

Factors Affecting Performance Using Touch-Entry Systems: Tactual Recognition Fields and System Accuracy

Anthony D. Hall and James B. Cunningham
Product Development Support, IBM Corporation
Research Triangle Park, North Carolina

Richard P. Roache and Julie W. Cox
Display Systems Development, IBM Corporation
Research Triangle Park, North Carolina

Two laboratory experiments were conducted that investigated the effects of a number of factors on performance using an on-display touch-entry system. Experiment 1 ($n = 60$) was carried out using a video display in a seated work station; horizontal angle of regard between the user and the display, size of the targets used, and gender were manipulated as factors. Experiment 2 ($n = 72$) was carried out in a standing work station; both horizontal and vertical angle of regard between the user and the display, presence or absence of optical parallax, and gender were manipulated as factors. Results showed that all of the factors affected how accurately the touch-entry system accepted the touches. Statistical simulation models were then constructed by computing system accuracy as a function of the size of tactual recognition field used to capture the touch. It was possible both to accommodate the variability in performance among users and to minimize the effects of the manipulated factors on performance. This was the outcome for both seated and standing work stations. Implications of these results for the design of touch-entry systems are discussed.

A variety of computer applications present information on a video display and then permit the user to make selections by pointing to a visual target on the surface of the display. These selection-based applications commonly support user tasks in air-traffic control, manufacturing, merchandising, information access, and training. Generally, the devices available to the user for making selections by pointing can be grouped into two categories—those that provide indirect control in a plane in space different from the surface of the video display (e.g., mouse, trackball, joystick, and graphics tablet) and those that provide direct control in the same plane as the surface of the display (e.g., touch-entry systems; Schneiderman, 1987).

Reviews of available performance data for touch-entry systems show that little is known about factors that affect accuracy when using these systems or, perhaps more important, about the changes in selected parameters required to achieve desired levels of system accuracy (Pfauth & Priest, 1981; Schneiderman, 1980). Moreover, there have been few well-controlled studies of performance using touch-entry devices, few studies on designing systems to reliably accept the human touch, and few reports of accuracy rates comparable to those known for other entry devices. Most closely related are accuracy rates from studies of pointing, positioning, and selection using various on-display and off-display devices.¹

Accuracy rates of 87% to 95% have been reported for selection tasks using mouse, step keys, text keys, and joystick devices (Card, English, & Burr, 1978). Goodwin (1975) found that lightpen and lightgun devices led to faster cursor-positioning

performance, but no accuracy rates were reported. Long, Whitfield, and Dennett (1984) studied the performance of users when pointing to key areas on a graphic tablet with a stylus, and reported an accuracy rate of 97%. In their observations of air traffic controllers using a touch-sensitive surface on a display, Stammers and Bird (1980) reported accuracy rates for pointing and selection that ranged from 91% to 95%; these rates were variable among users. Karat, McDonald, and Anderson (1984) compared preference and performance using a keyboard, mouse, and touch panel to select items from a menu. Information was reported that suggests an accuracy rate of 73% for the touch panel, under conditions in which users had no penalty for error and speed was emphasized over accuracy.

Whitfield, Ball, and Bird (1983) examined a number of entry devices and found accuracy rates that ranged from 83% to 94% for a menu selection task (94% for the on-display touch panel), 89% to 96% for a tabular display selection task (90% for the touch panel), and 67% to as high as 99% for a target acquisition task (96% for the touch panel under low-resolution requirements, and 67% under high-resolution requirements). Whitfield et al. concluded that the on-display touch-entry device is best suited for tasks requiring low tactual resolution. Recently, Schneiderman (1987) reviewed studies that compared a variety of pointing devices and published charts about cursor positioning speed, positioning accuracy, and subjective ratings about ease of use. Although touch panels were typically rated more

¹ Studies of performance using various designs of keyboards (Alden, Daniels, & Kanarick, 1972; Hirsch, 1970; Klemmer, 1971; Klemmer & Lockhead, 1962) have demonstrated that it is possible to achieve accuracy rates of more than 99%, particularly for experienced users. Unlike most selection-based applications, however, keying-based applications typically involve a fast rate of fine-motor responding during either a brief or a sustained work session (see Card, English, & Burr, 1978; Schneiderman, 1987).

Correspondence concerning this article, including a reprint of the article and a detailed technical edition (Hall, Cunningham, Roache, & Cox, 1988), should be addressed to Anthony D. Hall, Product Development Support, IBM Corporation, P.O. Box 12195-D20/656, Research Triangle Park, North Carolina 27709.

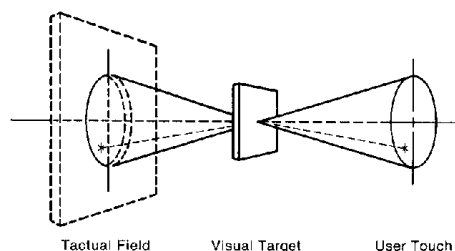


Figure 1. Three-dimensional relation between a touch and the capture of that touch by a tactual recognition field. (When a user touches the surface of the video display, information about the location of the touch is projected to the software [see star on figure]. Factors that affect the delivery of the touch from the user to the display have a corresponding effect on the projection of that touch to the field).

comfortable, easier to learn, and less tiring than were joysticks or keyboards, the panels appeared best suited for applications that did not require accurate positioning. Applications of touch-entry systems under low-resolution requirements have been described by others (e.g., Beringer, 1980; Stammers & Bird, 1980).

A number of authors have speculated about conditions that may potentially affect accuracy when one uses touch-entry systems (see, e.g., Olson, 1987). Pfauth and Priest (1981) suggested that sources of error include parallax and reach distance. Whitfield et al. (1983) also suggested that parallax is a potential problem for on-display touch-entry devices. In the study by Stammers and Bird (1980), users complained about parallax problems, and the authors concluded that a portion of the error rate had its basis in parallax. In addition to parallax, another potential source of error may be a complex function of the angle of regard between the user and the location of the target on the surface of the display (Beringer & Peterson, 1985).

Parallax was not manipulated as a factor in these studies (e.g., Beringer & Peterson, 1985; Pfauth & Priest, 1981; Stammers & Bird, 1980; Whitfield et al., 1983), and only in the study by Beringer and Peterson (1985) was information reported about angle of regard between the user and the location of the target on the display. Moreover, none of these studies reported system accuracy rates as a function of angle of regard, parallax, or anthropometric variability introduced by gender. Thus, it cannot be concluded for certain how these factors affect the accuracy of a touch-entry system. Should it be possible to assess the effects of these factors on system accuracy, the information would be useful in the design of tactual recognition areas for touch-entry systems and would contribute generally to what is known about performance using these systems.

