Touch Screen Performance as a Function of the Duration of Auditory Feedback and Target Size

by

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I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Psychology.

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DEDICATION

This dissertation is dedicated to my parents

Mr. Thomas Bender and Mrs. Gladys Bender

and to my brothers

Mr. Todd Bender and Mr. Theodore Bender

for their unwavering dedication to growth in all areas of my life as well as

their steadfast encouragement of my educational efforts throughout the last 10 years.

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ABSTRACT

Touch screens are commonly used in the retail industry as a replacement for mechanical key based devices. However, data entry speed and error rates are often worse with touch screens than with mechanical key based devices, possibly due to the decreased proprioceptic feedback provided by touch screens. An appropriate auditory feedback signal may help compensate for the reduced proprioceptic feedback and increase touch screen performance. Three studies were conducted to empirically evaluate the effect of the duration of auditory feedback (12.5, 25, 50, 100, 200, 400, & 800 ms) and target size (10 x 10 mm & 30 x 30 mm) on touch screen ten-key entry movement time, contact time, and errors. Results indicate that (a) performance is better with large targets than small targets, and (b) error rates with small targets are reduced if auditory feedback between 50 and 400 ms is provided. Design recommendations for touch screen point of sale interfaces are discussed.

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CHAPTER I

INTRODUCTION

Designing Point Of Sale (POS) interfaces for retail tasks present unique challenges for the human factors psychologist. At any given time, three users with unique goals must be satisfied: the corporation that purchases the interface, the cashier who directly interacts with the interface, and the shopper who is purchasing the product at the interface. A goal of the corporation is to invest as little as necessary to ensure return visits to the store. A goal of the cashier is to earn money by performing a safe and enjoyable task. A goal of the shopper is to purchase the product as quickly as possible. A properly designed POS, incorporating the aforementioned objectives, aids all three users in increasing efficiency and maximizing productivity.

One important interface at the POS is the cash register. The purpose of this device is twofold. The primary purpose is to quickly calculate the proper amount of money owed by each shopper. The secondary function is to record purchased items for inventory records. These records can then be used to determine when products must be restocked or reordered. Bar code scanning and manual entry devices are the primary means of recording items that have been purchased.

Although the use of a bar code scanning device is faster than manual entry, the nature of many retail environments, such as grocery stores, department stores and restaurants, prohibits the exclusive use of bar code scanning. Grocery stores contain produce that cannot be bar coded. Department stores contain large and unique items that cannot be bar coded or easily positioned to be read by a scanner. Restaurants are characterized by frequently changing menus and table layouts, and a product that precludes bar coding altogether. In these circumstances, manual entry is currently the only alternative.

Many manual entry devices have been designed to facilitate record keeping in these unique settings. The traditional manual entry device is the keyboard. The variety of keyboard designs includes the traditional cash register layout (characterized by a variable number of columns and nine rows, one for each digit excluding zero), alphanumeric QWERTY keyboards, ten-key pads (using either the telephone or calculator layout), and a host of industry specific devices with up to 100 or more keys. An alternative manual entry device is the touch screen. The touch screen is attractive for several reasons. First, utilizing the same display for output and input can conserve space at the POS. Second, since touch screens contain no moving parts, spilled food or beverage is less likely to render it inoperable. Third, buttons can be placed at any location on the display, facilitating the implementation of cognitive organization techniques and providing flexibility in frequently changing environments. For these reasons, several retail industries (most notably restaurants) use touch screens almost exclusively at their POS's.

