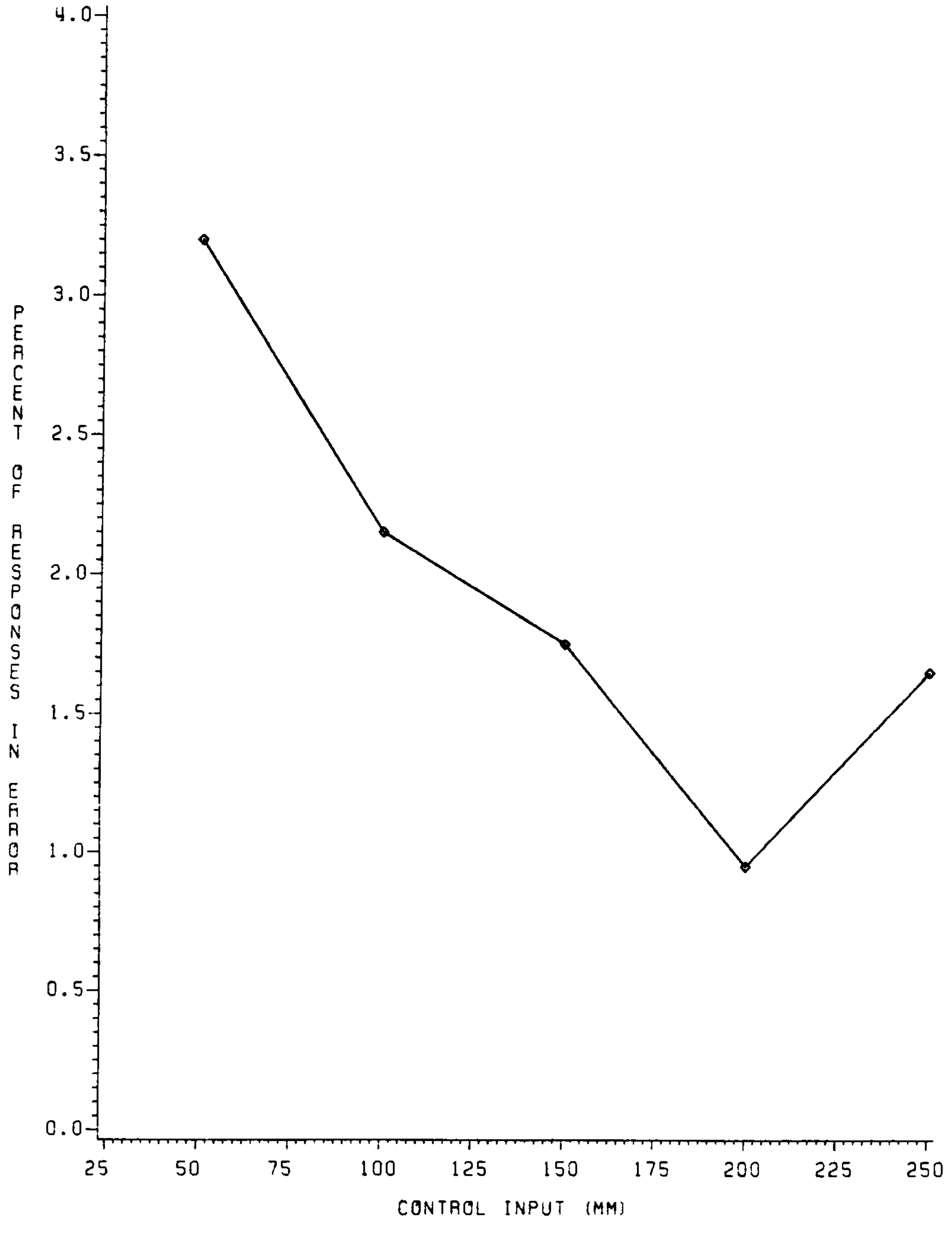


Figure 7: Effect of Control Input on Trackball Errors.

TABLE 19

Comparison of Trackball Errors for Control Inputs

Control Input (mm)	Mean Errors (%)	Grouping*
50	3.20	A
100	2.15	A B
150	1.75	A B
250	1.65	A B
200	0.95	B

* Means with different letters are significantly different ($p < 0.05$).

TABLE 20

Means for Trackball Control-Display Combinations with the Same Gain Values

Gain	Display Width (mm)	Control Input (mm)	Gross Time (ms)	Fine Time (ms)	Total Time (ms)	Errors (%)
0.5	50	100	476.3	283.3	761.6	1.25
	75	150	475.1	287.2	762.9	0.50
	100	200	508.8	314.4	823.2	0.25
	125	250	571.8	259.6	832.2	1.50
0.75	75	100	473.4	248.7	726.3	2.75
	150	200	533.3	261.6	794.9	1.50
1.0	50	50	394.6	273.8	672.7	1.75
	100	100	432.4	281.8	715.0	1.50
	150	150	491.1	273.2	766.0	1.50
1.50	75	50	458.6	291.7	755.5	5.00
	150	100	450.6	269.6	723.7	3.50

Underlined values for the same gain differ significantly ($p < 0.05$).

= 2.44, $p = 0.0860$, and $F = 1.74$, $p = 0.1828$, respectively). For gains of 0.75 and 1.5, t-tests indicate no significant differences for any of the dependent measures.

Subjective rankings. Table 21 shows the rank sums for the trackball sensitivities and the display widths across the 10 subjects. A Friedman rank sum test for the trackball control inputs indicates significant differences in rankings ($p < 0.001$). Post-hoc distribution-free multiple comparisons show that the two most preferred control inputs, 100 and 150 mm, were ranked significantly higher than the two least preferred inputs, 50 and 250 mm ($p < 0.05$). The 200-mm input was also ranked significantly higher than the 50-mm input ($p < 0.05$).

There were no significant differences among the rankings of the display widths for those subjects using the trackball ($p = 0.2$).

TABLE 21

Rank Sums for the Trackball

Control Input (mm)	Rank Sum	Grouping*
50	45.0	A
250	42.0	A B
200	25.0	B C
150	21.0	C
100	17.0	C

Display Width (mm)	Rank Sum	Grouping*
50	38.0	A
150	34.0	A
75	29.0	A
125	27.0	A
100	22.0	A

* Means with different letters are significantly different ($p < 0.05$).

EXPERIMENT 1 DISCUSSION

To summarize the results for the first study, the hypothesized control-display interaction was not found for either input device for any dependent measure. For the touch tablet, the control input was the main determinant of gross and total movement times, and fine adjustment time. Large tablets increased gross movement times and decreased fine adjustment times, while small tablets produced the opposite results. Total movement times increased with both large and small tablets, a result to be expected since total movement time is composed of gross movement and fine positioning. There were no significant effects on the percentage of responses in error for the touch tablet.

For the trackball, the control input was significant for the gross and total movement times and errors, while the display output significantly affected fine adjustment and total movement times. The most sensitive trackball inputs (50-, 100-, and 150-mm movements) led to the shortest gross and total movement times, although they also led to the most errors. The largest displays (125 and 150 mm) resulted in the best fine adjustment and total movement times.

In general, performance with the trackball was superior to performance with the touch tablet. All aspects of target acquisition took almost twice as long with the touch tablet as they did with the trackball. The mean gross movement, fine adjustment, and total movement times for the touch tablet were 806, 469, and 1276 ms, respectively. The corresponding times for the trackball were: 495, 280, and 778 ms. Mann-Whitney U tests indicated that the three acquisition time measures differed significantly ($p < 0.001$).

The reaction times for the tablet were also significantly longer than those for the trackball, as indicated by a Mann-Whitney U test ($p < 0.001$). The mean reaction time for the tablet was 665.33 ms, while the mean for the trackball was 528.97 ms. The longer reaction time for the tablet may be due to the need to reposition the hand on the tablet at the beginning of each trial. However, since the acquisition times did not include reaction time, the longer reaction times did not contribute to the poorer performance already indicated.

There are several possible explanations for the superior trackball performance. First, the group of subjects using the trackball had, on the average, slightly more experience with trackballs than the subjects using the touch tablets had with tablets. However, the fact that an asymptotic performance level was reached for both groups suggests that this is not a likely explanation. In addition, those subjects who had used a trackball previously had not done so for any extended period of time.

A second possibility is that trackballs in general are superior for target acquisition. Several researchers have reported that performance in terms of acquisition time and/or errors was better with a trackball than with a tablet (Albert, 1982; Epps et al. 1986; Gomez, Wolfe, Davenport and Calder, 1982; and Whitfield, Ball, and Bird, 1983).

A third possibility is that the performance of the particular tablet used in the present study could be improved. If this were true, it is possible that the differences in the control and display effects may be partially due to the manner in which the tablet was used. This possibility will be discussed further below.

The subjective rankings for each input device provide an interesting comparison to the objective measures. For the touch tablet, the subjects liked the 100- and 125-mm tablets best, and those sizes also provided the best overall performance. However, although there was no effect of display for any of the objective measures for the touch tablet, the subjects showed clear preferences for the medium display sizes when using the touch tablet. For the trackball, the ranks for the five control inputs do not coincide with the target acquisition times; subjects did not like the most sensitive input (50 mm) although the total and gross movement times showed this input to be superior. However, the 50-mm trackball input led to the most errors; it is perhaps for this reason that subjects disliked it. Finally, although for the trackball there was a significant main effect of display for both fine adjustment time and total movement time, there was no clear agreement among subjects regarding a preferred display size.

It is interesting that the subjective preferences for the display show an effect for the tablet and not the trackball, while the objective measures show the opposite. The basis for this difference may lie in the fact that in general the tablet was more difficult to use than the trackball, as reflected in the longer acquisition times. This difficulty may mean that subjects spent more time looking at the display or that they became more dependent upon the display in making their target acquisitions with the tablet. In either case, subjects might be more likely to develop preferences for particular display widths.

Display/control gain does not provide a satisfactory explanation of the observed performance differences, at least for the touch tablet. Excluding errors, for which no significant differences were found, two-thirds of the comparisons performed on conditions with the same gain achieved through different interfaces showed significant differences for the touch tablet. However, only 3 of 12 possible comparisons were significant for the trackball. There are two possible explanations for the failure to find significant differences for conditions with the same gain achieved in different ways for the trackball. First, since the control and the display both affected certain aspects of performance, gain may actually be a sufficient explanation of some aspects of performance. Alternatively, the failure to find differences in performance may be a result of the fact that performance with the trackball was simply better and more uniform than was performance with the tablet; therefore, there were very few differences among any of the conditions.

The results obtained in the first study are in some ways similar to those reported by other researchers. Buck (1980) reported that for a joystick, target acquisition time, a measure equivalent to gross movement time, showed a main effect of the control input, as did gross movement time for both devices in the present study. Buck reported significant main effects of control input and display output for overshoot time, a measure comparable to fine adjustment time. Neither the touch tablet nor the trackball results for fine adjustment time showed both effects to be significant in the present study, but the effect of display width was significant for the trackball and approached significance for the tablet, and the effect of the control input was significant for the touch tablet. Finally, Buck reported a significant Control x Display interaction for the total movement time. Although a similar effect was hypothesized for the present study, it was not found.

Using a touch tablet, Parng (1986) separated control target width and control amplitude. He reported that gross movement time was significantly affected by control amplitude and that there was a Control Target Width x Control Amplitude interaction. These results are consistent with the present results in that control input was the primary determinant of gross movement. Because control amplitude and control target width were confounded in the present study, no interaction could be tested.

Parng found significant main effects of control target width and control amplitude for fine adjustment and total movement time, consistent with the results found in the present study for the touch tablet. He reported a Control Target Width x Display Target Width interaction for fine adjustment, an effect hypothesized but not found for either input device in the present study.

To summarize the results of the previous studies, while the specifics of the experimental manipulations varied, both Buck (1980) and Parng (1986) have reported some effect of the control input on gross positioning, while there was some effect of both the control and the display for fine adjustment and total movement time. The results of the present study for gross movement times are similar. However, neither the touch tablet nor the trackball results show both the control and the display significant for fine adjustment, although the total movement time for the trackball had significant effects of control and display.

Other researchers have suggested mechanisms that may explain the results for the trackball. Sheridan (1979) has suggested that ballistic movements are primarily a function of the effector mechanism and are most affected by movement amplitude. Controlled movements (such as those needed at the end of a movement for fine adjustment) have a decision mechanism as the limiting factor; the decision mechanism is primarily affected by the target width and the extent to which visual feedback is used. Given that the target width is shown on the display for interfaces with separate control and display components, it is not surprising for the display to have a significant effect on fine adjustment time.

Sheridan's suggestions may explain the present results found with the trackball but not those for the touch tablet (although since display amplitude and display target width were confounded the source of the trackball display effect is unclear). The fact that previous researchers report some effect of the display for a joystick (Buck, 1980) and a touch tablet (Parng, 1986) suggests that the display effect is not limited to the trackball. The question remains then, why were different results obtained for the touch tablet and the trackball and, in particular, why was there no effect of the display on touch tablet performance?

There are several possibilities. First, the control inputs of the two devices may differ enough so that the touch tablet requires a very different type of movement for fine adjustment. Since Parng (1986) used a Fitts' tapping task, no effect of the display has been shown for a task involving continuous movement on a tablet. If the movement is difficult enough, any effect of the display may be overshadowed by the necessary control movement. A second possibility is that the touch tablet in the present study was more difficult to use than the trackball, not because of any inherent difficulty in the control movement required, but because of the response of the tablet itself to the control input. The touch tablet appeared to be more difficult to use than the trackball, based upon two observations. First, as indicated previously, all aspects of the movement time took longer for the touch tablet than they did for the trackball. Second, several subjects who used the touch tablet remarked that the cursor was extremely "jumpy" or sensitive, while none of the trackball users indicated such a problem. This "jumpiness" may be due to a limitation of the tablet itself, or it may be due to the inability of the subjects to make sufficiently small movements with their fingertips to allow smooth fine positioning.