The purpose of the present article is twofold. The first purpose is to investigate the effects of a number of factors on the accuracy of a touch-entry system. The results of two experiments are reported. In Experiment 1, a seated work station was used, and target size, horizontal angle, and gender were manipulated as factors. In Experiment 2, a standing work station was used, and optical parallax, horizontal and vertical angle, and gender were manipulated as factors. When a subject touched a target on the screen, the display system calculated an estimate

of the location of the subject's touch (see Figure 1). If the location of the touch was within a prescribed software boundary (a *tactual recognition field*, defined on the x and y axes), the display system would accept the touch for the intended target; if, however, the location of the touch was outside the boundary, the system would reject the touch.

The second purpose of the article is to demonstrate a relation between the level of accuracy at which a display system will capture the human touch and both (a) the size of the tactual recognition fields used and (b) the number of fields desired simultaneously on the surface of the display. This relation can be quantified and represents the *tactual resolution characteristics* of the display system. The results of Experiments 1 and 2 are applied toward accommodating variability in performance among users and toward minimizing the effects of the manipulated factors on performance.

Experiment 1

Method

Subjects. Participants ($n = 60$) in Experiment 1 were U.S. adults who had limited experience using touch panels (41 had no experience and 19 had less than 30 min total time using any form of touch panel in the 2 months preceding the experiment). All of the subjects had normal or corrected-normal visual acuity and reported no known deficiencies in color vision. All of the subjects were right-handed.

One half of the subjects were men, and one half were women. The mean standing height for men was 70.8 in. (179.8 cm), for women 64.7 in. (164.3 cm), and for all of the subjects combined 67.8 in. (172.2 cm). Each subject was tested individually.

Touch-entry system. An engineering prototype of the IBM 4055 (InfoWindow) color display terminal was used to present visual targets to the subjects. The video display measured 13 in. (33.02 cm) on the diagonal and was equipped with an on-display touch panel. The touch panel consisted of a preformed piece of glass fitted to the front surface of the video display. Piezo-electric technology was used, in which a small amount of force (units)—when applied to the surface of the touch panel—was transferred to four force transducers, one transducer at each of the four corners of the display. To determine the location of a touch, the display system captured force data from all of the transducers and calculated a composite locus of force on the surface of the touch panel. The calculations for each touch were stored in the form of x -error and y -error (distance) coordinates using a computer. The data were characteristically continuous and were recorded in millimeters to two places beyond the decimal.²

Screen layout and targets. The visual targets used were of two basic types, a single character (a plus sign) and solid boxes (three sets, each sized to permit as many as 36, 64, and 100 visual targets on the screen at one time). Figure 2 (a-d) shows the dimensions for each of the targets used in Experiment 1. The tactual recognition fields were not visible to the subject and, in this experiment, were used solely for the purpose of scoring the data for accuracy rates. Visual targets were presented in 36 different locations on the screen. The screen was equally divided into 9 sectors, having 4 targets each. During the experiment, visual targets

² Various forms of touch-entry technology have been described (Carroll, 1986; Pfauth & Priest, 1981; Schwartz, 1986), each differing in extent of continuity in the distance estimates and the precision of the estimates. The technology used in the studies by Beringer and Peterson (1985), for example, permitted assessment of distance error in discrete units of 3.2 mm each in both x and y dimensions.

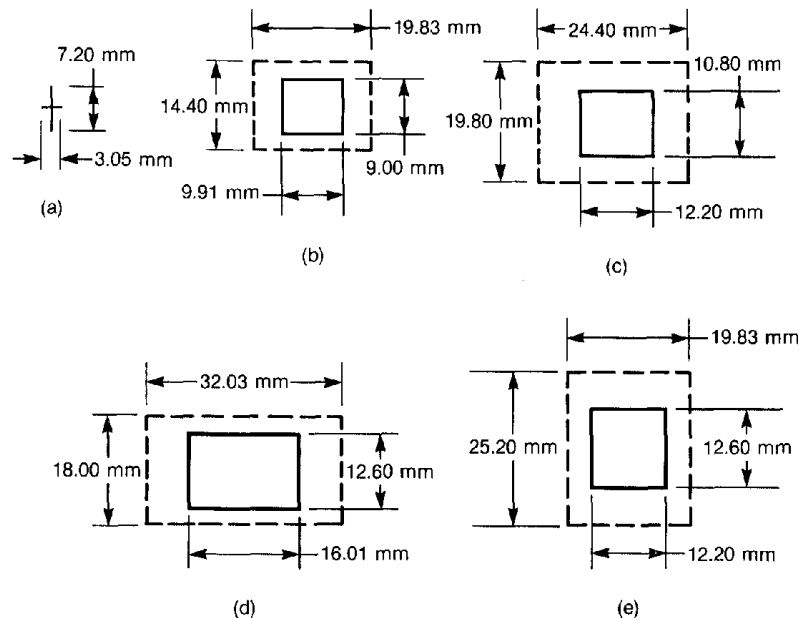


Figure 2. Targets used in Experiments 1 and 2. (Figures 2a–2d show the dimensions of targets used in Experiment 1, and Figure 2e shows the dimensions of the target used in Experiment 2. Figure 2a was a plus-sign character and had no tactual recognition field. Figures 2b–2e were solid-box visual targets, each having a tactual field surrounding the visual target. Targets used in Experiment 1 were all bright white on a black background, and the target used in Experiment 2 was bright red on a black background. Tactual recognition fields were not visible to the subject.)

were presented on the screen, one target at a time, and the order in which the targets appeared at the various locations on the screen was randomized.

Work-station anthropometry. A seated work station was constructed for the 50th percentile U.S. user in an attempt to accommodate adults having standing heights in the range of 4 ft, 10 in. (147.3 cm) to 6 ft, 2 in. (187.9 cm). Figure 3 summarizes the main measurements for this work station used in Experiment 1 (see Diffrient, Tilley, & Bardagiy, 1979; Kroemer, 1983; Panero & Zelnik, 1979; Stammerjohn, Smith, & Cohen, 1981).

Experimental design. The design was a 2×3 between-subjects factorial in which the independent variables were gender (male, female) and horizontal angle of regard between the surface of the display and the subject (left of center, center, right of center). Five sets of trials were manipulated within subjects in which 36 visual targets (a plus-sign character) were presented as a pretest, followed by three sets of 36 visual targets (solid boxes, one set of 36 for each of the three sizes of targets used), and then 36 additional visual targets (again, a plus-sign character) were presented as a posttest. Also, within the sets of trials, the location of visual targets on the screen was controlled within subjects (36 targets grouped equally into 9 sectors having 4 targets each). The order in which subjects received the three sets of solid-box visual targets was randomized, and subjects were randomly assigned to treatments within gender.