Despite the benefits touch screens provide, touch screen performance is often slower and less accurate than traditional mechanical key performance (Barrett & Krueger, 1994; Wilson, Inderrieden, & Liu, 1995). Wilson et al. (1995) compared touch screens with various sized buttons, ten-key pads, and a NCR DynaKey™ (a 9.4 inch LCD integrated with eight mechanical function keys and a standard mechanical keypad). Participants completed a number of tasks representative of typical retail POS activities. Results indicated that participants are slower and less accurate with the touch screen, regardless of button size, than with the mechanical key devices. Another study (Barrett & Krueger, 1994) compared typing performance on a conventional mechanical alphanumeric QWERTY keyboard with a flat piezoelectric alphanumeric keyboard. Piezoelectric keyboards operate by means of changes in electrical potential when pressure is applied. They are similar to touch screens in that both devices provide little, if any, proprioceptic feedback. The conventional keyboard outperformed the piezoelectric keyboard in regard to both speed and accuracy.

Therefore, manufacturers of retail POS devices (e.g., NCR) are investigating methods of improving touch screen manual entry performance. Previous research investigating touch screen performance hypothesized that the greatly reduced proprioceptic feedback provided by touch screens is responsible for the performance differences between touch screens and mechanical keys (Alden, Daniels, & Kanarick, 1972; Pollard & Cooper, 1979; Wilson et al., 1995). In other words, mechanical keys allow users to determine when a key is actuated by the proprioceptic force displacement curve associated with the key. Numerous researchers have found that visual and auditory feedback are relatively unimportant factors in mechanical key operation (Akamatsu, MacKenzie, & Hasbroucq, 1995; Banton, 1995; Diehl & Seibel, 1962; Pollard & Cooper, 1979; Roe, Muto, & Blake, 1984). However, because touch screens provide very little proprioceptic feedback, visual and auditory feedback may be important factors for improving performance.

The current study is concerned with determining the effect of the duration of auditory feedback and target size on touch screen target acquisition performance. Duration of auditory feedback refers to the length of the auditory signal produced when the screen is touched. Target size refers to the height and width of a button on the display.

Audition

The use of auditory signals to transmit information is widespread. Computers, radar detectors, microwaves, and a multitude of everyday devices use a plethora of sounds to confirm actions taken by users. A great deal of research has investigated the human perception of sound as related to intensity, frequency, and duration. However, little empirical research has investigated the effect of the duration of auditory feedback on performance, and no research has examined this effect on target acquisition performance. The duration of auditory feedback may be a factor that improves touch screen performance by compensating for the decreased proprioceptic feedback inherent with touch screens.

Perceived Loudness and Duration

As a sound is initiated, it goes through a period of time during which the perceived loudness of the sound increases. For this reason, brief sounds are perceived as less loud than longer sounds of equal intensity (Algom, Rubin, & Cohen-Raz, 1989; Scharf, 1978; Dallos & Olsen, 1964; Garner & Miller, 1947; Green, Birdsal, & Tanner, 1957; Massaro & Idson, 1976; Munson, 1947; Stevens & Davis, 1938). In fact, there is a reciprocal relationship between intensity and duration. For brief sounds, intensity and duration are directly proportional to one another. That is, the loudness of two sounds, A and B, with A of twice the duration of B and B of twice the intensity of A, will be perceived as equivalent. This relationship is known as the Bunsen-Roscoe Law, the Law of Reciprocity, or the time-intensity trade-off and is expressed mathematically as $It = C$, where I is intensity, t is duration, and C is a constant (Stevens, 1951; Stevens & Davis, 1938). The point in time at which the perceived loudness of a sound ceases to increase is referred to as the critical duration and its absolute value is a matter of debate. However, an international experimental program conducted in more than 20 laboratories suggests that the critical duration is 80 ms (Pedersen, Lyregaard, & Poulsen, 1977 as cited in Scharf, 1978). Therefore, as a general rule, sounds briefer than 80 ms are perceived as less loud than sounds longer than 80 ms in duration. Frequency and bandwidth have little effect on this relationship (Scharf, 1978).