As indicated previously, the display effect for fine adjustment with the touch tablet approached significance. It is possible that improvements in the tablet operation would allow any potential display effects to be uncovered. Ellingstad et al. (1985) have reported that touch tablet performance was improved by the use of a stylus. The stylus may aid gross movement by reducing the amount of arm or wrist motion required in moving the cursor across the screen. It may also help fine adjustment by providing a smaller point of pressure in comparison to the finger. Thus, one possible improvement would be to use a stylus with the tablet.

Another factor that may have contributed to the absence of a display effect on touch tablet performance is the number of cursor locations on the display provided by the software for cursor movement. Unlike other studies, as the display size increased from 50 to 150 mm, the number of usable coordinates in the X and Y axes stayed the same (130 and 60 coordinates, respectively). The purpose of this restriction was to ensure that any effects of changes in the tablet or display sizes were not due to an increase in the number of coordinates available for positioning within the targets, since the size of the targets increased as the display size increased. Other studies have not used such restrictions. It is possible that one reason for the reported "jumpiness" of the tablet is that smooth movements are less likely as the display size increases but the number of potential cursor positions does not increase. It is unclear, however, why this factor would not also have affected trackball performance in the same manner.

In addition to the reason for the differences found between the two input devices, another question unanswered by the first study is the reason for the effect of the display on fine adjustment time with the trackball. As indicated previously, the control inputs and display outputs of an interface can each be divided into two components:

amplitude and target width. Because the display target width increased proportionately as the display amplitude increased in the present study, it is unclear whether the effect of display width on fine adjustment and total movement times with the trackball was due to the display target size or the display amplitude. By definition, fine positioning took place once the cursor had entered the target for the first time. Therefore, it is likely that target size was the primary determinant of fine positioning. However, it is necessary to separate display target width and display amplitude before such an explanation can be supported.

The second study attempts to sort out the effects of display target width and amplitude. While Parng (1986) varied control target width, control amplitude, and display target width, the present second study varies display target width, display amplitude, and control amplitude. Clearly, once three of the four control-display interface components are fixed, the fourth component is also determined. Thus, this difference between the studies is primarily in emphasis.

The display will be emphasized in the present study for two reasons. First, a change in the display target width separate from a change in the display amplitude is immediately apparent to the subjects, while it is difficult to indicate clearly a change in the control target width separate from the control amplitude. Second, since no effect of the display was found for the touch tablet in the first study while the control input was found to affect performance with both input devices, it was desired to explore the display effect further. By providing possible improvements in the tablet, that is, by using a stylus, while also making changes in the number of cursor locations on the display and separating the display amplitude and the display target size, any potential effects of the display on touch tablet performance should become apparent. Additionally, the effect of the display output on trackball performance may be specified more fully.

The second study was designed to answer four questions. First, was the lack of an effect of the display for the touch tablet due to the particular nature of the touch tablet as it was used in the first study? That is, was any potential display effect overshadowed by difficulty in the control movements? It was hypothesized that the use of a stylus would lead to improvements in touch tablet performance.

The second question was whether the number of cursor locations on the display affected touch tablet performance.

It was hypothesized that if the number of cursor locations is allowed to increase as the display increases, smoother cursor movements would occur. This effect was only hypothesized for the touch tablet since an effect of the display had already been reported for the trackball and because the cursor did not jump as much when used with the trackball.

The third question was whether the display effect reported for fine adjustment time with the trackball was a result of the display target width or the display amplitude. Since by definition fine positioning occurred once the cursor had entered the target at least once, it was hypothesized that the target size is responsible for the performance differences.

Finally, given the changes that were made in the interfaces, the interactions between the display output and the control input that were hypothesized for the first study are again explored.

EXPERIMENT 2 METHOD

The hypotheses tested in the second study are:

1. The touch tablet performance will be improved with the use of a stylus.
2. Because an increase in the number of cursor locations on the display should lead to smoother cursor movements, the displays with increased numbers of cursor locations will provide improved performance, particularly with the touch tablet.
3. The effect of the display on fine adjustment with the trackball is due to a change in display target width, not a change in display amplitude.
4. Either the display amplitude or the display target width will interact with control amplitude to determine performance.

There were four independent variables: input device, control amplitude, display amplitude, and display target width. A within-subjects design was used, so that every subject received every combination of these independent variables.

Independent Variables

Input device. As in the first study, a touch tablet and a trackball were used. The touch tablet was used both with and without a stylus.

Control amplitude. Two levels of control amplitude were used for each device. For the touch tablet, the 50- and 100-mm tablets were chosen. The 50-mm tablet was used because it was thought that the advantage of a stylus would be maximized with the small tablet; the small tablet would allow the subject to move the stylus using only his fingers while keeping his wrist and arm motionless. The 100-mm tablet was used because it had provided the best overall performance in the previous study. In addition, these tablet sizes had shown significant performance differences for both gross and total movement times in the previous study.

For the trackball, the 50- and 200-mm input levels were chosen. The 50-mm input was used because it had provided the best performance in the first study in terms of acquisition time. The 200-mm input was chosen because it had differed significantly from the 50-mm input in the first study.

Display amplitude. Three display amplitudes were used: 50, 100, and 150 mm. As in the first study, these three displays had the same number of cursor locations based on the maximum number of locations for the small display (130 horizontally and 60 vertically). Two additional displays were tested: a 100-mm display with twice the number of cursor locations as the 50-mm display (260 horizontal and 120 vertical), and a 150-mm display with three times the number of cursor locations as the small display (390 horizontal and 180 vertical).

Display target width. Three target widths were used: 5, 10, and 15 mm. These values were chosen because they corresponded to the targets used in the 50-, 100-, and 150-mm displays in the first study. For the two displays in which the number of pixel locations changed, the number of cursor locations in the targets changed proportionately.

Apparatus

The apparatus was the same as that described for Experiment 1. A stylus 130 mm in length and 8 mm in diameter, weighing 15 g, was used. It had a plastic tip that slid easily over the mylar surface of the tablet.

Subjects

Six males ranging in age from 19 to 35 participated in the study. Five of the subjects were students and the sixth was a research associate. They were paid $5 per hour, with a bonus for completing the study. All subjects had 20/20 or better near acuity.

Subjects were questioned about their previous experience with touch tablets and trackballs. Only one subject had any experience with a touch tablet, and he estimated that he had used one for less than an hour. Three subjects had never used a trackball; of the three who had, all were in video game applications, and the estimates of total use ranged from 1 to 5 hours.

Task

The task was the same as that used in the first study. The targets were again located at either the top, bottom, left, or right of the screen, and the three target sizes appeared equally often at each location. The targets were placed so that their outside boundary was always in the same position, referenced to the placement of the targets in the first study. The cursor size increased as the display size increased as it had in the first study.

Procedure

There were six input device configurations: two touch tablet sizes, each used with and without a stylus, and two levels of trackball input. To reduce the potential for transfer effects across devices, subjects were tested on six consecutive days at approximately the same time each day. The order of presentation of the input devices was counterbalanced across subjects. On each day they used one input device configuration with all five displays (one small, two medium, and two large displays). The displays were presented in a random order each day, with these constraints: first, no order was presented to the same subject twice and, second, no display consistently preceded or followed any other display.

On the first day, subjects signed the informed consent (the consent form shown in Appendix A was modified for this study to indicate that the subjects would use both the tablet and the trackball over six days instead of five). They then read a set of general instructions describing the input devices and the task (Appendix D). Next, they read a specific set of instructions outlining how to perform the task with the particular input device they were to use first (these instructions were the same as those shown in Appendix B, modified where necessary to indicate that a stylus would be used and that five trial blocks with 72 trials to each block would be given). Following the first day, when the subject was assigned to a new input device, its use was described at the start of the session.

After indicating that they understood the instructions, the subjects performed a set of 12 training trials. Unlike the training given in the first study, subjects practiced with the input device configuration they were to use that day. In addition, subjects received 12 training trials at the start of each day on the input device assigned for that session. The reason for these changes is that the training given in the first study was simply to familiarize subjects with the task, while the training given in the second study was designed also to familiarize the subjects with the different input devices. As in the first study, however, a 170-mm display with 17-mm targets was used for training so that subjects would not become more practiced with any given display. Subjects were given an opportunity to ask questions throughout the initial instruction and training phase.

Following the training, the experimental trial blocks began. There were 72 target selections for each of the five displays: each of the three target sizes appeared in each of the four target locations six times. The order of presentation of the 12 possible combinations of target size and position was random with the exception that the first 36 and the last 36 trials each contained three replications of each combination.

Subjects were allowed to take a break after any of the trial blocks. The entire experiment required approximately three to four hours per subject across the six days. On the last day, subjects were asked to rank the six input devices and the display sizes in order of preference (see Appendix E).

EXPERIMENT 2 RESULTS

The dependent measures were the same as those described in the first study: total and gross movement times, fine adjustment time, the percentage of responses resulting in error, and subjective rankings. As in the previous experiment, the results for the touch tablet and the trackball will be presented separately; not only did the control amplitudes differ for the two devices, but the touch tablet had the additional factor of stylus.

Performance Stability

The target acquisitions were grouped into eight blocks of nine target acquisitions for the three input device configurations: touch tablet with and without stylus, and the trackball. Comparisons indicated that the last four blocks (the last 36 trials) did not differ significantly ($p > 0.05$) on any of the dependent measures for any of the input devices. Thus, it appears that performance had stabilized after 36 target acquisitions, and only the last 36 trials were used for subsequent analyses.

Number of Cursor Locations

One hypothesis is that an increase in the number of cursor locations on the display as the display amplitude increases improves performance. Although the hypothesis stated that the change would primarily improve touch tablet performance, the two medium (100-mm) displays (with and without the increase in cursor locations) were compared for all three input device configurations using one-tailed t-tests. Table 22 shows the results of the tests.

There were no significant differences in performance between the medium or large displays for any dependent measure for the finger-operated touch tablet. For the stylus-operated tablet, there was a significant difference for errors with the large display. For the trackball, gross movement time showed a significant difference for the large display.

Although the hypothesis only specifies a general improvement in performance, it is possible that the change in the number of cursor locations interacted with the tablet sizes to improve performance for one tablet size and not another. This hypothesis was tested for the finger-operated tablet. The results for these tests are shown in Table 23. There are no differences in the predicted direction between the displays with different numbers of cursor locations for

TABLE 22

Results of t-Tests on Number of Cursor Locations

	Display Amplitude (mm)			
	100		150	
	t	*p*	*t*	*p*
Touch Tablet, Finger-Operated				
Gross Movement	0.49	0.3213	-0.32	0.6202
Fine Adjustment	0.12	0.4556	0.70	0.2590
Total Movement	0.77	0.2390	0.37	0.3627
Errors	0.35	0.3718	0.73	0.2495
Touch Tablet, Stylus-Operated				
Gross Movement	-1.51	0.9048	-0.35	0.6311
Fine Adjustment	-2.06	0.9257	-0.57	0.7045
Total Movement	-2.33	0.9662	-0.48	0.6738
Errors	-0.79	0.7683	2.44	0.0294
Trackball				
Gross Movement	0.66	0.2679	2.31	0.0345
Fine Adjustment	-0.10	0.5362	-0.63	0.7230
Total Movement	0.91	0.2028	1.40	0.1101
Errors	-2.24	0.9622	-0.55	0.6972

Positive *t* values are in the predicted direction.

either the medium or large displays for any of the dependent measures for either tablet size, with one exception: errors showed a significant difference for the 100-mm tablet used with the large display.

Finally, it is possible that fine adjustment for the tablet was improved by providing more cursor locations within each target. However, t-tests indicated no significant differences in fine adjustment time between targets with and without changes in the number of cursor locations on the 100-mm display ($t = 1.05$, $p = 0.1701$ for 5-mm targets; $t = 0.08$, $p = 0.4679$ for 10-mm targets; and $t = 0.51$, $p = 0.3148$ for 15-mm targets). There was also no effect of the number of cursor locations for the targets on the 150-mm display ($t = 0.74$, $p = 0.2464$ for 5-mm targets; $t = 0.22$, $p = 0.4167$ for 10-mm targets; and $t = 0.75$, $p = 0.2428$ for 15-mm targets).

The results do not support the hypothesis that an increase in the number of cursor locations on the display would improve performance. Out of 46 comparisons, only three were significant. Two of the three significant differences were for errors, a measure which had not shown consistent results in the first study. Because the

TABLE 23

t-Tests on Number of Cursor Locations for Two Tablet Amplitudes

	Display Amplitude (mm)			
	100		150	
	t	*p*	*t*	*p*
50-mm Touch Tablet				
Gross Movement	0.65	0.2709	-0.64	0.7263
Fine Adjustment	1.27	0.1305	0.84	0.2205
Total Movement	1.21	0.1395	0.31	0.3858
Errors	-0.67	0.7343	0.18	0.4332
100-mm Touch Tablet				
Gross Movement	0.25	0.4059	0.50	0.3201
Fine Adjustment	0.28	0.3953	-0.02	0.5088
Total Movement	0.29	0.3927	0.49	0.3212
Errors	1.47	0.1014	2.24	0.0378

Positive *t* values are in the predicted direction.

predicted improvement in performance was not found, only the medium and large displays with no changes in the number of cursor locations were used in subsequent analyses. In this manner, the performance for the small display was based upon the same number of target acquisitions as was performance for the medium and large displays. In addition, the displays and targets are comparable to those in the first study.

Touch Tablet

Four independent variables were analyzed for the touch tablet: control amplitude, display amplitude, display target width, and stylus. These factors had been completely crossed, and an analysis of variance was performed for each of the four dependent measures. The results of the analyses are presented in Tables 24, 25, 26, and 27.

To summarize the results for the touch tablet, there is a main effect of control amplitude on fine adjustment and total movement times, but not for gross movement time or errors. The main effect of display amplitude is significant for all four measures. Display target width significantly affected the three acquisition time measures but not the percent of responses resulting in error. There is no effect of stylus for any of the measures, nor are any of the interactions of any factor with the stylus significant.