Data collected for each touch included (a) the horizontal distance error between the center of each visual target and the location of the touch determined by the display system (x error in millimeters) and (b) the vertical distance error between the center of each visual target and the location of the touch determined by the display system (y error in millimeters). In addition, for each solid-box target, data was recorded about whether the location of the touch, as determined by the display

system, was within both the x and y maximums for the tactual recognition field for that visual target. Measures were excluded from the data set if they were not reliably recorded. Any touch that generated (a) an x error or a y error greater than 999.99 mm or (b) a response-to-stimulus onset asynchrony less than 0 ms was removed from the set before data analysis.

Procedure. Each subject was seated comfortably at the display work station and was then administered the five sets of trials. For each set of trials, 36 visual targets were presented on the screen, one at a time. Subjects were instructed to watch the screen and, when a visual target appeared, touch the center of the target using the index finger of the right hand. Also, subjects were instructed to proceed at their own pace and to touch the targets as accurately as possible. Although accuracy was given emphasis over speed, it was observed that subjects touched targets at approximately one touch every 1 or 2 s, with roughly 10 to 30 s between the sets of 36 touch responses (time to reload the program).

Results

For the purpose of analysis, the dependent measures for all trials were x error and y error for each subject's touch responses. For trials in which different sizes of tactual recognition fields were used (see Figure 2b–2d), an additional dependent measure was the mean number of touch responses accepted by the system as valid for each of the three different sizes of tactual recognition fields. The 2×3 (Gender \times Horizontal Angle of Regard) factorial design was collapsed over nine sectors, and accuracy scores were computed as the mean percentage of responses accepted for each subject. An analysis of variance (ANOVA), with

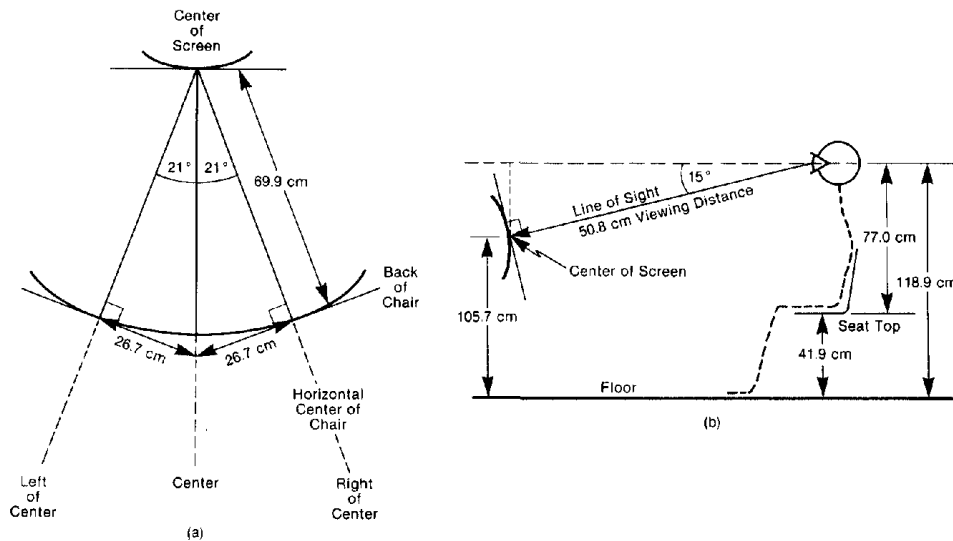


Figure 3. Summary of anthropometric relations between the subject and the display in Experiment 1. (Figure 3a shows the horizontal dimensions for each of the three horizontal positions, and Figure 3b shows the vertical dimensions for the seated work station.)

three box sizes within subjects, was carried out on these data. The results are presented later, separately for each dependent measure.

x error. A significant main effect was obtained for horizontal angle of regard, $F(2, 50) = 40.67$, $SS_e = 275.99$, $p < .01$, and no other main effects and no interactions were significant ($p > .05$). The mean x error was -0.66 mm for subjects seated to the left of the display, 0.58 mm for subjects seated directly in front of the display, and 3.70 mm for subjects seated to the right of the display; Duncan's multiple-range test showed that each of these three means was significantly different from the other ($p < .05$). The mean x error was 1.34 mm for the small-size target, 1.32 mm for the medium-size target, and 1.35 mm for the large-size target. These means did not differ significantly from one another ($p > .05$).

y error. No main effects and no interactions were significant ($p > .05$). The mean y error was -1.61 mm for the small-size target, -1.71 mm for the medium-size target, and -1.50 mm for the large-size target. These means did not differ significantly from one another ($p > .05$).

Accuracy. Significant effects were obtained for horizontal angle of regard, $F(2, 54) = 3.24$, $SS_e = 1.94$, $p < .05$, and field size, $F(2, 108) = 33.45$, $SS_e = 2.35$, $p < .01$. Duncan's multiple-range test showed that the mean number of touch responses accepted by the display system was 98.1% for subjects seated at the left of the display and 97.9% for subjects seated at the center of the display, and these two means did not differ significantly from one another ($p > .05$), but both of these means were higher ($p < .05$) than the mean number accepted for subjects seated at the right of the display (96.1%). Duncan's multiple-range test showed that the mean number of touch responses accepted by the display system was 94.3% for the small-size field, 98.2% for

the medium-size field, and 99.6% for the large-size field. Each of these means differed significantly from one another ($p < .05$).

Regression. A step-wise multiple regression analysis was performed on the accuracy scores using gender, horizontal angle of regard between the subject and the display, x error, and y error as predicting factors. When subjects used the large-size field, y error explained 10% of the performance variance, $F(1, 45) = 4.91$, $SS_e = 0.04$, $p < .05$, $r^2 = .10$. When subjects used the medium-size field, x error explained 8% of the performance variance, $F(1, 46) = 3.87$, $SS_e = 0.77$, $p = .055$, $r^2 = .08$, and when subjects used the small-size field, x error explained 11% of the performance variance, $F(1, 48) = 6.06$, $SS_e = 2.58$, $p < .05$, $r^2 = .11$. Collapsing on the size of field surrounding the targets presented to subjects, x error and y error explained 21% of the performance variance, $F(2, 36) = 4.83$, $SS_e = 0.36$, $p < .05$, $r^2 = .21$. For each of these four regression analyses, x error and y error were not correlated with each other ($p > .05$), and no other factors contributed to the predictive power of the regression models ($p > .05$).