Behavior can be affected by the intensity of sounds. Several studies have investigated the effect of warning signal intensity on simple and choice reaction time (Keuss & van der Molen, 1982; Niemi, 1982; van der Molen & Keuss, 1979). The typical procedure is to present an auditory warning signal of a variable intensity and then present an auditory response signal of a constant intensity. Reaction time to the response signal is the dependent variable. Results indicate that simple reaction time to the response signal decreases as warning signal intensity increases (Keuss & van der Molen, 1982; van der Molen & Keuss, 1979). This relationship holds for warning signal intensities ranging from 50 to 110 dB(A). Furthermore, this effect develops only when the warning signal lasts until the presentation of the response signal (Niemi, 1982). If the warning signal terminates prior to the response signal, simple reaction time to the response signal increases as warning signal intensity increases. On the other hand, choice reaction time to the response signal decreases as warning signal intensity increases up to about 90 dB(A), then choice reaction time increases again through 110 dB(A) (Keuss & van der Molen, 1982; van der Molen & Keuss, 1979).

Auditory Signals as Feedback

Several studies have investigated the relative importance of visual and auditory feedback in alphanumeric and piano keyboards, telephone and membrane keypads, and mouse-type devices (Akamatsu, MacKenzie & Hasbroucq, 1995; Banton, 1995; Diehl & Seibel, 1962; Pollard & Cooper, 1979; Roe et al., 1984). Diehl and Seibel (1962) had experienced typists use a standard IBM typewriter under four conditions: normal, visual masking (no visual sight of typewriter carriage or typewritten sheet), auditory masking (tape recording through earphones of four typists typing simultaneously), and visual and auditory masking (combination of the visual and auditory masking conditions). The normal and visual masking conditions resulted in significantly more gross words per minute than the auditory masking condition. The normal condition resulted in significantly more net words per minute than the auditory masking or visual and auditory masking conditions. Although these results are somewhat inconsistent, and the auditory masking condition is confounded by the wearing of earphones, the results may suggest a performance decrement when auditory feedback is not present. However, the authors caution that although the results are significant, the effect size is too small to be meaningful.

Banton (1995) compared piano sight-reading errors under normal, no-visual (keyboard not visible), and no-auditory (notes were unable to be heard) feedback conditions. The no-visual feedback condition resulted in significantly more errors than either normal or no-auditory feedback conditions. There were no differences between the normal and no-auditory feedback conditions.

Pollard and Cooper (1979) conducted a series of experiments investigating the use of auditory feedback signals for telephone keypads. An initial study indicated no differences in keying times, errors, or preference using a conventional pushbutton keypad with MF4 signaling tones, a single 820 Hz tone, a click on depression and release, or no feedback conditions. Subsequent studies with capacitive keypads indicated that a 820 Hz feedback tone facilitates faster keying times than either a click on depression or illumination of a panel above the keypad. Neither preference nor error differences were observed between the three types of feedback. An additional study indicated that keying times are faster and errors are fewer when auditory feedback came from the handset as opposed to the body of the phone.

Roe et al. (1984) measured keying rate, keying errors, and preference on membrane (key travel less than 0.5 mm) keypads with and without domes, embossing, and a 50 ms 1000 Hz tone. Results indicated that participants preferred domed keypads and auditory feedback, keyed faster with domed keypads than non-domed keypads, and made fewer keying errors with domed keypads and auditory feedback.

Akamatsu et al. (1995) modified a mouse to provide normal, auditory (2000 Hz tone when the cursor was over the target), tactile (pin pressed index finger when the cursor was over the target), visual (target changed color when the cursor was over the target), and combined feedback conditions. No differences between the conditions were observed for response time or error rate. However, the tactile feedback condition resulted in shorter final positioning time (time to click mouse button once the cursor had entered the target) compared to the normal condition.

The pattern of results that emerges from these studies suggests that auditory feedback is relatively unimportant for mechanical key actuation performance. On the other hand, the results of the membrane keypad study (Roe et al., 1984) suggest that auditory feedback can be an important factor when proprioceptic feedback is minimized. The results from the capacitive telephone keypad study (Pollard & Cooper, 1979) suggest that certain types of auditory feedback (tones) result in better keying performance than other types of auditory feedback (clicks).