TABLE 24

ANOVA Summary Table for Touch Tablet Gross Movement Times (Experiment 2)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	5	1066390.63		
<u>Within</u>				
Control Amplitude (C)	1	456353.39	1.61	0.2606
C x Sub	5	283851.86		
Display Amplitude (D)	2	5776712.73	21.35	0.0002
D x Sub	10	270574.34		
Target Width (T)	2	10225705.32	33.03	0.0001
T x Sub	10	309632.32		
Stylus (S)	1	99388.15	0.32	0.5962
S x Sub	5	310900.46		
C x D	2	503578.02	2.12	0.1710
C x D x Sub	10	237750.63		
C x T	2	840520.38	4.11	0.0499
C x T x Sub	10	204648.76		
C x S	1	128903.43	1.61	0.2604
C x S x Sub	5	80100.01		
D x T	4	461951.93	3.94	0.0161
D x T x Sub	20	117162.43		
D x S	2	102214.76	0.49	0.6293
D x S x Sub	10	210667.97		
T x S	2	127315.65	4.03	0.0520
T x S x Sub	10	31586.40		
C x D x T	4	278365.73	1.35	0.2867
C x D x T x Sub	20	206338.16		

Table 24, continued

C x D x S	2	49420.20	0.61	0.5642
C x D x S x Sub	10	81500.81		
C x T x S	2	70825.76	1.48	0.2725
C x T x S x Sub	10	47694.47		
D x T x S	4	28693.47	0.50	0.7367
D x T x S x Sub	20	57491.84		
C x D x T x S	4	25846.09	0.62	0.6557
C x D x T x S x Sub	20	41917.49		
Total	215			

TABLE 25

ANOVA Summary Table for Touch Tablet Fine Adjustment Times (Experiment 2)

Source	df	MS	*F*	*p*
Between				
Subjects (Sub)	5	1910066.78		
Within				
Control Amplitude (C)	1	3615161.85	21.26	0.0058
C x Sub	5	170028.37		
Display Amplitude (D)	2	4296987.80	22.21	0.0002
D x Sub	10	193436.02		
Target Width (T)	2	6838444.21	19.29	0.0004
T x Sub	10	354426.55		
Stylus (S)	1	559256.68	2.00	0.2167
S x Sub	5	279941.34		
C x D	2	1647074.29	10.71	0.0033
C x D x Sub	10	153792.90		
C x T	2	1501072.94	13.26	0.0015
C x T x Sub	10	113208.83		
C x S	1	762955.21	4.03	0.1009
C x S x Sub	5	189168.86		
D x T	4	1565362.17	25.85	0.0001
D x T x Sub	20	60543.95		
D x S	2	61534.92	0.38	0.6937
D x S x Sub	10	162192.01		
T x S	2	95780.81	0.60	0.5699
T x S x Sub	10	160920.39		
C x D x T	4	825896.83	11.46	0.0001
C x D x T x Sub	20	72088.33		

Table 25, continued

C x D x S	2	105542.63	2.23	0.1584
C x D x S x Sub	10	47367.61		
C x T x S	2	140947.78	1.89	0.2016
C x T x S x Sub	10	74656.88		
D x T x S	4	13706.34	0.14	0.9673
D x T x S x Sub	20	101119.77		
C x D x T x S	4	14342.00	0.59	0.6710
C x D x T x S x Sub	20	24146.70		
Total	215			

TABLE 26

ANOVA Summary Table for Touch Tablet Total Movement Times (Experiment 2)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	5	5313112.33		
<u>Within</u>				
Control Amplitude (C)	1	6669354.20	7.68	0.0393
C x Sub	5	868746.79		
Display Amplitude (D)	2	19522763.84	23.27	0.0002
D x Sub	10	838885.57		
Target Width (T)	2	34085170.71	26.58	0.0001
T x Sub	10	1282477.47		
Stylus (S)	1	1189381.49	1.13	0.3364
S x Sub	5	1052578.47		
C x D	2	3887667.62	5.49	0.0246
C x D x Sub	10	708322.30		
C x T	2	4624411.58	14.40	0.0011
C x T x Sub	10	321074.02		
C x S	1	1546752.06	4.63	0.0840
C x S x Sub	5	333897.82		
D x T	4	3614260.69	13.88	0.0001
D x T x Sub	20	260382.53		
D x S	2	43971.21	0.09	0.9130
D x S x Sub	10	478730.24		
T x S	2	482003.51	2.16	0.1665
T x S x Sub	10	223577.47		
C x D x T	4	1983843.95	5.90	0.0026
C x D x T x Sub	20	336009.10		

Table 26, continued

C x D x S	2	95242.81	0.51	0.6167
C x D x S x Sub	10	187697.99		
C x T x S	2	194087.56	1.09	0.3725
C x T x S x Sub	10	177794.14		
D x T x S	4	40283.55	0.42	0.7956
D x T x S x Sub	20	97013.65		
C x D x T x S	4	6081.16	0.07	0.9891
C x D x T x S x Sub	20	81397.35		
Total	215			

TABLE 27

ANOVA Summary Table for Touch Tablet Errors (Experiment 2)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	5	0.49		
<u>Within</u>				
Control Amplitude (C)	1	3.57	6.25	0.0545
C x Sub	5	0.57		
Display Amplitude (D)	2	7.11	9.85	0.0043
D x Sub	10	0.72		
Target Width (T)	2	3.47	2.62	0.1215
T x Sub	10	1.32		
Stylus (S)	1	1.29	0.54	0.4971
S x Sub	5	2.40		
C x D	2	3.68	3.46	0.0723
C x D x Sub	10	1.06		
C x T	2	1.54	0.64	0.5467
C x T x Sub	10	2.39		
C x S	1	0.00	0.00	1.00
C x S x Sub	5	0.26		
D x T	4	1.48	0.73	0.5840
D x T x Sub	20	2.04		
D x S	2	0.11	0.13	0.8811
D x S x Sub	10	0.84		
T x S	2	0.75	1.30	0.3158
T x S x Sub	10	0.58		
C x D x T	4	0.84	0.49	0.7397
C x D x T x Sub	20	1.70		

Table 27, continued

C x D x S	2	0.11	0.11	0.9001
C x D x S x Sub	10	1.01		
C x T x S	2	0.11	0.08	0.9265
C x T x S x Sub	10	1.39		
D x T x S	4	0.70	0.76	0.5606
D x T x S x Sub	20	0.91		
C x D x T x S	6	0.70	1.00	0.4307
C x D x T x S x Sub	20	0.70		
Total	215			

All of the two- and three-way interactions for the control amplitude (C), display amplitude (D), and display target width (T) factors are significant for gross and total movement times, and fine adjustment time, with two exceptions: gross movement shows no C x D or C x D x T interactions. No interactions are significant for the percentage of responses in error.

Figure 8 shows the Control Amplitude x Display Target Width interaction for gross movement time. As can be seen in the figure and in Table 28, the significant C x T interaction for gross movement time reflects the fact that the small targets are more difficult to acquire, especially with the small tablet.

Figure 9 shows the Display Amplitude x Display Target Width interaction for gross movement time. Table 29 shows the results of a Student Newman-Keuls test on the nine combinations of the display amplitudes and target widths. The small target with the large display leads to the longest gross movement times. In general, gross movement times for the smallest targets are more affected by an increase in display amplitude than are the larger targets.

The three-way C x D x T interaction for fine adjustment time can be seen in Figure 10. A simple-effects F test (Table 30) shows that the effect of the control amplitude is

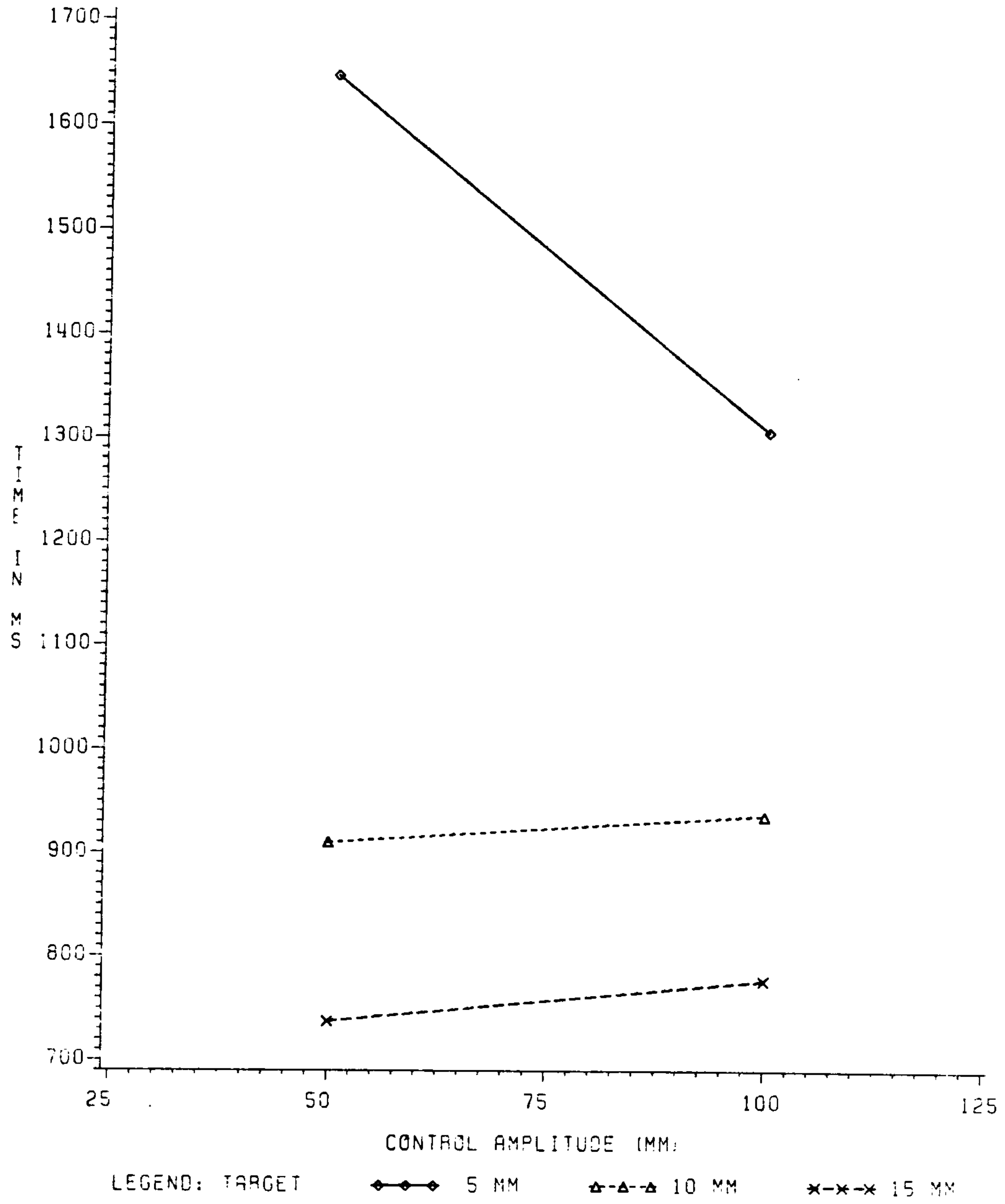


Figure 8: Effect of Control Amplitude and Display Target Width on Touch Tablet Gross Movement Times.

TABLE 28

Student Newman-Keuls Test on C x T Interaction for Touch Tablet Gross Movement Times

Control Amplitude (mm)	Display Target Width (mm)	Mean Time (ms)	Grouping*
50	5	1647.3	A
100	5	1305.9	B
100	10	936.2	C
50	10	909.7	C
100	15	776.4	C
50	15	737.3	C

* Means with different letters are significantly different ($p < 0.05$).

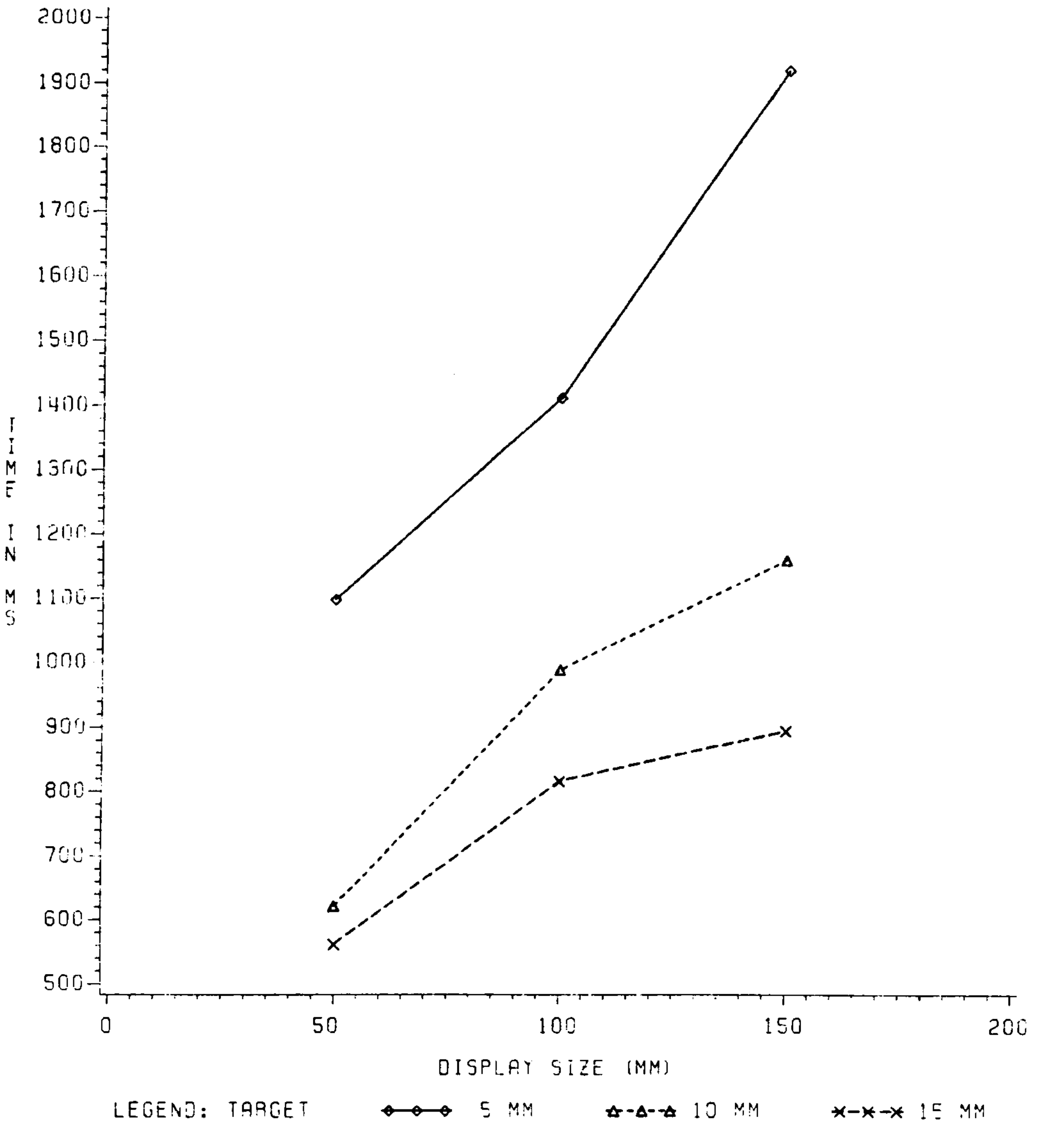


Figure 9: Effect of Display Amplitude and Display Target Width on Touch Tablet Gross Movement Times.