Pretest-posttest comparisons. A 2×3 (Gender \times Horizontal Position) ANOVA was carried out to compare available mean x error and mean y error recorded during the pretest to mean x error and mean y error recorded during the posttest (pretest-posttest, within subjects). For x error, significant effects were obtained for horizontal angle of regard, $F(2, 41) = 9.88$, $SS_e = 111.32$, $p < .01$, and Gender \times Horizontal Angle of Regard, $F(2, 41) = 4.12$, $SS_e = 111.32$, $p < .05$; the main effect and interactions for the pretest-posttest comparison were not significant ($p > .05$). The mean x error was 3.65 mm for subjects touching targets while they were seated to the right of the display, 0.47 mm for subjects seated directly in front of the display, and -1.19 mm for subjects seated to the left of the display; Dun-

can's multiple-range test showed that these means were significantly different from one another, and the differences among the means were greater for women than for men ($p < .05$). For y error, a significant effect was obtained for the pretest-posttest comparison, $F(1, 5) = 11.48$, $SS_e = 0.93$, $p < .01$. Inspection of the means for the pretest-posttest comparison indicated that y error was larger in the posttest (-2.29 mm) than in the pretest (-1.34 mm). However, some caution is required in interpreting the results of the pretest-posttest comparisons because x and y data were not reliably recorded for all of the subjects during the pretest and posttest, and the data that were recorded may not be generalizable to the rest of the sample. Nevertheless, the effects were significant ($p < .05$) using procedures corrected for unequal cell sizes (e.g., general linear models) and suggest a trend for subjects to touch somewhat lower than the center of the character target later in the experiment than at the beginning of the experiment.

Experiment 2

Method

Subjects. Participants ($n = 72$) in this experiment were U.S. adults who had limited experience using touch panels (37 had no experience and 35 had less than 30 min total time using any form of touch panel in the 2 months preceding the experiment). Subjects who participated in Experiment 1 did not participate in Experiment 2. All of the subjects had normal or corrected-normal visual acuity and reported no known deficiencies in color vision. All of the subjects were right-handed.

Again, one half of the subjects were men, and one half were women. The mean standing height for men was 70.1 in. (178.0 cm), for women 65.2 in. (165.6 cm), and for all of the subjects combined 67.7 in. (171.9 cm). Each subject was tested individually.

Touch-entry system. The same type of video display, touch panel, and technique for data capture used in Experiment 1 was used in Experiment 2. In addition, for one half of the subjects in Experiment 2, a thin, translucent overlay was fitted to the top surface of the touch panel glass, and the visual targets were etched onto the surface of the overlay. When each visual target was presented by the display system, the corresponding target on the surface of the overlay was illuminated. Thus, under this condition, optical parallax was negligible in the system. The other half of the subjects were presented visual targets without the overlay, retaining inherent optical parallax in the system.

Screen layout and targets. The visual targets used were of one type, a solid box sized to permit as many as 60 visual targets on the screen at one time (see Figure 2e). Again, the visual targets were presented in 36 different locations on the screen, and the screen was equally divided into 9 areas, each area having 4 visual targets. Also, during Experiment 2, visual targets were presented one at a time, and the order in which the targets appeared at the various locations on the screen was randomized.

Work-station anthropometry. A standing work station was constructed to accommodate standing heights for the 2.5th percentile U.S. women to the 97.5th percentile U.S. men. Figure 4 summarizes the main measurements for this work station (see Diffrient et al., 1979; Kroemer, 1983; Panero & Zelnik, 1979; Stammerjohn et al., 1981). The distance from the center of the display to the floor was hydraulically adjustable and had a vertical range of 38 in. (96.5 cm) to 68 in. (172.7 cm). By adjusting the height of the center of the display and then locking the display into position, it was possible to simulate user heights for 95% of the adult population. For example, a subject with an eye-to-floor height of 63 in. (160.0 cm) was converted to a 2.5th percentile female user by moving the center of the display to 60 in. (152.4 cm) from the floor, to a 50th percentile male or female user by moving the center of

the display to 53 in. (134.6 cm) from the floor, or to a 97.5th male percentile user by moving the display to 45 in. (114.3 cm) from the floor. Conversion tables were formulated to the nearest inch (2.54 cm), separately for men and women, and the tables were used during the experiment to determine the height of the display for each subject in each vertical treatment condition.

Experimental design. The design was a $2 \times 2 \times 3$ between-subjects factorial in which the independent variables were gender (male, female), parallax (inherent, reduced), and vertical angle of regard between the surface of the display and the subject (2.5th, 50th, and 97.5th percentile of U.S. adults). Three sets of trials were manipulated within subjects in which each subject was positioned left of center, center, and right of center. At each horizontal position, 36 visual targets were presented to the subject. Also, within the sets of trials, the location of visual targets on the screen was controlled within subjects (36 targets grouped into 9 sectors having 4 targets each). The order in which subjects used the three positions was randomized, and subjects were randomly assigned to treatments within gender.

Procedure. Each subject stood comfortably at the display work station and was then administered three sets of trials, one set at each of the three horizontal positions. For each set of trials, 36 solid-box visual targets were presented on the screen, one at a time. Instructions to the subjects and remaining aspects of the procedure were the same as were used in Experiment 1.

Results

For the purpose of analysis, the dependent measures for all of the trials were x error, y error, as well as the mean number of touch responses accepted by the system as valid for the size of tactual recognition field used. The $2 \times 2 \times 3$ (Gender \times Optical Parallax \times Vertical Angle of Regard) factorial design was collapsed over nine sectors, and accuracy scores were computed as the mean percentage of responses accepted for each subject. An ANOVA, with three horizontal positions within subjects, was carried out on these data. The results are presented later, separately for each dependent measure.

x error. Significant effects were obtained for parallax, $F(1, 60) = 5.59$, $SS_e = 105.83$, $p < .05$; horizontal angle of regard, $F(2, 108) = 240.20$, $SS_e = 99.60$, $p < .01$; Parallax \times Horizontal Angle of Regard, $F(2, 108) = 96.02$, $SS_e = 99.60$, $p < .01$; and Gender \times Parallax \times Horizontal Angle of Regard, $F(2, 108) = 4.00$, $SS_e = 99.60$, $p < .05$. Gender and vertical angle of regard had no main effects on x error ($p > .05$). Inspection of the means for the parallax main effect indicated that x error was larger for subjects touching targets with inherent optical parallax in the display (2.79 mm) than for subjects with optical parallax reduced by the overlay (2.40 mm). Duncan's multiple-range test on the means for the main effect for horizontal angle of regard showed that mean x error was larger when subjects stood at the right of the display (4.50 mm) than when they stood at the center of the display (2.69 mm), and both of these means were larger than the mean x error when subjects stood at the left of the display (0.70 mm). This effect was greater for subjects touching targets with inherent optical parallax than for subjects touching targets with optical parallax reduced by the overlay ($p < .05$). In addition, x error was a complex function of the gender of the subject, presence of optical parallax, and horizontal angle of regard between the subject and the display.