Howell and Powell (1987) conducted an experiment in which they manipulated the delay and duration of speech and non-speech feedback to participants. Dependent variables included the decibel level and rate at which participants spoke. Results indicated that participants spoke louder as feedback delay and duration increased. Additionally, participants spoke slower as feedback delay and duration increased up to about 200 ms delay. After this delay, participants spoke faster as feedback delay and duration continued to increase up to 300 ms delay. This relationship was maintained regardless of whether the feedback was speech or non-speech. The findings of Howell and Powell (1987) suggest that the duration of auditory feedback can affect performance.

Fitts Law

Movement Time

Fitts (1954) immortalized the concept of target width in his development of Fitts Law. Fitts Law states that movement time between two targets is a linear function of the Index of Difficulty. Index of Difficulty is the logarithm of the ratio of twice the amplitude between two targets and the width of the targets. Amplitude refers to the distance that must be navigated to acquire a target and width refers to the size of the target. The relationship expressed by Fitts Law has been shown to be very robust (Keele, 1981, 1986). Results from numerous studies indicate that movements to large, near targets are faster than movements to small, far targets (Adam & Paas, 1996; Adam et al., 1995; Adam, van der Bruggen, & Bekkering, 1993; Adam et al., 1997; MacKenzie, 1992; Fitts, 1954; Guiard, 1993). Experiments investigating Fitts Law are typically characterized by a reciprocal movement task. Movement time is inferred from the number of movements completed within a given period of time. Unfortunately, this method of calculating movement time yields an inflated value because it includes the time spent on the target, or contact time (Fitts & Radford, 1966).

Contact Time

Research has shown that contact time (also known as dwell time or time on target) is a function of target width and amplitude (Adam & Paas, 1996). Specifically, dwell time increases as target width decreases and target amplitude increases. Target width appears to have a greater influence on dwell time than target amplitude. Dwell time has been shown to be a function of visual verification time, motor programming time, and movement efficiency (Adam, 1992; Adam & Paas, 1996; Guiard, 1993).

Statement of Purpose and Hypotheses

The purpose of this research is to determine if touch screen ten-key entry speed and/or accuracy can be improved by the introduction of an appropriate auditory feedback signal. Three experiments were conducted. Experiment 1 was conducted to determine if the presence of an auditory feedback signal differentially affects touch screen ten-key entry movement time, contact time, and/or errors. Experiment 2 was conducted to determine if the duration of an auditory feedback signal differentially affects touch screen ten-key entry movement time, contact time, and/or errors. Experiment 3 was conducted to validate any differences observed in Experiment 2 in a setting with higher fidelity.

Experiment 1 Hypotheses

a) Touch screen ten-key entry movement time will be different in the presence of an auditory feedback signal than in the absence of an auditory feedback signal.

b) Touch screen ten-key entry contact time will be different in the presence of an auditory feedback signal than in the absence of an auditory feedback signal.

c) Touch screen ten-key entry errors will be different in the presence of an auditory feedback signal than in the absence of an auditory feedback signal.

d) Touch screen ten-key entry movement time will decrease as target size increases.

e) Touch screen ten-key entry contact time will decrease as target size increases.

f) Touch screen ten-key entry errors will decrease as target size increases.

Experiment 2 Hypotheses

a) Touch screen ten-key entry movement time will differ as a function of the duration of the auditory feedback signal.

b) Touch screen ten-key entry contact time will differ as a function of the duration of the auditory feedback signal.

c) Touch screen ten-key entry errors will differ as a function of the duration of the auditory feedback signal.

d) Touch screen ten-key entry movement time will decrease as target size increases.

e) Touch screen ten-key entry contact time will decrease as target size increases.

f) Touch screen ten-key entry errors will decrease as target size increases.