TABLE 29

Student Newman-Keuls Test on D x T Interaction for Touch Tablet Gross Movement Times

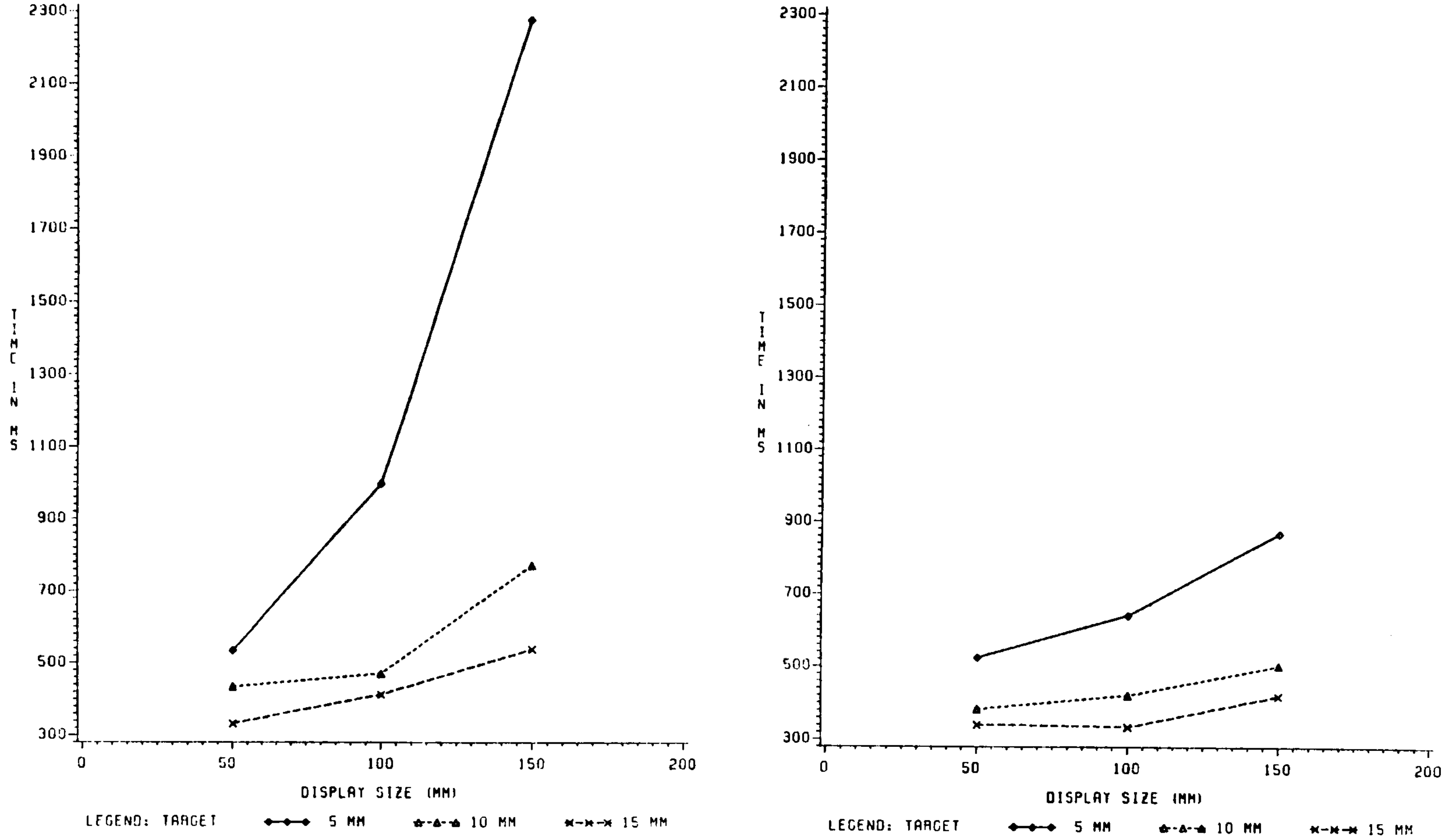
Display Amplitude (mm)	Display Target Width (mm)	Mean Time (ms)	Grouping*
150	5	1921.5	A
100	5	1410.8	B
150	10	1160.1	B C
50	5	1097.6	B C
100	10	988.0	B C
150	15	894.4	B C
100	15	815.2	B C
50	10	620.8	B C
50	15	561.0	C

* Means with different letters are significantly different ($p < 0.05$).

significant only for the 5-mm targets; fine adjustment was faster with the larger tablet. The effect of display amplitude is significant at all levels of target width. For both the 5- and 10-mm targets, a Student Newman-Keuls test indicated that the large display led to significantly longer fine adjustment times than did the 50- or 150-mm displays ($\underline{p} < 0.05$). For the 15-mm targets, all of the display sizes showed significant differences, with fine adjustment improving as the display size decreased ($\underline{p} < 0.05$).

The Control Amplitude x Display Amplitude is significant for fine adjustment with the 5-mm targets. Table 31 shows the results of a Student Newman-Keuls test on these factors. The small tablet used with the largest display leads to significantly poorer performance than any other combination.

The C x D x T interaction for total movement time is shown in Figure 11. A simple-effects F test shows a pattern of results similar to those found for fine adjustment (see Table 32). Control amplitude was a significant factor only at the 5-mm target level, and total movement time was better with the larger tablet for this target width. Display amplitude was significant at all levels of target width. Student Newman-Keuls tests indicated that for the 5-mm targets, the 150-mm display led to longer total movement times than the two smaller displays ($\underline{p} < 0.05$). There were



a. 50-mm tablet

b. 100-mm tablet

Figure 10 : The C x D x T Interaction for Touch Tablet Fine Adjustment Times.

TABLE 30

Summary Table of the Simple-Effects F test for the Touch Tablet Fine Adjustment Times

Source	df	MS	*F*	*p*
5-mm Target				
Control Amplitude (C)	1	3137075.6	22.91	0.0049
Display Amplitude (D)	2	3468930.4	30.16	0.0001
C x D	2	1589136.9	13.38	0.0015
10-mm Target				
Control Amplitude (C)	1	135926.2	2.74	0.1589
Display Amplitude (D)	2	180345.4	4.90	0.0329
C x D	2	47685.1	1.98	0.1883
15-mm Target				
Control Amplitude (C)	1	35652.0	3.06	0.1409
Display Amplitude (D)	2	64580.3	11.86	0.0023
C x D	2	12612.1	2.06	0.1788

TABLE 31

Student Newman-Keuls Test on C x D Interaction for Touch Tablet Fine Adjustment Times for the 5-mm Target

Control Amplitude (mm)	Display Amplitude (mm)	Mean Time (ms)	Grouping*
50	150	2274.2	A
50	100	996.2	B
100	150	867.4	B
100	100	641.3	B
50	50	534.0	B
100	50	524.4	B

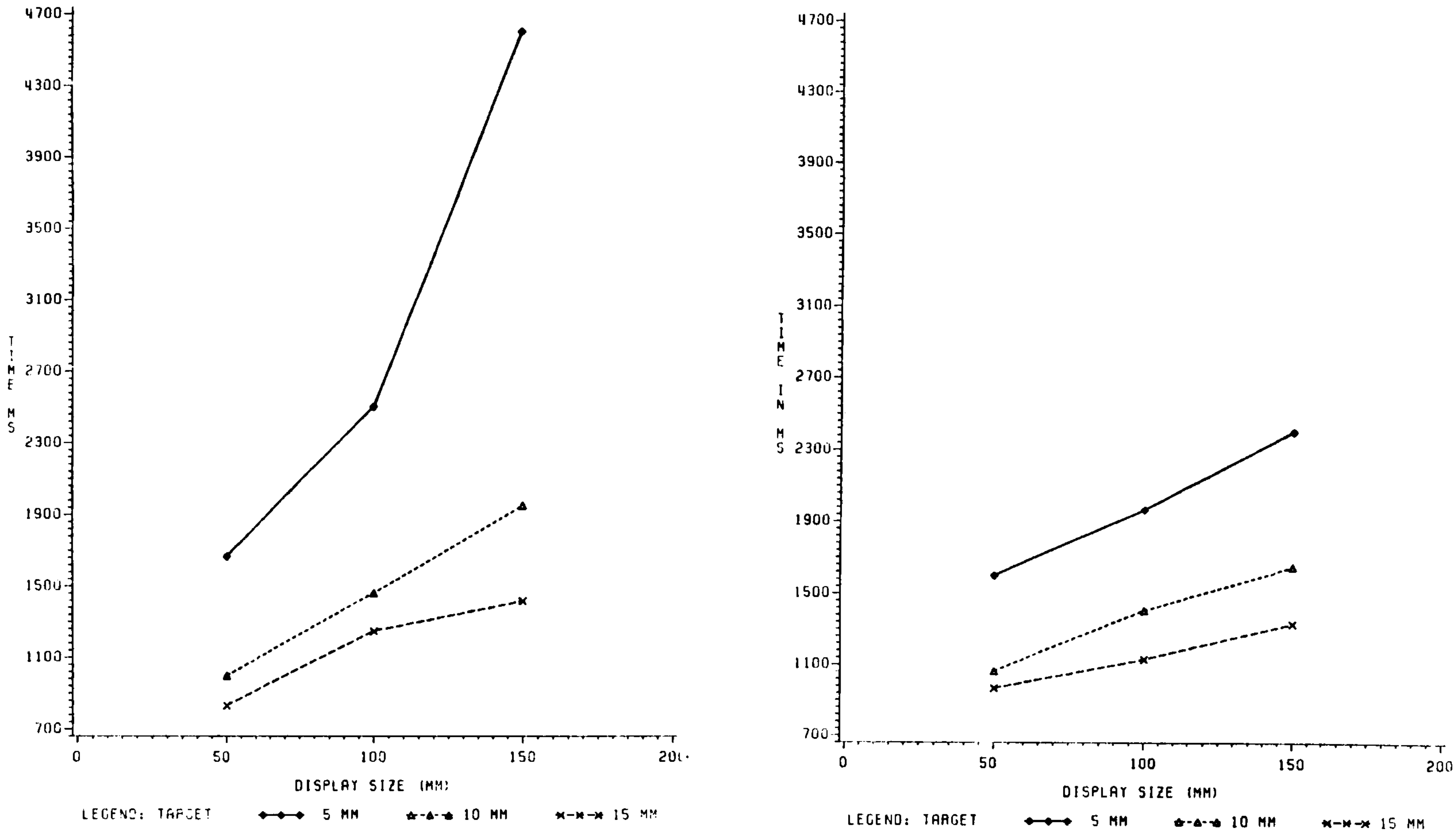
* Means with different letters are significantly different ($p < 0.05$).

significant differences between all display amplitudes for both the 10- and 15-mm target widths, with performance improving as the display amplitude decreased ($p < 0.05$).

As seen with fine adjustment, the C x D interaction is significant for total movement time with the 5-mm targets. Table 33 presents the results of a Student Newman-Keuls test on these factors. The small tablet used with the largest display leads to significantly poorer performance than any other combination of control and display amplitudes. Thus, for both fine adjustment and total movement times, the C x D x T interaction is a result of the fact that as the display amplitude increases smaller targets are harder to acquire, and this decrease in performance is even greater when a small tablet is used.

Trackball

The analyses of variance for the trackball are shown in Tables 34, 35, 36, and 37. The results for the trackball show a slightly different pattern of effects than do those for the touch tablet. The main effect of control amplitude is not significant for any dependent measure. The display amplitude main effect and the D x T interaction are significant only for gross and total movement times, and not for fine adjustment time or errors. The display target



a. 50-mm tablet

b. 100-mm tablet

Figure 11: The C x D x T Interaction for Touch Tablet Total Movement Times.

TABLE 32

Summary Table of the Simple-Effects F test for the Touch Tablet Total Movement Times

Source	df	MS	*F*	*p*
5-mm Target				
Control Amplitude (C)	1	7870750.8	11.69	0.0189
Display Amplitude (D)	2	10922569.6	19.10	0.0004
C x D	2	3763882.3	6.01	0.0193
10-mm Target				
Control Amplitude (C)	1	83696.9	1.73	0.2460
Display Amplitude (D)	2	1770119.9	20.78	0.0003
C x D	2	105769.1	2.53	0.1295
15-mm Target				
Control Amplitude (C)	1	4641.0	0.14	0.7247
Display Amplitude (D)	2	682953.1	30.12	0.0001
C x D	4	58026.3	2.58	0.1246

TABLE 33

Student Newman-Keuls Test on C x D Interaction for Touch Tablet Total Movement Times for the 5-mm Targets

Control Amplitude (mm)	Display Amplitude (mm)	Mean Time (ms)	Grouping*
50	150	4601.0	A
50	100	2502.8	B
100	150	2401.2	B
100	100	1965.1	B
50	50	1666.1	B
100	50	1598.1	B

* Means with different letters are significantly different ($p < 0.05$).

width main effect is significant for all three acquisition time measures. The C x D interaction is significant for total movement time and error rate. Finally, the C x D x T interaction was significant for the three acquisition time measures.