y error. Significant effects were obtained for vertical angle of regard, $F(2, 60) = 8.13$, $SS_e = 491.78$, $p < .01$; parallax, $F(1,$

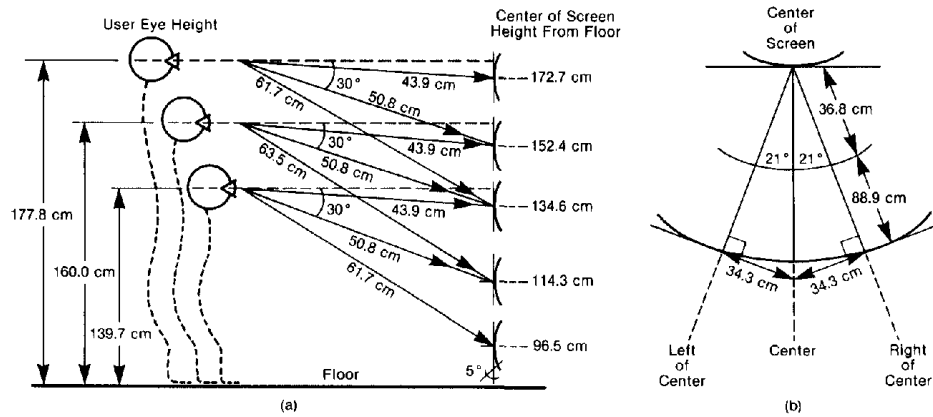


Figure 4. Summary of anthropometric relations between the subject and the display in Experiment 2. (Figure 4a shows the range of vertical dimensions for each of the three vertical relations between the standing subject and the display, and Figure 4b shows the horizontal dimensions for each of the three horizontal positions.)

60) = 14.00, $SS_e = 491.78$, $p < .01$; Parallax \times Vertical Angle of Regard, $F(2, 60) = 4.75$, $SS_e = 491.78$, $p < .05$; Gender \times Horizontal Angle of Regard, $F(2, 108) = 7.28$, $SS_e = 72.56$, $p < .01$; Gender \times Horizontal Angle of Regard \times Vertical Angle of Regard, $F(4, 108) = 2.89$, $SS_e = 72.56$, $p < .05$; and Gender \times Horizontal Angle of Regard \times Vertical Angle of Regard \times Parallax, $F(4, 108) = 4.07$, $SS_e = 72.56$, $p < .01$. Duncan's multiple-range test on the means for the main effect for vertical angle of regard showed that mean y error for subjects simulating the 2.5th percentile height (3.57 mm) was equal ($p > .05$) to that for subjects simulating the 50th percentile height (3.42 mm), but both of these means were larger ($p < .05$) than the mean y error for subjects simulating the 97.5th percentile height (1.60 mm). Inspection of the means for the main effect for parallax indicated that the mean y error for subjects touching targets with inherent optical parallax (3.76 mm) was larger than that for subjects touching targets with optical parallax reduced by the overlay (2.02 mm). In addition, y error was a complex function of the gender of the subject, vertical and horizontal angle of regard between the subject and the display, and optical parallax.

Accuracy. Significant effects were obtained for vertical angle of regard, $F(2, 60) = 4.26$, $SS_e = 435.61$, $p < .05$; parallax, $F(1, 60) = 6.91$, $SS_e = 435.61$, $p < .05$; Gender \times Vertical Angle of Regard, $F(2, 60) = 6.20$, $SS_e = 435.61$, $p < .01$; Gender \times Parallax, $F(2, 60) = 5.08$, $SS_e = 435.61$, $p < .05$; Gender \times Vertical Angle of Regard \times Parallax, $F(2, 60) = 4.05$, $SS_e = 435.61$, $p < .05$; horizontal angle of regard, $F(2, 108) = 38.08$, $SS_e = 264.27$, $p < .01$; and Parallax \times Horizontal Angle of Regard, $F(2, 108) = 7.71$, $SS_e = 264.27$, $p < .01$. Duncan's multiple-range test showed that the mean accuracy score for subjects simulating the 50th percentile height (96.4%) was equal ($p > .05$) to that for subjects simulating the 97.5th percentile height (96.1%), but both of these means were larger ($p < .05$) than the mean accuracy score for subjects simulating the 2.5th percentile height (92.8%), and this effect was greater for women than for men ($p < .05$). Inspection of the means for the parallax main

effect indicated that significantly more touch responses were accepted as valid by the system when subjects touched targets with parallax reduced by the overlay (96.6%) than when subjects touched targets with inherent parallax in the display (93.5%), and this effect was greater for women than for men. Duncan's multiple-range test showed that the mean accuracy score when subjects stood directly in front of the display (97.4%) was equal ($p > .05$) to that when subjects stood to the left of the display (96.3%), but both of these means were larger ($p < .05$) than those when subjects stood to the right of the display (91.3%), and this effect was greater for subjects touching targets with inherent optical parallax in the display than for those touching targets with optical parallax reduced by the overlay ($p < .05$). Moreover, whether or not the display system accepted a touch as valid was a complex function of the gender of the subject, vertical angle of regard between the subject and the display, and optical parallax.