Experiment 3 Hypotheses

a) Touch screen ten-key entry movement time will be different in the presence of a 200 ms auditory feedback signal than a 800 ms auditory feedback signal.

b) Touch screen ten-key entry contact time will be different in the presence of a 200 ms auditory feedback signal than a 800 ms auditory feedback signal.

c) Touch screen ten-key entry errors will be different in the presence of a 200 ms auditory feedback signal than a 800 ms auditory feedback signal.

d) Touch screen ten-key entry movement time will decrease as target size increases.

e) Touch screen ten-key entry contact time will decrease as target size increases.

f) Touch screen ten-key entry errors will decrease as target size increases.

CHAPTER II

GENERAL METHODS

Participants

Thirty-two right-handed students from Wichita State University voluntarily participated in these experiments. Volunteer participants were recruited from the psychology department's human participant pool following established procedures. Thirty-one of the participants completed all three experiments; one participant completed only Experiments 1 and 2.

Apparatus & Materials

A NCR 5962 Wedge Touch Screen served as both the input and output device. The Touch Screen is characterized by a 10.5-inch passive matrix (DSTN) color LCD and a MicroTouch capacitive touch screen. The touch screen/display was connected to a NCR 7453 POS computer workstation. A Sound Blaster AWE 64 sound card (see Appendix B) and external Altec Lansing GCS 100 speakers (see Appendix C) generated auditory feedback. A 1000 Hz sine wave was used as the auditory feedback signal.

A custom computer program written using Microsoft Visual Basic 6.0 was used to present stimuli and collect data. The ten-key entry task presented a calculator-style ten-key pad centered on the display (see Figures 1, 2, and 3). All buttons were square with centered labels. A land-on touch selection strategy was used to activate all buttons.

Figure 1. Calculator-style ten-key pad with 30 x 30 mm targets used in Experiments 1, 2, and 3 to enter digits.