Figure 12 shows the effects of the display amplitude and target width on gross movement time for both of the trackball control amplitudes. Table 38 shows the results of a simple-effects F-test for each the control and display amplitudes for each target width. The effect of control amplitude is not significant at any level of target width. The effect of display amplitude is significant at all levels of target width. Student Newman-Keuls test indicated that for the 5-mm targets, there were significant differences between all display amplitudes ($p < 0.05$), and gross movement time increased as the display amplitude increased. For the 10- and 15-mm targets, the 50-mm display amplitude led to significantly shorter gross movement times than either the 100- or 150-mm displays ($p < 0.05$).

The C x D interaction is significant only for performance with the 5-mm targets. The results of Student Newman-Keuls tests on the C x D interaction for the 5-mm targets are shown in Table 39. The 50-mm input with the large display leads to the poorest performance with the 5-mm target, and

TABLE 34

ANOVA Summary Table for Trackball Gross Movement Times (Experiment 2)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	5	570034.02		
<u>Within</u>				
Control Amplitude (C)	1	178378.71	1.45	0.2824
C x Sub	5	122986.88		
Display Amplitude (D)	2	2468990.20	37.55	0.0001
D x Sub	10	65744.87		
Target Width (T)	2	1661089.80	55.06	0.0001
T x Sub	10	30169.95		
C x D	2	94211.02	3.16	0.0864
C x D x Sub	10	29813.95		
C x T	2	44868.93	3.01	0.0949
C x T x Sub	10	14919.27		
D x T	4	55458.63	2.95	0.0456
D x T x Sub	20	18797.55		
C x D x T	4	49002.15	5.50	0.0037
C x D x T x Sub	20	8911.02		
Total	107			

TABLE 35

ANOVA Summary Table for Trackball Fine Adjustment Times (Experiment 2)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	5	121486.63		
<u>Within</u>				
Control Amplitude (C)	1	30671.72	0.48	0.5180
C x Sub	5	63485.33		
Display Amplitude (D)	2	13597.97	0.65	0.5414
D x Sub	10	20828.04		
Target Width (T)	2	369094.72	6.32	0.0168
T x Sub	10	58376.20		
C x D	2	63228.56	2.77	0.1106
C x D x Sub	10	22854.70		
C x T	2	82488.94	3.04	0.0928
C x T x Sub	10	27096.14		
D x T	4	25986.81	1.23	0.3317
D x T x Sub	20	21211.93		
C x D x T	4	58572.26	3.82	0.0182
C x D x T x Sub	20	15320.63		
Total	107			

TABLE 36

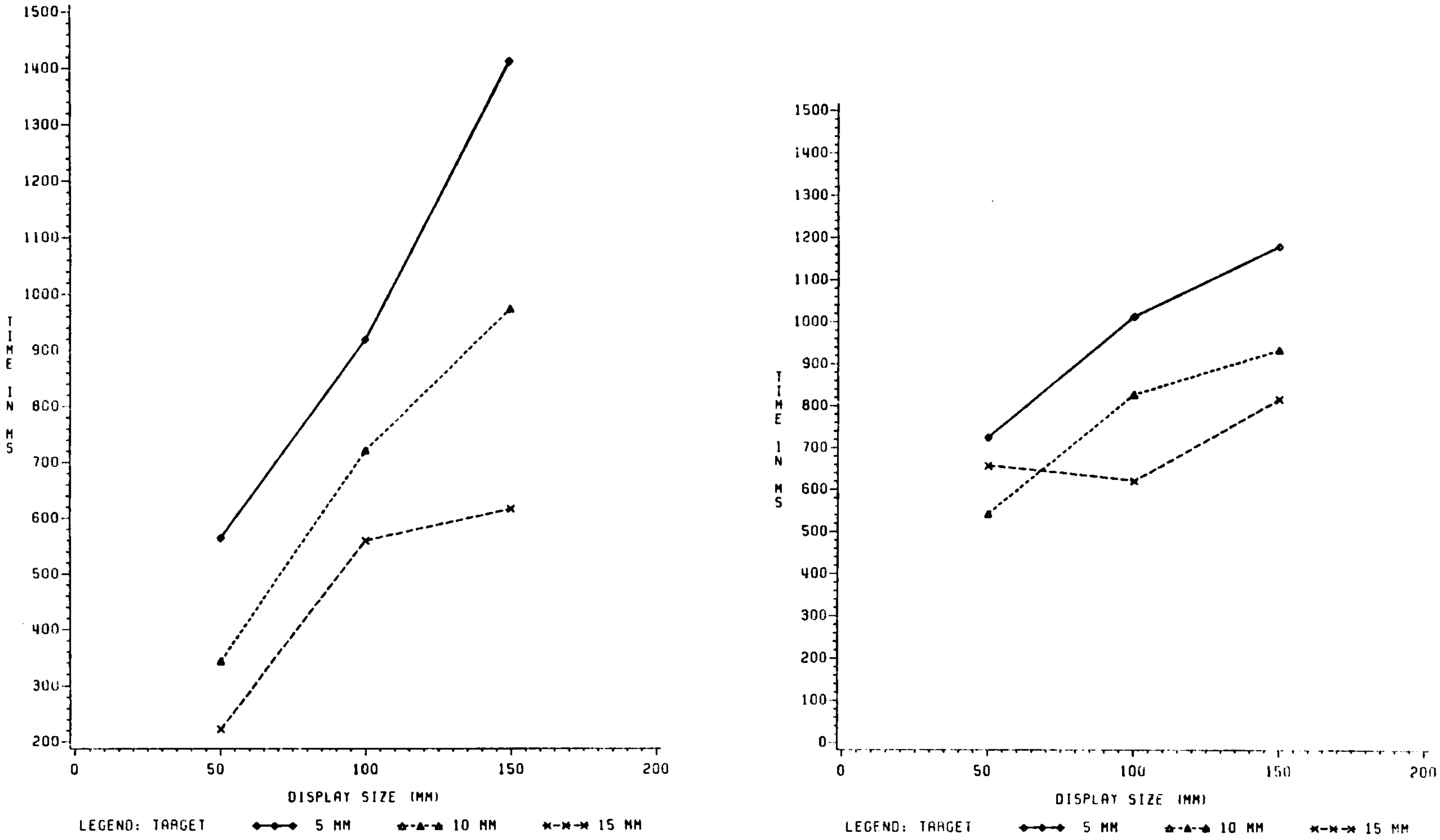
ANOVA Summary Table for Trackball Total Movement Times (Experiment 2)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (Sub)	5	1107228.30		
<u>Within</u>				
Control Amplitude (C)	1	62232.00	0.30	0.6058
C x Sub	5	205563.78		
Display Amplitude (D)	2	2828856.40	46.05	0.0001
D x Sub	10	61427.95		
Target Width (T)	2	3514120.70	40.86	0.0001
T x Sub	10	86001.06		
C x D	2	313757.54	6.27	0.0172
C x D x Sub	10	50035.80		
C x T	2	237759.01	5.24	0.0277
C x T x Sub	10	45348.55		
D x T	4	139577.06	5.70	0.0031
D x T x Sub	20	24481.94		
C x D x T	4	176214.78	6.47	0.0016
C x D x T x Sub	20	27240.82		
Total	107			

TABLE 37

ANOVA Summary Table for Trackball Errors (Experiment 2)

Source	df	MS	*F*	*p*
<u>Between</u>				
Subjects (S)	5	0.41		
<u>Within</u>				
Control Amplitude (C)	1	1.79	4.31	0.0925
C x Sub	5	0.41		
Display Amplitude (D)	2	1.15	3.08	0.0909
D x Sub	10	0.37		
Target Width (T)	2	0.29	1.00	0.4019
T x Sub	10	0.29		
C x D	2	2.00	5.38	0.0259
C x D x Sub	10	0.37		
C x T	2	1.15	4.00	0.0529
C x T x Sub	10	0.29		
D x T	4	0.82	1.89	0.1525
D x T x Sub	20	0.44		
C x D x T	4	0.39	0.90	0.4816
C x D x T x Sub	20	0.44		
Total	107			



a. 50-mm amplitude

b. 200-mm amplitude

Figure 12: The C x D x T Interaction for Trackball Gross Movement Times.

TABLE 38

Summary Table of the Simple-Effects F test for the Trackball Gross Movement Times

Source	df	MS	*F*	*p*
<u>5-mm Target</u>				
Control Amplitude (C)	1	481.4	0.01	0.9266
Display Amplitude (D)	2	1270839.4	43.36	0.0001
C x D	2	131482.0	10.64	0.0033
<u>10-mm Target</u>				
Control Amplitude (C)	1	70593.8	1.22	0.3191
Display Amplitude (D)	2	802813.3	17.54	0.0005
C x D	2	43443.9	2.03	0.1822
<u>15-mm Target</u>				
Control Amplitude (C)	1	197041.3	4.50	0.0872
Display Amplitude (D)	2	506254.8	17.91	0.0005
C x D	2	17289.4	1.25	0.3283

it is likely that this condition is primarily responsible for the significant C x D x T interaction. In general, as target size decreases and display amplitude increases, the target acquisitions all take longer.

The effects of the control amplitude, display amplitude, and display target width on fine adjustment time are shown in Figure 13. The lack of a display main effect is evident in this figure. Since neither the main effects of control and display amplitude nor the the C x D interaction are significant in the overall analysis of variance, the simple effects tests for fine adjustment were done for the display amplitude and target width factors at each level of the control amplitude. Table 40 indicates the results of these tests.

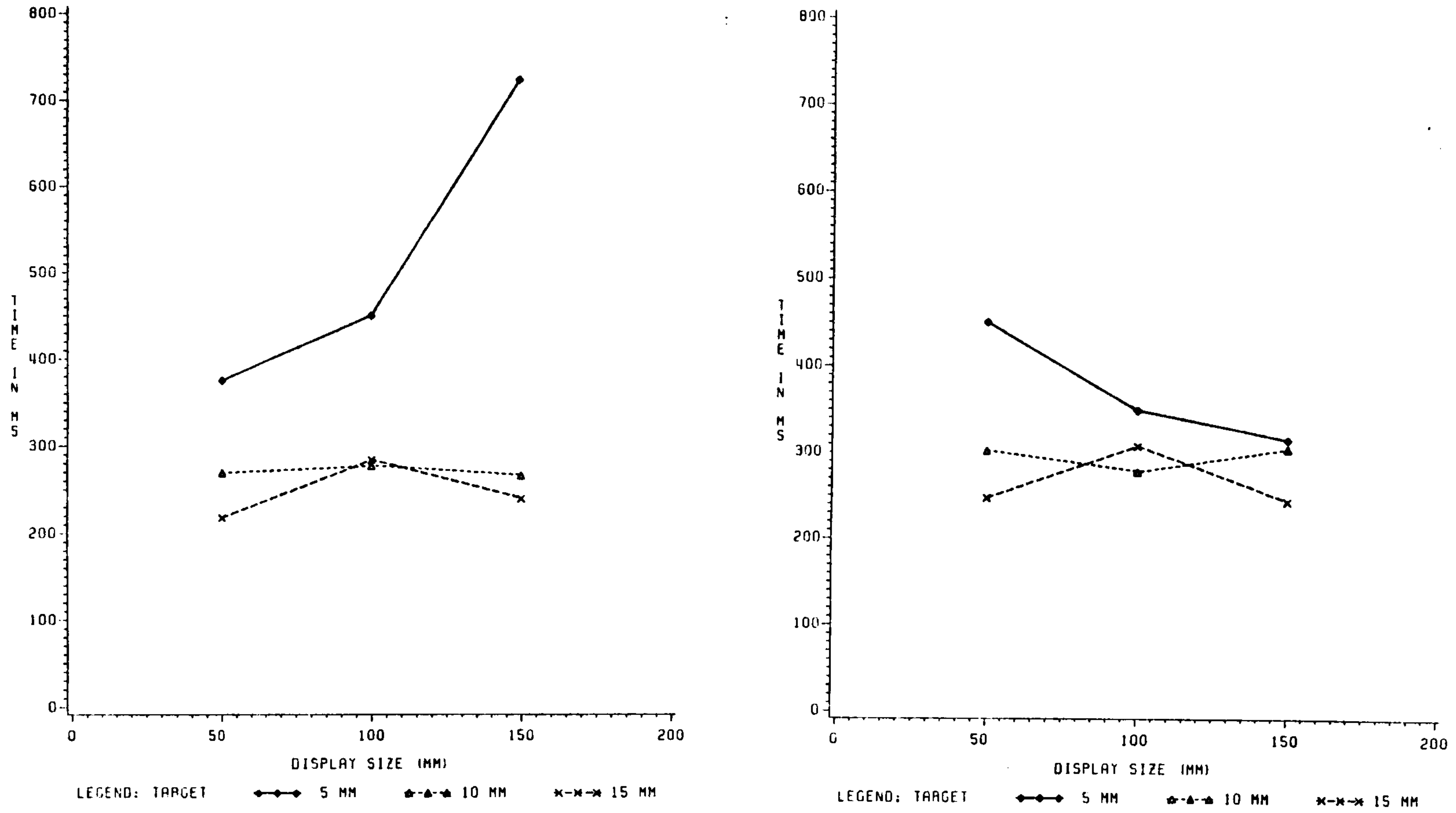
The effect of display target width is significant for both control amplitudes, the display amplitude is significant at only the 200-mm control amplitude, and the D x T interaction is not significant for either control amplitude. Student Newman-Keuls tests indicated that for both the 50- and 200-mm trackball amplitudes, the smallest target size leads to significantly longer fine adjustment times than either of the larger targets ($p < 0.05$), while the larger targets do not differ significantly. With respect to the significant display amplitude effect for the

TABLE 39

Student Newman-Keuls Test on C x D Interaction for Trackball Gross Movement Times for the 5-mm Targets

Control Amplitude (mm)	Display Amplitude (mm)	Mean Time (ms)	Grouping*
50	150	1410.6	A
200	150	1179.2	B
200	100	1011.7	B C
50	100	918.1	C D
200	50	723.9	D E
50	50	564.2	E

* Means with different letters are significantly different ($p < 0.05$).



a. 50-mm amplitude

b. 200-mm amplitude

Figure 13: The C x D x T Interaction for Trackball Fine Adjustment Times.