Regression. A step-wise multiple regression analysis was performed on the accuracy scores, using gender, optical parallax, vertical angle of regard between the subject and the display, x error, and y error as predicting factors. When subjects stood to the left of the display, y error, x error, and optical parallax explained 37% of the performance variance, $F(3, 65) = 12.99$, $SS_e = 196.93$, $p < .01$, $r^2 = .37$, and x error was correlated with y error, $r(67) = -.34$, $p < .01$. When subjects stood directly in front of the display, y error explained 28% of the performance variance, $F(1, 68) = 26.76$, $SS_e = 151.97$, $p < .01$, $r^2 = .28$, and x error was not correlated with y error ($p > .05$). When subjects stood to the right of the display, x error and y error explained 36% of the performance variance, $F(2, 62) = 17.28$, $SS_e = 389.78$, $p < .01$, $r^2 = .36$, and x error was correlated with y error, $r(63) = .39$, $p < .01$. Collapsing on horizontal angle of regard between the subject and the display, y error explained 44% of the performance variance, $F(1, 58) = 45.77$, $SS_e = 1275.55$, $p < .01$, $r^2 = .44$, and x error was not correlated with y error ($p > .05$). In each of these analyses, gender and vertical

Table 1
Accuracy Rates as a Function of Size of Tactual Recognition Field: Seated Work Station With Inherent Optical Parallax

Length of side (in millimeters)	Likelihood to accept touch (%)		
	<i>x</i> only	<i>y</i> only	Biconditional on <i>x</i> and <i>y</i>
10	79.6	82.8	66.7
12	85.9	90.4	78.5
14	90.9	94.7	86.6
16	94.0	97.2	91.8
18	96.3	98.5	95.1
20	97.6	99.2	97.0
22	98.5	99.5 ^a	98.1
24	99.0	99.7	98.7
26	99.4	99.8	99.2 ^a
28	99.6 ^a	99.8	99.5
30	99.7	99.9	99.7
32	99.8	99.9	99.7
34	99.9	99.9	99.8
36	99.9	99.9	99.9
38	99.9	99.9	99.9
40	100.0	99.9	99.9

^a Level at and beyond which independent variables had no effect on performance.

angle did not contribute to the predictive power of the regression models ($p > .05$).

Tactual Recognition Fields and Accuracy Models

The results of these two experiments indicate that the size of the tactual recognition field used determines whether the entry system will (a) reliably accept the human touch, (b) unreliably accept the touch (system error of commission to adjacent targets when present), or (c) reject the touch entirely (system error of omission). Touches that the system identifies as being located within the boundaries of the field will be accepted as accurate for the given target, whereas touches identified as being located outside of the boundaries of the field will not be accepted as accurate. Intuitively, large tactual recognition fields would lead to high accuracy rates and small ones would lead to low accuracy rates.

Three data bases were constructed from the *x* error and *y* error data, one for Experiment 1 and two for Experiment 2. The data base for Experiment 1 contained 8,884 touches captured for users in a seated work station (horizontal angle of regard, location of target on the screen, size and type of target used, and gender were proportionally represented in the data base). One of the data bases for Experiment 2 contained 3,879 touches captured for users in a standing work station with inherent optical parallax, and the other data base contained an additional 3,879 touches captured for users in a standing work station with optical parallax reduced by the overlay (vertical and horizontal angle of regard, location of target on the screen, and gender were proportionally represented in each data base). In all, the data bases combined consisted of approximately 60K recorded and generated variables, including the data for more than 16K touches taken under laboratory controlled conditions.

To model the effect of size of recognition field on accuracy rates, two types of analyses were carried out while varying the size of the field: (a) a biconditional analysis in which both the *x* error and the *y* error distances for a touch were used to determine whether the touch would have been accepted as accurate for each size of field, and (b) a unconditional analysis in which the *x*-error and the *y*-error distances for a touch were used separately to determine whether the touch would have been accepted as accurate for each size of field in the *x* dimension only and in the *y* dimension only, respectively.

Values for *x* and *y* dimensions (in millimeters) for various sizes of tactual recognition fields were used to sweep the three data bases. Touches falling inside the fields were accepted as accurate, and accuracy rates for each size of field were computed as the likelihood that a given touch would be accepted by the entry system as accurate. The results of these analyses are summarized in Tables 1, 2, and 3.

For users of the seated work station, a reanalysis of the independent variables and controls used in Experiment 1 showed no significant effects on accuracy rates ($p > .05$) when the *x* dimension of the field reached 28 mm (unconditional likelihood of 99.6%) and the *y* dimension of the field reached 22 mm (unconditional likelihood of 99.5%), or when the *x* and *y* dimensions were both 26 mm (biconditional likelihood of 99.2%, symmetrical). Similarly, for users of the standing work station with optical parallax reduced by the overlay, a reanalysis of the independent variables and controls used in Experiment 2 showed no significant effects on accuracy rates ($p > .05$) when the *x* dimension of the field reached 28 mm (unconditional likelihood of 99.7%) and the *y* dimension of the field reached 26 mm (unconditional likelihood of 99.7%), or when the *x* and *y* dimensions were both 26 mm (biconditional likelihood of 99.2%, symmetrical). And for users of the standing work station

Table 2
Accuracy Rates as a Function of Size of Tactual Recognition Field: Standing Work Station With Inherent Optical Parallax

Length of side (in millimeters)	Likelihood to accept touch (%)		
	<i>x</i> only	<i>y</i> only	Biconditional on <i>x</i> and <i>y</i>
10	66.9	62.5	41.4
12	75.4	72.3	54.2
14	83.0	79.4	65.4
16	88.2	86.0	76.0
18	92.8	90.5	84.2
20	95.6	93.2	89.3
22	97.7	95.6	93.6
24	98.6	97.3	96.1
26	99.1	98.1	97.3
28	99.4	98.8	98.3
30	99.7 ^a	99.2	99.0 ^a
32	99.8	99.5 ^a	99.4
34	99.9	99.8	99.7
36	100.0	99.8	99.8
38	100.0	99.9	99.9
40	100.0	99.9	99.9

^a Level at and beyond which independent variables had no effect on performance.

Table 3
Accuracy Rates as a Function of Size of Tactual Recognition Field: Standing Work Station With Optical Parallax Reduced by an Overlay

Length of side (in millimeters)	Likelihood to accept touch (%)		
	x only	y only	Biconditional on x and y
10	72.2	79.4	57.7
12	80.6	87.2	71.0
14	87.1	92.8	81.2
16	91.2	95.8	88.3
18	95.0	97.5	92.8
20	97.0	98.4	95.6
22	98.2	99.1	97.3
24	99.1	99.4	98.6
26	99.4	99.7 ^a	99.2 ^a
28	99.7 ^a	99.8	99.5
30	99.8	99.9	99.7
32	99.8	100.0	99.8
34	99.9	100.0	99.9
36	99.9	100.0	99.9
38	99.9	100.0	99.9
40	100.0	100.0	100.0

^a Level at and beyond which independent variables had no effect on performance.

with inherent optical parallax, a reanalysis of the independent variables and controls used in Experiment 2 showed no significant effects on accuracy rates ($p > .05$) when the x dimension of the field was 30 mm (unconditional likelihood of 99.7%) and the y dimension of the field was 32 mm (unconditional likelihood of 99.5%), or when the x and y dimensions were both 30 mm (biconditional likelihood of 99.0%, symmetrical).