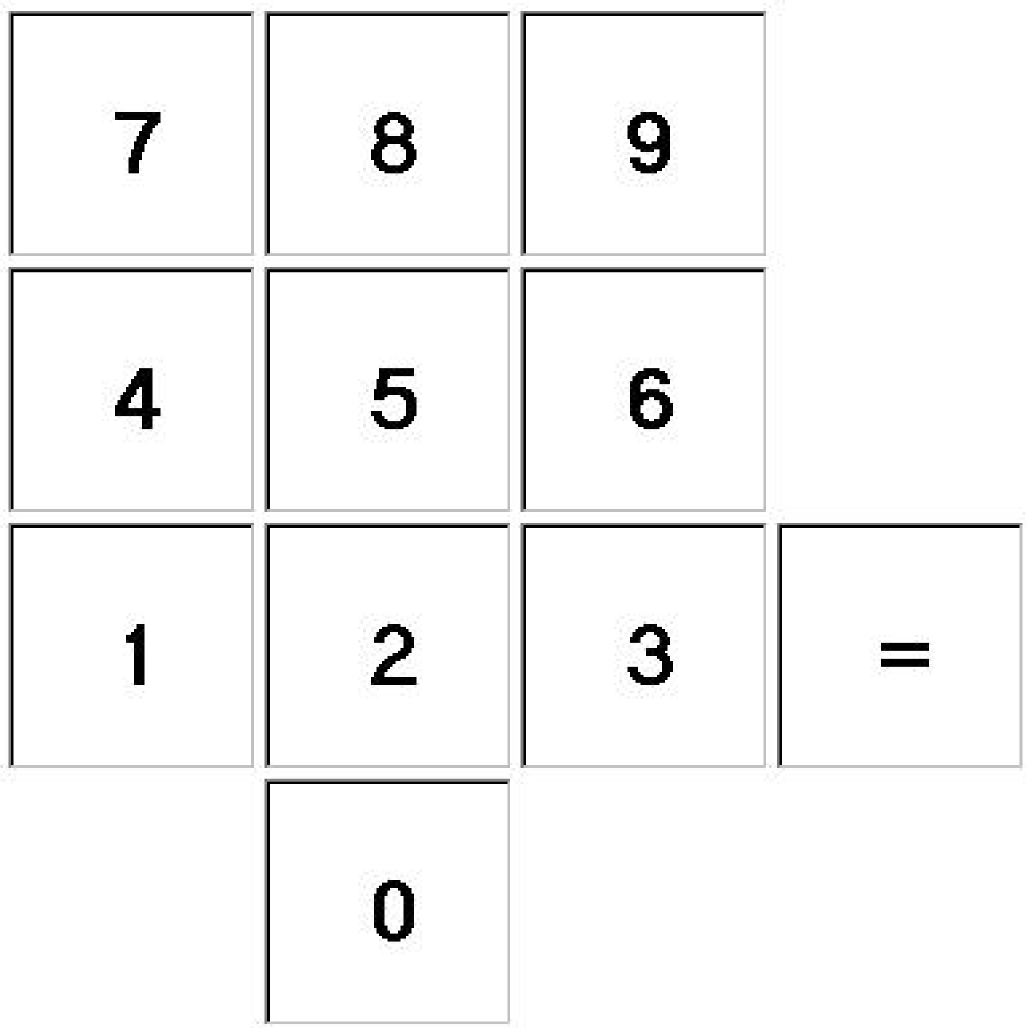


Figure 2. Calculator-style ten-key pad with 10 x 10 mm targets used in Experiments 1 and 2 to enter digits.

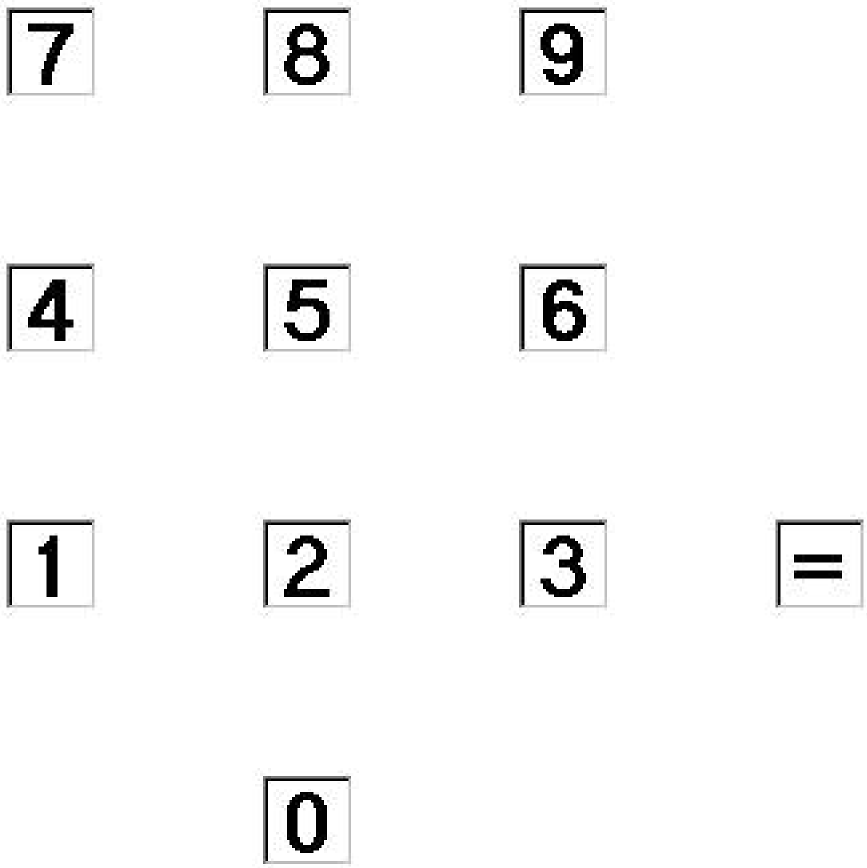
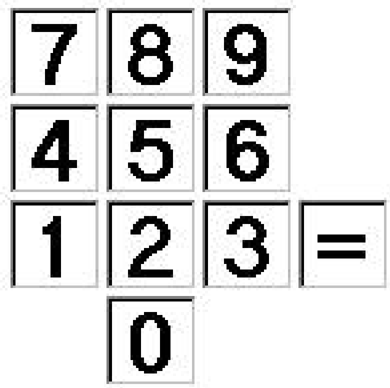