TABLE 40

Summary Table of the Simple-Effects F test for the Trackball Fine Adjustment Times

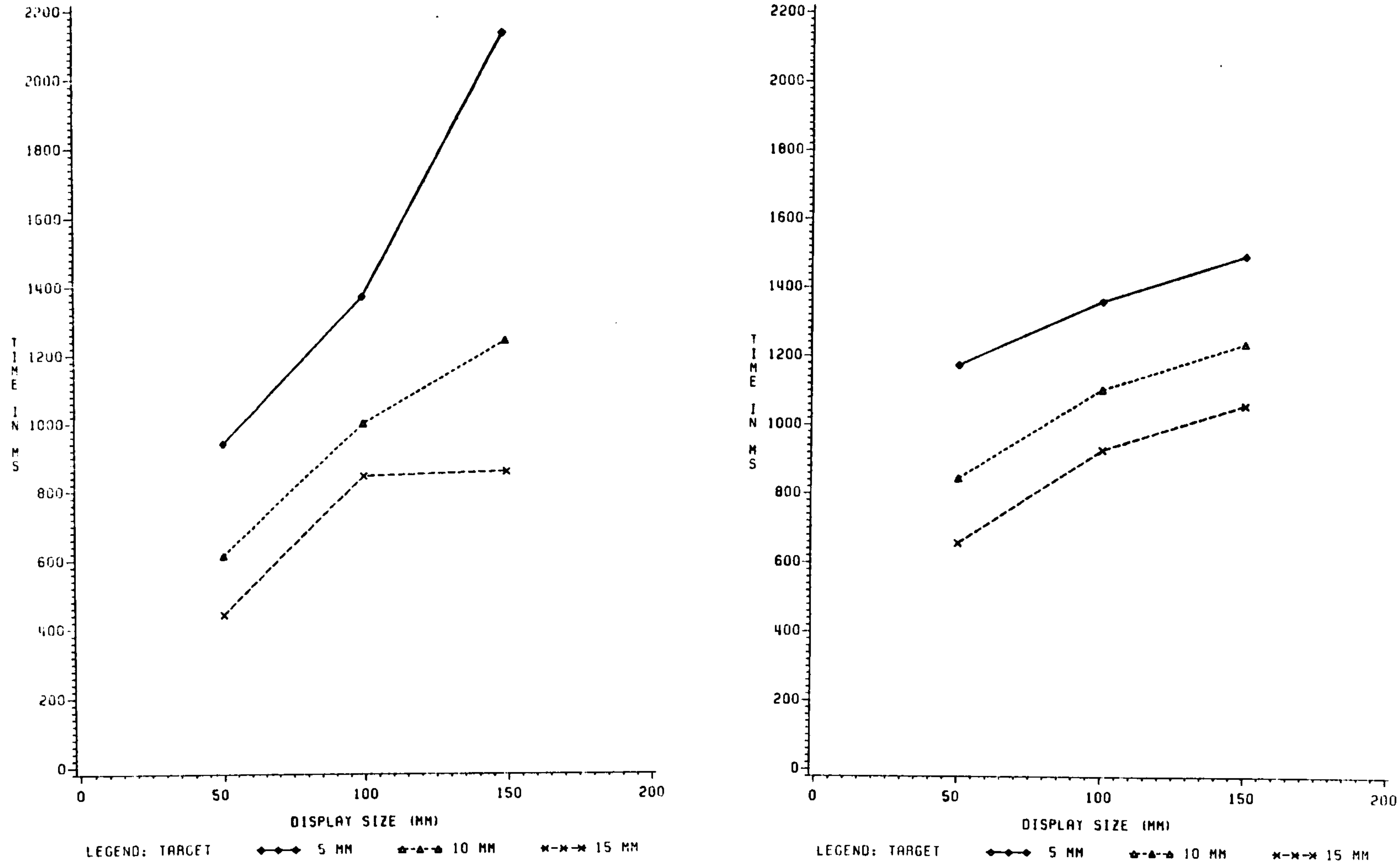
Source	df	MS	*F*	*p*
50-mm Control Amplitude				
Display Amplitude (D)	2	67652.8	1.61	0.2485
Target Width (T)	2	398180.0	5.19	0.0285
D x T	4	69853.3	2.44	0.0806
200-mm Control Amplitude				
Display Amplitude (D)	2	640066.2	9.62	0.0047
Target Width (T)	2	974844.6	56.33	0.0001
D x T	4	4135.4	0.39	0.8127

200-mm amplitude, the 150-mm display led to significantly shorter fine adjustment times than the 50-mm display ($p < 0.05$).

Figure 14 presents the effects of the display and target sizes on total movement time for both of the trackball control amplitudes. The simple-effects tests for the C x D interaction for the three target widths are shown in Table 41. The effect of control amplitude is not significant at any level of target width. The main effect of display amplitude is significant at all target width levels. For both the 5- and 10-mm targets, Student Newman-Keuls tests indicate significant differences between all the displays ($p < 0.05$), with total movement time increasing as the display size increases. For the 15-mm targets, the 50-mm display amplitude leads to significantly shorter total movement times than the larger displays ($p < 0.05$).

The results of a Student Newman-Keuls test on the C x D interaction for the 5-mm targets are shown in Table 42. Performance with the 50-mm control amplitude and the 150-mm display is poorer than for any other control and display amplitude combination.

Figure 15 illustrates the significant Control Amplitude x Display Amplitude interaction for the percent of responses in error. Because of the low percentage of responses that were in error, this measure was not analyzed further.



a. 50-mm amplitude

b. 200-mm amplitude

Figure 14: The C x D x T Interaction for Trackball Total Movement Times.

TABLE 41

Summary Table of the Simple-Effects F test for the Trackball Total Movement Times

Source	df	MS	*F*	*p*
5-mm Target				
Control Amplitude (C)	1	168673.1	0.82	0.4070
Display Amplitude (D)	2	1739382.4	31.27	0.0001
C x D	2	609843.9	9.86	0.0043
10-mm Target				
Control Amplitude (C)	1	114186.5	2.62	0.1665
Display Amplitude (D)	2	797246.0	24.62	0.0001
C x D	2	40565.8	1.38	0.2963
15-mm Target				
Control Amplitude (C)	1	254890.4	5.46	0.0666
Display Amplitude (D)	2	98520.6	25.53	0.0001
C x D	2	15777.4	1.19	0.3430

TABLE 42

Student Newman-Keuls Test on D x T Interaction for Trackball Total Movement Times for the 5-mm Targets

Control Amplitude (mm)	Display Amplitude (mm)	Mean Time (ms)	Grouping*	
50	150	2132.6	A	
200	150	1494.2	B	
50	100	1367.4	B	C
200	100	1360.4	B	C
200	50	1173.7	B	C
50	50	939.0		C

* Means with different letters are significantly different ($p < 0.05$).

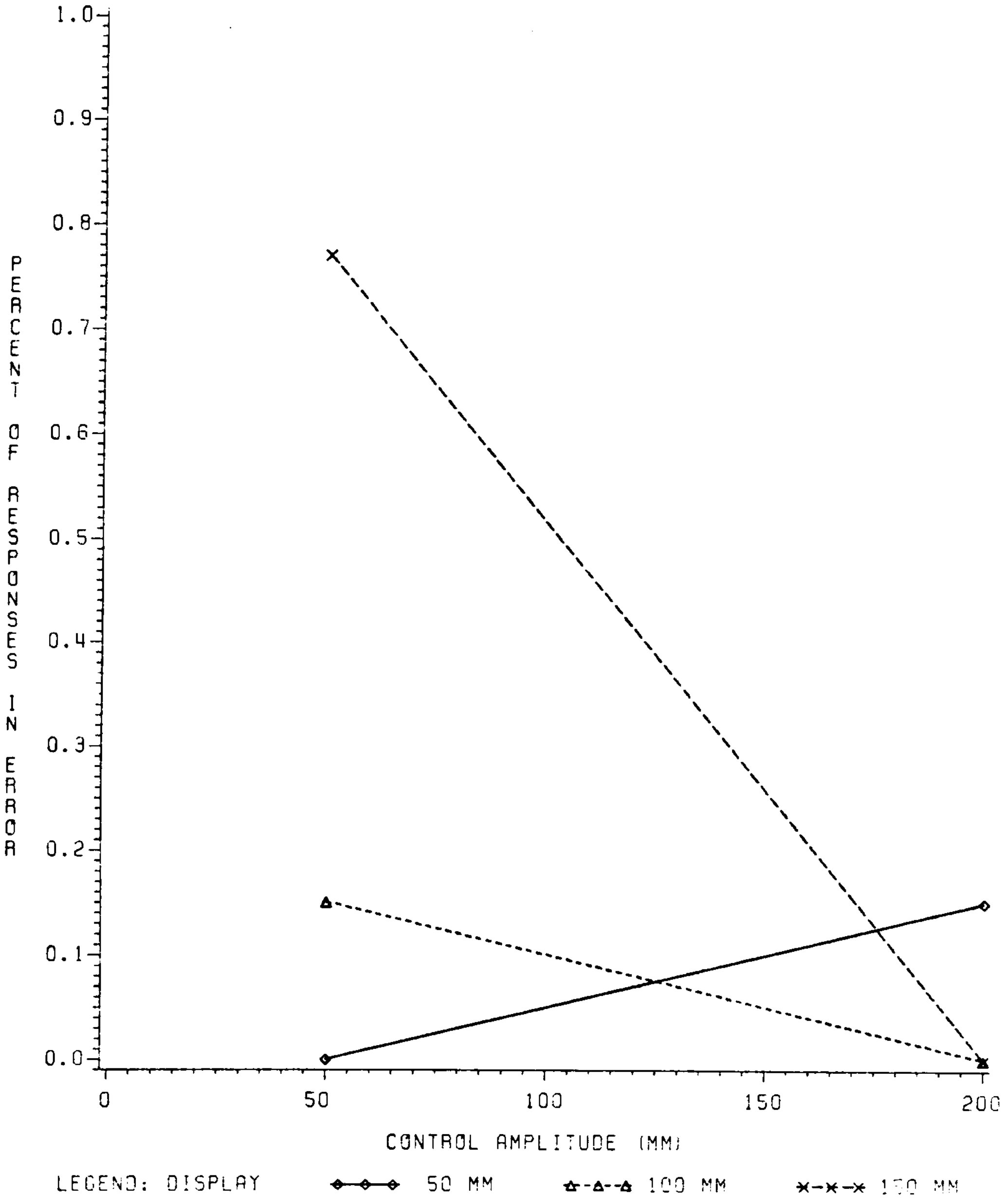


Figure 15: Effect of Control Amplitude and Display Amplitude on Trackball Errors.

Subjective Rankings

Subjects were asked to rank the six input device configurations and the three display amplitudes. The rank sums are shown in Table 43. A Friedman rank sum test indicated no significant differences among the six input devices ($p = 0.30$), although there appears to be a tendency for the trackball to be preferred (a low rank sum indicates that the device was preferred).

The rank sums for the display are significantly different ($p = 0.03$). Post-hoc distribution-free multiple comparisons (Hollander and Wolfe, 1973) indicated that the 50-mm display is significantly preferred to the 150-mm display. This finding agrees with the poorer performance seen with the large display for the objective dependent measures.

TABLE 43

Rank Sums for the Input Devices and Displays

Device	Rank Sum	Grouping*
50-mm tablet (finger)	25.0	A
50-mm tablet (stylus)	25.0	A
100-mm tablet (stylus)	24.0	A
100-mm tablet (finger)	21.0	A
50-mm trackball	19.0	A
200-mm trackball	12.0	A

Display Amplitude (mm)	Rank Sum	Grouping*
150	17.0	A
100	11.0	A B
50	8.0	B

* Means with different letters are significantly different ($p < 0.05$).

EXPERIMENT 2 DISCUSSION

The purpose of the second study was to examine more closely the effect of the display found for the trackball and to attempt to determine whether the display could affect performance with the touch tablet given certain changes in the tablet and the display. Specifically, the second study was designed to answer four questions. The first question was whether the use of a stylus could improve touch tablet performance by either improving the control movements required or by providing a smaller area of pressure in comparison to the finger. The main effect of the stylus was not significant, nor were any of the interactions between the stylus and the other independent variables. Thus, it appears that the stylus did not alter any aspect of performance.

There are several explanations for the lack of a stylus effect. It is possible that the particular stylus used was not optimal. Ellingstad et al. (1985) used a stylus with a ball bearing in the tip, and this design may be better than one with a stationary tip. Another reason may be that due to the nature of the tablet, if more than one location on the tablet is pressed, the cursor location is determined by the centroid of these activated areas. Thus, subjects could only rest their hand on an inactive area of the tablet, and this may have decreased the usefulness of the stylus. However, the 50-mm tablet was small enough that this constraint did not present a problem. Since there was no interaction between the tablet size and the use of the stylus, it appears that the stylus was not more difficult to use with the larger tablet than with the smaller one. Thus, it is unlikely that the constraint on the hand placement affected performance. A final explanation may be that for the present task the stylus simply does not aid performance. Since the reported jumpiness of the cursor did not decrease with the use of the stylus, the potential benefit of the stylus was mitigated.

It is possible that the jumpiness of the cursor with the tablet is due to the fact that the cursor path is determined primarily by the finger ballistics, while the trackball movement tends to be self-damping and more dependent upon trackball than finger movement. However, in the present case, even if a line was drawn on the tablet using the stylus along a ruler edge, the cursor still moved somewhat erratically on the screen. Thus, it appears that the jumpiness of the cursor when used with the tablet is due to the particular tablet used, and not to the differences between the tablet and trackball in general.

The second question to be answered by the second study was whether providing a proportionate increase in the number of cursor locations on the display as the display amplitude increased would improve performance with either input device. No effect was found for the number of cursor locations on the display, nor was there an effect of an increase in the number of cursor locations in the targets. In addition, there was no difference between the displays when used with different tablet sizes. It appears that, regardless of how the display amplitude and target width are changed, it is the size of the target and/or the display, and not the number of cursor locations they contain, that determines performance.