The data bases for optical-parallax and parallax-reduced treatments were then combined, and the same dimensions reached during the reanalysis with optical parallax were used to screen the combined data base and determine the percentage of touches captured. A reanalysis of the data for Experiment 2 conditioning only on the x dimension (30 mm), or only on y dimension (32 mm), or on both x and y dimensions (both at 30 mm), showed that optical parallax had no effect on either the biconditional or the unconditional accuracy rates ($p > .05$). Generally, for the controlled data bases on which these models were constructed, the independent variables and subject variability were accommodated by symmetrical tactual recognition fields when the biconditional accuracy rate exceeded 99.0%.

For any given level of accuracy, the size of the tactual recognition fields for the standing work station with inherent optical parallax always encompassed those of the other two data bases. The data base for the standing work station with inherent optical parallax was used to construct a set of iso-functions to characterize the accuracy rates for the touch-entry system for each possible value of the x and y dimension on the field. (Each dimension is symmetrically distributed around the visual target.) As can be seen in Figure 5, by locating on the graph a length for the x dimension and a length for the y dimension for a given tactual recognition field, and by then finding the intersection of their vertical and horizontal lines on the graph, it is possible

to estimate the expected biconditional accuracy rate for that particular size of field. For example, a tactual recognition field having an x dimension 36 mm long and a y dimension 32 mm long (with its visual target centered in the tactual field) would have a corresponding accuracy rate of approximately 99.5%. And, conversely, to provide an accuracy rate of approximately 99.5%, one combination of lengths for the x and y dimensions for the tactual recognition field would be 36 mm and 32 mm, respectively.

By determining the size of the tactual recognition field to be used for each target, one can easily calculate the maximum possible number of targets that can be accommodated simultaneously (or sized as such) on the surface of the display for a desired level of accuracy for a touch-entry system. Continuing with the same example, using a field in which x is 36 mm and y is 32 mm, it is possible for a 13-in. (33.02-cm) display to accommodate 6 of these fields vertically on the screen and 7 of the fields horizontally on the screen, while maintaining an accuracy rate of 99.5%. Thus, the maximum possible number of simultaneous (or sized as such) fields on the display would be 42. In addition, using the information in this graph, a 13-in. (33.02-cm) display can accommodate simultaneously (or sized as such) as many as 80 or as few as 30 fields while maintaining accuracy rates from 96% to more than 99.5% (though variability in performance is most resilient to the effects of extraneous variables when the biconditional accuracy rate is at or beyond the 99.0% level). These are essentially measures of the tactual resolution of the on-display touch-entry system.

General Discussion

It has been suggested in previous research that optical parallax and various angles of regard between the surface of the display contribute to error when using touch-entry systems (Beringer & Peterson, 1985; Pfauth & Priest, 1981; Stammers & Bird, 1980; Whitfield et al., 1981). But, only in the study by Beringer and Peterson (1985) was angle of regard systematically

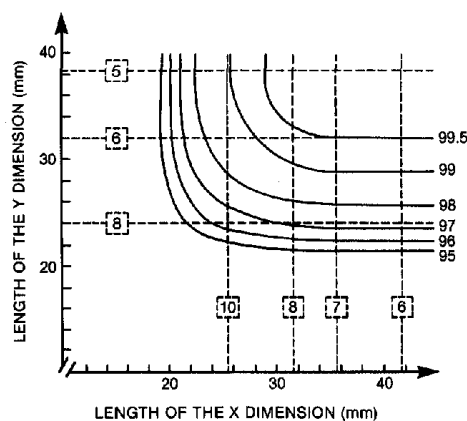


Figure 5. Tactual resolution characteristics of the 13-in. (33.02-cm) on-display touch-entry system. (Estimates of rates assume visual targets centered in tactual fields.)

manipulated and location of target controlled, and in none of the studies were the effects on accuracy rates of both horizontal and vertical angles, parallax, or gender experimentally investigated. The results of Experiments 1 and 2 reported here confirm previous speculation that these variables contribute to error and affect accuracy rates.

Beringer and Peterson (1985) stated that most of the touch errors were within ± 3.2 mm, and suggested that increasing the size of the tactual recognition field to $9.5 \text{ mm} \times 9.5 \text{ mm}$ would eliminate most errors. Although this recommendation is in accord with the size of touch areas for stylus entry used previously by Long et al. (1984), the size of the recognition field is somewhat smaller than that initially recommended by Pfauth and Priest (1981), and no experimental evidence was provided about any resulting changes in accuracy rates as a function of increasing the size of the tactual recognition field. Results of the present laboratory studies show that considerable variability in error exists among users of touch-entry systems and that performance was generally best when the size of the field exceeded $30 \text{ mm} \times 30 \text{ mm}$. Moreover, it was shown that the size of the field used is not a discrete selection. Rather, the size and design of a particular field should be a function of the level of accuracy desired for the target.

Given the results of previous studies, an obvious conclusion is that touch-entry systems appear best suited for applications having low-resolution requirements (Schneiderman, 1987). However, the distinction between low resolution and high resolution is relative, and there have been no definitive findings to date about the nature of this distinction regarding accuracy rates for touch-entry systems. Results of the present studies show that relatively continuous increases in the size of the tactual recognition field around the visual target produced corresponding increases in system accuracy. In fact, it was possible both (a) to accommodate the variability in performance among users and (b) to minimize the effects of the manipulated variables (e.g., optical parallax, vertical and horizontal angles, the location of the target on the screen, size of target used, and gender) on performance. This was generally the outcome for both seated and standing work stations. Using this approach, it was demonstrated that accuracy rates and tactual resolution are inversely related. As the size of the recognition field was decreased, the accuracy rate for the field decreased, but the maximum possible number of fields on the display at one time (or sized as such) increased. Conversely, as the size of the recognition field was increased, the maximum possible number of fields on the display at one time (or sized as such) decreased, but the accuracy rate for the field increased.

Published studies of human performance using touch-entry devices maintain that either (a) the system should be designed in such a way as to permit software modeling of the biases of each user and then compensate for the touch biases of that user or (b) the user should be trained to touch the system in particular ways to minimize error. Stammers and Bird (1980) suggested that special effort may be required toward training users to reduce error rates and recommended extended practice, as well as enhanced feedback from the device, to improve performance. Similarly, Beringer and Peterson (1985) emphasized the importance of duration and scheduling of training sessions and the type of feedback during training. However, in their detailed

comparisons of performance using on-display and off-display entry devices, Whitfield et al. (1983) showed no beneficial effects of computer-generated feedback on finger position. Beringer and Peterson reported that training was effective in some respects, although it was limited in its improvement in response precision. Results from training procedures showed that y error could be reduced from -0.52 mm (without feedback) down to -0.20 mm (with feedback). Moreover, potential users of touch-entry systems may be completely naive to the requirements of the system, and special training may not be possible, as in the case of public-access users (Pfauth & Priest, 1981), or in the case of users of commercially available products (see, e.g., Olson, 1987).