Thus, the hypothesis that performance improves as the number of cursor locations on the display increases is not supported. This finding was not surprising since the change in the number of cursor locations was not evident on the display; the cursor still appeared somewhat jumpy when the touch tablet was used for target acquisition regardless of the number of cursor locations. The cursor had appeared to have smoother movements when used with the trackball in the first study and since performance with the trackball was already quite good, there had been no reason to expect improvements for this device.

The lack of improvement in touch tablet performance is supported by the fact that all of the acquisition times were significantly longer for the tablet than they were for the trackball, as shown by a Sign test ($p = 0.016$). The mean gross movement, fine adjustment, and total movement times for the tablet were: 1123, 676, and 1803 ms. For the trackball the corresponding values were: 776, 338, and 1114 ms.

The third question was whether the main effect of the display found for the fine adjustment and total movement times with the trackball was due to the display amplitude or target width. It was hypothesized that display target width was the important factor, since by definition fine adjustment occurred once the target had been entered at least once. Since the main effect of display amplitude was not significant for fine adjustment times with the trackball in the second study, but the main effect of display target width was, it appears that the effect of the display is due to the size of the target and not the active area of the display. Thus, the third hypothesis was supported.

The fourth question to be answered by the second study was whether the changes in the tablet and display sizes would provide the hypothesized Control x Display interactions not found in the first study. Before this question can be fully answered, however, it is necessary to look at another issue of interest, the effect of the display amplitude and target width found for the two input devices. There was no significant effect of the display width on any of the dependent measures for the tablet in the first study. When the display amplitude and target width components were separated in the second study, both effects were significant for all of the target acquisition time measures (only the display amplitude had a significant effect on errors with the tablet). Since it was found that increasing display amplitude degrades performance, while increasing target width improves performance, it is possible that these effects simply canceled each other in the first study.

In the first study, the larger displays (and associated larger targets) led to improved trackball fine adjustment and total movement times. When display amplitude and target width were unconfounded, the smaller display amplitudes and the larger target widths were associated with improved performance. Thus, as indicated above for the third hypothesis, the effect of the display in the first study appears to have been due to the target width.

Because of the clear effects of both components of the display, it appears that the fourth question regarding the interaction between the control input and the display output was insufficient and that the hypothesis regarding a Control x Display interaction was incorrectly specified. This conjecture is supported by the fact that while the Control Amplitude x Display Amplitude interaction is significant for several dependent measures, the higher-order Control Amplitude x Display Amplitude x Display Target Width interaction is significant for all measures except gross movement time for the touch tablet and errors for either input device. Thus, it appears that not only are the effects of the control and the display amplitudes interdependent, the size of the target can change the nature of the control-display interaction. This is, in retrospect, not surprising as Arnaut and Greenstein (in press) and Epps et al. (1986) found similar relationships.

GENERAL DISCUSSION

The hypothesis tested in the first study was that an interaction between the control input and the display output of an interface would determine performance. This hypothesis was not supported for either input device tested. The touch tablet showed a significant effect of the control input on gross and total movement times, and on fine adjustment time. The Control x Display interaction was not significant for any dependent measure, nor was the main effect of display width. For the trackball, there was a significant main effect of the control input on gross and total movement time and errors, and a main effect of display on the fine adjustment and total movement times. As with the tablet, the interaction between the control and the display variables was not significant for any dependent measure for the trackball.

Although the hypothesis regarding a Control x Display interaction was not supported in the first study, the results for the touch tablet did indicate that D/C gain did not sufficiently explain performance. Conditions having the same numeric value of gain achieved through different control-display combinations showed significantly different performance. While the trackball did not show as many significant differences for conditions having the same gain achieved in different ways, the fact that only the control input was significant for gross movement time suggests that gain is not a sufficient predictor of gross movement. That is, if display width does not affect this measure, then only control input and not gain (which includes both the display and the control effects) is necessary to explain gross movement performance. Similarly, the same logic may be applied to the fine adjustment time, for which only the display main effect was significant. Only total movement time, for which both the control and display main effects were significant, appears to offer the the potential for gain to be used to specify movement times.

Given the significant three-way interactions found in the second study, optimization of a control-display interface would necessitate that not only the amplitudes of the control movement and the cursor movement on the display be taken into account, but also the size of the targets on the display. A concept such as D/C gain would be inadequate to handle such optimization, since only two factors can be specified. For example, even if gain is defined as Parng (1986) and Buck (1980) defined it, that is, as the ratio of display target width to control target width, the factors of control amplitude and display amplitude cannot be included. Clearly then, as indicated by the results of the first study, D/C gain is an inadequate specification for the optimization of at least the touch tablet and the trackball for target acquisition tasks.

Another method of characterizing motor performance tasks is to apply Fitts' Law (Fitts, 1954). Fitts' Law may be stated as follows:

$$\text{Movement time} = a + b \log_2 (2C/T). \qquad (3)$$

In this equation, a and b are empirically determined constants, C is the movement amplitude, and T is the target width. While D/C gain is a concept that can only be used with a separate control and display, Fitts' Law was developed for use with interfaces where the target was on the control surface. However, it is possible that if the amplitude and target width specified by Fitts' Law are defined to be on the display, Fitts' Law may provide a good fit to target acquisition time data. Epps (1986) applied Fitts' Law to a target acquisition task in which the distance to the target on the display and the display target width were changed while the control was not changed. He reported that Fitts' Law provided a good fit for target acquisition with a trackball and a mouse.

Other researchers have applied Fitts' Law to interfaces with separate controls and displays to characterize movement time (see, for example, Card, English, and Burr, 1978; Jagacinski et al., 1978; Jagacinski, Repperger, Ward, and Moran, 1980). For interfaces where the control and display are separate, the movement of the effector mechanism (such as the arm, hand, or finger) and the size of the target on the display are often used for C and T, repectively. This application of Fitts' law may be valid when only two of the four control-display components are varied independently for an interface.

However, it is clear that, by definition, Fitts' Law has the same limitation as does D/C gain; that is, it cannot account for independent variations of three of the four factors of control amplitude, control target width, display amplitude, and display target width. Given the results of the second study, it is thus an inadequate specification for performance if three of the four control-display components are independently specified.

To test this logic formally, Fitts' Law was applied to the acquisition time data from the second study. Table 44 indicates the R^2s found for each of the dependent measures for both input devices when using Fitts' Law to describe the data. It is clear that Fitts' Law does not provide a good

TABLE 44

Applying Regression Models to the Data

	R^2	
Model	Touch Tablet	Trackball
Fitts' Law: $\log_2(2C/T)$		
Gross Movement	0.5138	0.2425
Fine Adjustment	0.1441	0.0354
Total Movement	0.3522	0.1784
$\log_2(2(C+D)/T)$		
Gross Movement	0.3762	0.3880
Fine Adjustment	0.1671	0.0828
Total Movement	0.2856	0.3526
$\log_2(2C/T) + \log_2 D$		
Gross Movement	0.2733	0.4636
Fine Adjustment	0.1103	0.0276
Total Movement	0.1930	0.3338
$C + D + T$		
Gross Movement	0.4350	0.5741
Fine Adjustment	0.3154	0.1569
Total Movement	0.4030	0.4960
$C + D + T + CxD + CxT + DxT + CxDxT$		
Gross Movement	0.4977	0.6145
Fine Adjustment	0.4885	0.2553
Total Movement	0.5465	0.5742

fit for any of the dependent measures, in particular for those with a significant Control Amplitude x Display Amplitude x Display Target Width interaction (all of the target acquisition times with the exception of gross movement time on the tablet). Thus, it appears that a more comprehensive specification including more than target width and movement amplitude is required when three of the interface components are independently varied.

In an attempt to define a model that fits the present data more closely, two revisions to Fitts' law were tried. The first included the display amplitude in the numerator of the index of difficulty, so that the equation became:

$$\text{Movement time} = a + b \log_2 (2(C+D)/T). \qquad (4)$$

where D is the display amplitude. The second version included the logarithm of display amplitude as a second term in the equation:

$$\text{Movement time} = a + b \log_2 (2C/T) + c \log_2 D. \qquad (5)$$

The R^2s for these equations when applied to the data for the touch tablet and trackball are shown in Table 44.

In an attempt to provide a more accurate fit to the data, with less emphasis on retaining the Fitts' Law formulation, several regressions were performed using different subsets of the control amplitude, display amplitude, and display target width factors and their interactions. The model which provided the best fit to the data was the full model; that is (excluding the weights for each factor):

$$\text{Movement time} = C + D + T + CxD + CxT + DxT + CxDxT. \qquad (6)$$

The R^2s for this model and for a model containing only the main effects for the touch tablet and the trackball are also shown in Table 44. The full model provides the best fit to the data of the models tested.

There are several limitations to the present research. First, the results do not explain either the discrepant acquisition times or the slightly different pattern of control and display effects found for the two input devices. A possible explanation is that only a zero-order position gain was used for both input devices. Several researchers have found that the addition of a velocity gain for both a trackball and a touch tablet can lead to performance improvements for target acquisition (see Becker and Greenstein, 1986; Epps et al., 1986). If the two devices were closer to their optimal performance levels the results might be more similar. The fact that the devices may not have been configured optimally is probably not the sole explanation of any differences, since Epps et al. (1986)

reported that even when devices are separately optimized, the trackball still results in superior target acquisition performance when compared to a touch tablet.

A second explanation is that the control movements may have been sufficiently different to cause performance differences. For example, with the 200-mm trackball input, although the trackball had to move 200-mm to move the cursor across the entire display, the subject's hand did not have to be on the trackball at all times. That is, subjects would often quickly spin the trackball, remove their hand until the cursor was in the target vicinity, and then stop the trackball for fine positioning. Thus, it was possible to operate the trackball with the 200-mm input in a manner requiring no real change in control movements over the more sensitive 50-mm input. This was not possible with the tablet; in all conditions subjects had to make movements on the tablet corresponding in length to the required cursor movement distance. If the cursor had to move 100 mm across the medium display, this required a 50-mm movement on the 50-mm tablet and a 100-mm movement on the 100-mm tablet. Thus, the control movements for the touch tablet had to change across control amplitudes while those for the trackball could remain somewhat uniform. This discrepancy may explain the differences between the two input devices in the control effects; the control input was clearly more of a determinant of performance for the touch tablet in both studies.

A third and less fortunate explanation is that the particular touch tablet used may have been responsible for the consistent effect of control input. The reported jumpiness of the cursor may be due to the fact that the tablet is inherently inconsistent or that the resolution of movement is not fine enough. Future research aimed at identifying the cause of the differences between the input devices would be beneficial in helping to specify the best method of control-display interface optimization. In particular, evaluating the nature of the control movements and improving the tablet response are important areas of investigation.

Also unexplained by the present set of studies is the basis of the effect of the target width on gross and total movement time for both the tablet and the trackball. One reason for this result may be that the smaller targets were confounded with slightly longer cursor movement distances, since the common reference for positioning the targets was the outer boundary of the targets (that is, the side away from the cursor). This reference was used so that the targets that had been associated with a given display width in the first study (e.g., the 5-mm target on the 50-mm display) were in the same position on that display in the second study. Due to this restriction, the size of the medium and large targets on the small display could not be referenced to the inside target boundary, or they would have been partially outside the display active area. This placement meant that the cursor travel was 10 mm longer for the small target and 5 mm longer for the medium target than it was for the large target. The cursor movement distances from the original cursor position to the inside target boundary are shown for all display amplitude and target width combinations in Table 45. Also shown in the table are the proportions of the display travelled by the cursor in each condition. It is clear that the proportion of the screen traversed by the cursor increased slightly for each target size as the display amplitude increased.

Note that the proportion of the screen traversed by the cursor is the same value of 0.75 in three conditions: the 5-mm target on the 50-mm display, the 10-mm target on the 100-mm display, and the 15-mm target on the 150-mm display. If the change in cursor movement distance caused the increase in gross and total movement times, then these conditions should not differ significantly. Post-hoc F-tests were performed for the finger-operated touch tablet and the trackball to evaluate this possibility.

TABLE 45

Summary of Display Output (Experiment 2)

Display Amplitude (mm)	Target Width (mm)	Cursor Movement Distance (mm)	Display Proportion
50	5	37.5	0.75
50	10	32.5	0.65
50	15	27.5	0.55
100	5	80.0	0.80
100	10	75.0	0.75
100	15	70.0	0.70
150	5	122.5	0.82
150	10	117.5	0.78
150	15	112.5	0.75

For gross movement time, the Control Amplitude x Display Amplitude interaction was not significant in the second study for either input device. Therefore performance was averaged across the two control amplitudes. For the touch tablet, there were no significant differences among the three conditions ($F = 0.35$, $p = 0.7120$). However, there were significant differences among the three conditions for the trackball ($F = 5.99$, $p = 0.0195$).

For both devices, there is a significant Control Amplitude x Display Amplitude interaction for total movement time, and therefore the effect of distance was tested for each control amplitude for each device. The tablet showed no significant differences for either the 50-mm amplitude ($F = 1.96$, $p = 0.1918$) or the 100-mm amplitude ($F = 2.58$, $p = 0.1247$). The trackball showed significant differences for both control amplitudes ($F = 10.11$, $p = 0.0040$ for the 50-mm amplitude, and $F = 6.52$, $p = 0.0154$ for the 200-mm amplitude).

While the lack of significance of these tests for the tablet cannot prove that distance caused the increase in gross and total movement times, they do confirm the plausibility of such an explanation. The significant differences seen for the trackball suggest that some other factor is responsible for the changes in performance.

Another possible explanation is that when subjects approach a small target, they tend to slow the cursor before they reach the target area. In this case, the definition of gross movement in the present study would actually have included some fine positioning, and as a result total movement time would have changed also.

The number of cursor entries into the target prior to confirmation may help to evaluate this possibility. For the trackball in the second study, approximately six percent of the small target acquisitions involved more than one target entry before target acquisition, compared to four and three percent for the medium and large targets, respectively. The difference in the number of target entries across the three target sizes is not large, and thus it is possible that the for the 94% of the small target acquisitions involving only one target entry, subjects slowed the cursor before entering the target for the first time. This tendency would lead to increased gross and total movement times for small targets. (Eighty-nine percent of the small target acquisitions for the tablet required only one target entry; therefore, the same effect may be operating to a lesser extent for the tablet.)