Beringer and Peterson (1985) maintained that if the first entry must be accurate, extended training or response modeling or biasing may be needed. They added that the additional time and effort required for training may not be practical and that use of a model to adjust system response may be the preferred approach to improving system accuracy. Unfortunately, their results showed no consistent pattern favoring a best model to reduce error, and population modeling was dismissed because of variance in performance among users.

In keeping with major tenets of human-factors engineering and the psychology of human-computer interaction, systems should be designed to accommodate (a) the diversity of human form (limitations and abilities, overt and covert), (b) the various tasks that users want to perform, and (c) the environments in which the system is used (Card, Moran, & Newell, 1983; Grandjean, 1980; Grandjean & Vigliani, 1980; Schneiderman, 1987; Wickens, 1984; Wickens & Kramer, 1985). We report the effects of a number of these factors on performance when using an on-display touch-entry system and then demonstrate further that it is possible to accommodate their effects by using carefully designed tactual recognition fields in the software. The results of Experiments 1 and 2 and tactual fields simulations show that it is possible to achieve accuracy rates as high as 99.9% and 100%, and suggest that there is no apparent need to adjust the spontaneous behavior of users of touch-entry systems. Moreover, the tactual resolution of the touch-entry system was characterized in terms of a relation among (a) the size of the tactual recognition field, (b) the number of fields desired simultaneously on the surface of the display (or sized as such), and (c) the desired system accuracy rate.

Some care, of course, is warranted in applying directly the results of these studies to different types of touch-entry systems and to applications having various penalties for error. Additional research is needed to determine the extent to which the results of these laboratory studies generalize to users when making touch entries in natural settings. Until such information is made available, the information presented here will be useful to designers of tactual recognition fields and will contribute generally to what is known about performance using touch-entry systems.

References

- Alden, D. G., Daniels, R. W., & Kanarick, A. F. (1972). Keyboard design and operation: A review of the major issues. *Human Factors*, 14, 275-293.

- Beringer, D. B. (1980). The design and evaluation of complex systems: Application to a man-machine interface for aerial navigation. *Navigation*, 27, 200-206.
- Beringer, D. B., & Peterson, J. G. (1985). Underlying behavioral parameters of the operation of touch-input devices: Biases, models, and feedback. *Human Factors*, 27, 445-458.
- Card, S. K., English, W. K., & Burr, B. J. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. *Ergonomics*, 21, 601-613.
- Card, S. K., Moran, T. P., & Newell, A. (1983). *The psychology of human-computer interaction*. Hillsdale, NJ: Erlbaum.
- Carroll, A. B. (1986, November). Touch technology: Variety of systems spur maturity. *Information Display*, pp. 15-20.
- Diffrient, N., Tilley, A. R., & Bardagay, J. C. (1979). *Humanscale 1/2/3*. Cambridge, MA: MIT Press.
- Goodwin, N. C. (1975). Cursor positioning on an electronic display using lightpen, lightgun, or keyboard for three basic tasks. *Human Factors*, 17, 289-295.
- Grandjean, E. (1980). *Fitting the task to the man: An ergonomic approach*. London: Taylor & Francis.
- Grandjean, E., & Vigliani, E. (Eds.). (1980). *Ergonomic aspects of visual display terminals*. London: Taylor & Francis.
- Hall, A. D., Cunningham, J. B., Roache, R. P., & Cox, J. W. (1988). *Factors affecting performance using touch-entry systems: Tactual recognition fields and resolution characteristics* (TR 29.0787). Research Triangle Park, NC: IBM Corporation, Communication Products Division.
- Hirsch, R. S. (1970). Effects of standard versus alphabetical keyboard formats on typing performance. *Journal of Applied Psychology*, 54, 484-490.
- Karat, J., McDonald, J., & Anderson, M. (1984). *A comparison of selection techniques: Touchpanel, mouse, and keyboard* (TR 51.0166). Austin, TX: IBM Corporation, Entry Systems Division.
- Klemmer, E. T. (1971). Keyboard entry. *Applied Ergonomics*, 2, 2-6.
- Klemmer, E. T., & Lockhead, G. R. (1962). Productivity and errors in two keying tasks: A field study. *Journal of Applied Psychology*, 46, 401-408.
- Kroemer, K. H. E. (1983, February). Ergonomics of VDU workplaces. *Digital Design*, pp. 25, 31-35.
- Long, J. B., Whitfield, A., & Dennett, J. (1984). The effect of display format on the direct entry of numerical information by pointing. *Human Factors*, 26, 3-18.
- Olson, J. B. (1987, January). Case study: The first automotive-display touch panel. *Information Display*, pp. 12-16.
- Panero, J., & Zelnik, M. (1979). *Human dimension and interior space*. New York: Library of Design.
- Pfauth, M., & Priest, J. (1981). Person-computer interface using touch screen devices. *Proceedings of the Human Factors Society*, 25, 500-504.
- Schneiderman, B. (1980). *Software psychology: Human factors in computer and information systems*. Boston: Little, Brown.
- Schneiderman, B. (1987). *Designing the user interface: Strategies for effective human-computer interaction*. Reading, MA: Addison-Wesley.
- Schwartz, T. A. (1986). The AT&T soft touch-sensitive screen. *AT&T Technical Journal*, 65, 62-67.
- Stammerjohn, L. W., Smith, M. J., & Cohen, B. G. F. (1981). Evaluation of workstation design factors in VDT operations. *Human Factors*, 23, 401-412.
- Stammers, R. B., & Bird, J. M. (1980). Controller evaluation of a touch input air traffic data system: An 'indelicate' experiment. *Human Factors*, 22, 581-589.
- Whitfield, D., Ball, R. G., & Bird, J. M. (1983). Some comparisons of on-display and off-display touch input devices for interaction with computer generated displays. *Ergonomics*, 26, 1033-1053.
- Wickens, C. D. (1984). *Engineering psychology and human performance*. Columbus, OH: Merrill.
- Wickens, C. D., & Kramer, A. (1985). Engineering psychology. *Annual Review of Psychology*, 36, 307-348.

Received March 27, 1987

Revision received February 15, 1988

Accepted December 28, 1987 ■