As was the case for display target width, the reason for the effect of display amplitude on gross and total movement time is unclear since the control movements for all display amplitudes were the same for a given control amplitude. This effect may also be due to the differences in cursor movement distances across the display discussed above. Since there is evidence that target distance affects total movement time for a target acquisition task (see Epps et al., 1986), an additional study that does not confound target size and cursor movement distance would be extremely useful in determining the extent of the latter effect.

A third shortcoming of the present research is that the basis for the interaction between the display size and the target size is unclear. It is possible that the effect just discussed (that is, the increase in the proportion of the display traveled by the cursor as target width decreased and display amplitude increased) could be responsible for this result. Alternatively, in both the first and second studies, the cursor size increased as the display size increased. It may be that the difficulty in acquiring the small target on the large display was that the cursor for the large display was larger than the target box. While the cursor did not obscure the target, nor was it difficult to see whether the center of the cursor was inside the box, it is still possible that the cursor size may have affected performance.

The fact that the small targets were more difficult to acquire than the larger targets even when using a small cursor (on the smallest display) indicates that the effect of changes in target size is not merely limited to an increase in the cursor size. Nevertheless, future research aimed at separating the difference between a change in the size of the display and the size of the cursor would be helpful in resolving this question.

A fourth question not clearly answered by the present studies is whether there were transfer effects across control inputs. All of the studies cited in the literature review had some aspect of control input as a within-subjects factor with the exception of Buck's (1980) study, and a within-subjects design was used in the present research as well. With any motor performance task, there is a potential for practice with one control configuration to affect performance with another configuration if a within-subjects design is used (Poulton, 1974). Pretesting indicated such a potential in the present studies, and thus the presentation of control inputs was counterbalanced, different control inputs were used on different days, and performance was only analyzed after it had reached an asymptotic level.

In order to informally assess the presence of transfer effects, the pattern of performance for each subject across control inputs for each device was examined. All subjects showed essentially the same pattern of performance across control inputs regardless of the order in which they had been presented, although the magnitude of the differences in performance across control inputs varied across subjects. This observation, coupled with the fact that an asymptotic performance level had been reached, suggests that transfer effects were minimized. However, the error Mean Squares for the control input for the first study are in all cases much larger than the error terms for the Display Width and Control x Display interactions. This same effect occurs for the trackball in the second study, but not for the touch tablet (the absence of this finding for the tablet may be due to the choice of control amplitudes). This increase in variance suggests that changing the control conditions increases subject variability more than changing the display, and thus subjects may have more trouble transferring across controls than across displays. The variability may also reflect the fact that the controls were tested on different days, and performance may vary more from day to day than within one day.

Another type of transfer effect may have occurred in the second study in which subjects were tested using both input devices; that is, not only may there be transfer effects within a device, but there may also be effects across devices. Several subjects in the second study indicated that they disliked the tablet after using the trackball, and it is possible that using the trackball caused the subjects' performance on the tablet to deteriorate even further. However, the fact that the tablet performance was worse than trackball performance in the first study, in which subjects used only one of the devices, indicates that if such an effect was working it is still not likely to be the only cause of better trackball performance in the second study.

In sum, it is possible that there were some transfer effects both across control inputs for one device and across the two devices. While the second effect does not appear to have changed the overall superiority of the trackball, the potential magnitude of the first effect cannot be assessed directly from the present studies, since all levels of control input for one device were presented to all subjects in both studies.

A final result of unclear origin in the present set of studies is the general lack of agreement between the movement time dependent measures and the percent of responses in error. It is possible that the very low percentage of errors may have caused this lack of agreement. An additional explanation may be that the subjects tended to emphasize accuracy over speed. While subjects were instructed to make the target acquisitions as quickly as possible while also minimizing errors, they did not receive any feedback regarding their acquisition times. Errors were signalled by a low-frequency tone, and the number of errors made during a trial block was displayed after the block was over. Thus, subjects may have unintentionally attempted to maximize the one aspect of performance for which they received feedback. Future research with modifications in instructions or with feedback regarding target acquisition times may help to make the effects of the independent variables on errors more consistent with the effects seen for the acquisition time measures.

CONCLUSIONS

Optimization of an interface must involve specification of at least three of the four design parameters of control amplitude, control target width, display amplitude, and display target width, as shown by the significant Control Amplitude x Display Amplitude x Display Target Width interactions found in the second study. Because of this, both D/C gain and Fitts' Law are inadequate specifications for optimization when three of the four control-display components are varied independently, since each only involves two of these four important parameters.

Three primary directions for future research are: 1) separating cursor movement distance from display amplitude and display target width; 2) determining the basis for the differences between the results found for the two input devices; and 3) quantifying the effect of instructions and acquisition time feedback on performance.

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Appendix A

PARTICIPANT'S INFORMED CONSENT

The purpose of this document is to obtain your consent to participate in this experiment and to inform you of your rights as a participant. This research is being conducted in the Human Factors Laboratory of the Department of Industrial Engineering and Operations Research by Dr. Harry L. Snyder and Ms. Lynn Y. Arnaut.

As a participant in this study you will use a touch tablet (trackball) to acquire designated targets on the display. Participation in the study is entirely voluntary. If you choose to participate you will receive instruction in the use of the input device and you will participate in five experimental sessions. The entire experiment will require three to four hours to complete. You will receive $5.00 per hour for the time that you are present.

We hope that this experiment will be an interesting experience for you. It is possible that at times you may feel frustrated or stressed. Your performance on the task reflects the difficulty of the task, not your personal abilities or talents.

Please note:

1. You have the right to stop participating in the experiment at any time. If you choose to terminate the experiment, you will receive pay only for the proportion of time you participated.

2. You have the right to see your data and to withdraw them from the experiment. If you decide to withdraw your data, please notify the experimenter immediately. Otherwise, identification of your particular data will not be possible, because the data will be separated from your name.

3. You have the right to be informed of the overall results of the experiment. If, after participation, you wish to receive information regarding this study,

please include your address (three months hence) with your signature below. If more detailed information is desired after receiving the results summary, please contact the Human Factors Laboratory, and a full report will be made available to you.

Your participation is greatly appreciated. If you have any questions about the experiment or your rights as a participant, please do not hesitate to ask. Should you have any additional questions or problems, contact Ms. Lynn Y. Arnaut, at , or Mr. Charles D. Waring, Chairman of the Institutional Review Board for Research Involving Human Subjects, at .

Your signature below indicates you have read the above stated rights and you consent to participate. If you include your printed name and address below, a summary of the experimental results will be sent to you.

____
Signature

____
Printed Name

____
Address

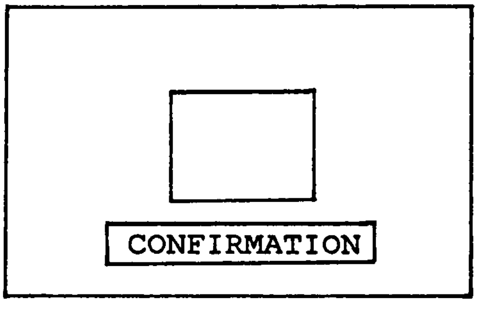
____
City, State, Zip

Appendix B

TOUCH TABLET INSTRUCTIONS (EXPERIMENT 1)

In this experiment you will be required to select a target presented on the display as quickly and as accurately as possible by moving the cursor into the target and then confirming your selection.

On the table in front of you is a touch tablet. At the bottom there is a large rectangle. This area is the confirmation area, as shown in the following diagram.



Press the confirmation area now, and an example of the display will appear. Do not press the touch tablet again until you are instructed to do so.

The cursor is the crosshair (+) which you see on the display. The target is the square across from the cursor. The larger square around both the target and the cursor indicates the active area of the display; that is, the cursor cannot go outside this area.

At the beginning of each trial, a display like the one which is now on the screen will be presented. To select the target, you will place your finger on the touch tablet and move your finger until the cursor is inside the target.

The center of the cursor must be inside the target for your selection to be correct. During the practice sessions, try putting the cursor on the sides and corners of the targets and then confirm your selection to get an idea as to when a selection will be considered correct. When moving your finger on the touch tablet, be sure that your hands do not touch any other area of the tablet.

Once you are sure that the cursor is inside the target, lift your finger and use your other hand to press the confirmation area on the tablet. If your target selection was correct, you will hear a high frequency tone. If your selection was incorrect, a low frequency tone will sound.

After a two-second pause, a new target will be presented and two brief tones will indicate the beginning of the next trial. As soon as the two tones sound, the trial begins, and the clock will begin to time your response. Be sure to remove your finger from the confirmation area before you begin to move the cursor with your other hand.

Different combinations of tablet sizes and display sizes will be used in this study. You will complete 5 sets of trials today, each one with the same size tablet, but with a different display size. Each day you will use a different tablet size with the five displays.

You will be required to select 80 targets for each display size. Try to select the targets as quickly as possible while minimizing errors. At the end of each set, a message will be displayed informing you that the trial block is finished. In addition, the number of correct target selections for that set of trials will be presented. You can then receive a rest break before the next set begins.

Do you have any questions? If not, turn to the next page to learn how to move the cursor on the display.

INSTRUCTIONS FOR CURSOR MOVEMENT - RELATIVE MODE

When you place your finger on the tablet the cursor will stay where it is on the display. Movement of your finger on the tablet will move the cursor from this current position. Thus, note that every time you place your finger on the tablet, the cursor remains where it is on the display.

You may place your finger anywhere on the tablet to initiate cursor movement. If your finger touches the edge of the tablet, simply lift your finger up and place it down elsewhere on the tablet.

Do you have any questions?

Appendix C

TRACKBALL INSTRUCTIONS (EXPERIMENT 1)

In this experiment you will be required to select a target presented on the display as quickly and as accurately as possible by moving the cursor into the target and then confirming your selection.

On the table in front of you are a trackball and a keyboard. The space key on the keyboard is marked "CONFIRM". Press the confirmation key now, and an example of the display will appear. Do not touch the trackball or the confirmation key again until you are instructed to do so.

The cursor is the crosshair (+) which you see on the display. The target is the square across from the cursor. The larger square around both the target and the cursor indicates the active area of the display; that is, the cursor cannot go outside this area.

At the beginning of each trial, a display like the one which is now on the screen will be presented. To select the target, you will use one hand to move the trackball until the cursor is inside the target.

The center of the cursor must be inside the target for your selection to be correct. During the practice sessions, try putting the cursor on the sides and corners of the targets and then confirm your selection to get an idea as to when a selection will be considered correct.

Once you are sure that the cursor is inside the target, lift your hand from the trackball and <u>use your other hand</u> to press the confirmation key. If your target selection was correct, you will hear a high-frequency tone. If your selection was incorrect, a low-frequency tone will sound.

After a two-second pause, a new target will be presented and two brief tones will indicate the beginning of the next trial. As soon as the two tones sound, the trial begins, and the clock will begin to time your response. Be sure to remove your finger from the confirmation key before you begin to move the cursor with your other hand.

The trackball sensitivity can be changed; that is, the trackball may have to be moved a lot or a little to move the cursor a given distance on the display. Different combinations of trackball sensitivities and display sizes will be used in this study. You will complete 5 sets of trials today, each one with the same trackball sensitivity, but with a different display size. Each day you will use a different trackball sensitivity with the five displays.

You will be required to select 80 targets for each display size. Try to select the targets as quickly as possible while minimizing errors. At the end of each set, a message will be displayed informing you that the trial block is finished. In addition, the number of correct target selections for that set of trials will be presented. You can then receive a rest break before the next set begins.

Do you have any questions? If not, you will begin a set of training trials to familiarize you with the task.

Appendix D

TOUCH TABLET QUESTIONNAIRE (EXPERIMENT 1)

Please rank the five tablet sizes in order of preference, with 1 being the most preferred and 5 being the least preferred.

50 mm (smallest) _____

75 mm _____

100 mm _____

125 mm _____

150 mm (largest) _____

Please rank the five display sizes in order of preference, with 1 being the most preferred and 5 being the least preferred.

50 mm (smallest) _____

75 mm _____

100 mm _____

125 mm _____

150 mm (largest) _____

Appendix E

TRACKBALL QUESTIONNAIRE (EXPERIMENT 1)

Please rank the five _trackball sensitivities_ in order of preference, with 1 being the most preferred and 5 being the least preferred.

highest _____

2nd highest _____

medium _____

2nd lowest _____

lowest _____

Please rank the five _display_ sizes in order of preference, with 1 being the most preferred and 5 being the least preferred.

50 mm (smallest) _____

75 mm _____

100 mm _____

125 mm _____

150 mm (largest) _____

Appendix F

GENERAL INSTRUCTIONS (EXPERIMENT 2)

In this study, you will be required to use two different input devices, a touch tablet and a trackball, to select targets on a display. Both of these devices can be set up in different ways. For example, the size of the touch tablet can be changed. Also, the touch tablet can be used with your finger or with a stylus. The trackball sensitivity can also be changed; that is, the trackball may have to be moved a lot or a little to move the cursor a given distance on the display.

On each of the six test days, you will perform the task with one of the input devices set up in a different way. On four days you will use the touch tablet; there will be two tablet sizes, and you will use each one both with and without a stylus. On the other two days, you will use two different trackball sensitivities.

On each of the six days, you will receive training on the particular input device you will use that day. Then you will use that device with five different displays.

On the table in front of you is one of the input devices. This is the one you will use today. If you have no questions, we can begin the training.

Appendix G

QUESTIONNAIRE (EXPERIMENT 2)

Please rank the six input devices in order of preference, with 1 being the most preferred and 6 being the least preferred.

_____ small tablet, finger-operated

_____ large tablet, finger-operated

_____ small tablet, stylus-operated

_____ large tablet, stylus-operated

_____ high-sensitivity trackball

_____ low-sensitivity trackball

Please rank the three display sizes in order of preference, with 1 being the most preferred and 3 being the least preferred.

_____ small

_____ medium

_____ large