Figure 3. Calculator-style ten-key pad with 10 x 10 mm targets used in Experiment 3 to enter digits.



Design and Procedure

Randomized block factorial designs were used in all three experiments to test the effect of auditory feedback and target size on touch screen ten-key entry performance. The dependent variables were ten-key entry movement time, contact time, and errors. Movement time was operationally defined as the length of time from when a participant's finger was removed from the touch screen until a participant's finger touched the touch screen again. Contact time was operationally defined as the length of time from when a participant's finger touched the touch screen until the participant's finger was removed from the touch screen. Errors were operationally defined as any incorrect entry of a string of digits.

For all three experiments, participants were presented and asked to read on-screen instructions (see Appendices E and F). Participants were instructed to touch the screen using only the index finger of their right hand. Participants stood at a standard check stand while performing all tasks. This requirement was implemented to better approximate a retail POS environment. Participants were instructed to adjust the angle of the touch screen so that it was comfortable to view and touch with the following ergonomic constraints: (a) the angle between the arm and torso was no more than 30°, (b) the neck was bent forward no farther than 15°, (c) the viewing angle was no greater than 30° from horizontal at eye level, (d) the elbow angle was between 90° and 135°, and (e) the wrist angle was 180° (Lehman & Sutarno, 1996).

In all three experiments, participants were presented pseudo-random sequences of four digits. The digits were computer generated in the following manner: (a) the first digit in the sequence could not be zero, and (b) a digit could not appear twice in succession within the sequence. Participants were instructed to enter the sequence of digits using the touch screen ten-key pad as quickly and accurately as possible. Completion of a sequence was indicated by pressing the equal (=) key. Upon pressing the equal key, participants were presented a new string of digits and a new trial began. Participants entered 48 sequences of four digits in each condition. The auditory feedback signal was generated when a participants' finger touched the touch screen. In order to isolate the effect of auditory feedback, no supplemental visual feedback was provided. That is, buttons neither changed color nor gave the impression of 3-dimensional depression when touched. Participants rested for 20 seconds between each block of trials.

CHAPTER III

EXPERIMENT 1

The purpose of Experiment 1 was to determine if the presence of an auditory feedback signal differentially affects touch screen ten-key entry movement time, contact time, and/or errors.

Method

Apparatus & Materials

A 1000 Hz sine wave was used as the auditory feedback signal. The auditory feedback signal was presented at 65 dB(A) in a 55 dB(A) room (Deatherage, 1972). The center of each button on the ten-key pad was located 32 mm from the center of the nearest neighboring button (see Figures 1 and 2).

Design and Procedure

A 2 x 2 randomized block factorial design was used to test the effect of the presence of auditory feedback and target size on touch screen ten-key entry performance. The presence of auditory feedback was manipulated within participants and contained two levels: no auditory feedback or 100 ms auditory feedback. Target size was manipulated within participants and contained two levels: 10 x 10 mm or 30 x 30 mm. Participants completed 4 blocks of 48 trials. The presence or absence of auditory feedback and target size were constant within blocks but randomized and counterbalanced across blocks.

Each trial began with the presentation of a pseudo-random sequence of four digits in the upper left-hand corner of the display. Upon completion of each trial, a new string of digits replaced the old string of digits and a new trial began. Participants required approximately 15 minutes to complete the experiment.

Results

Movement Time

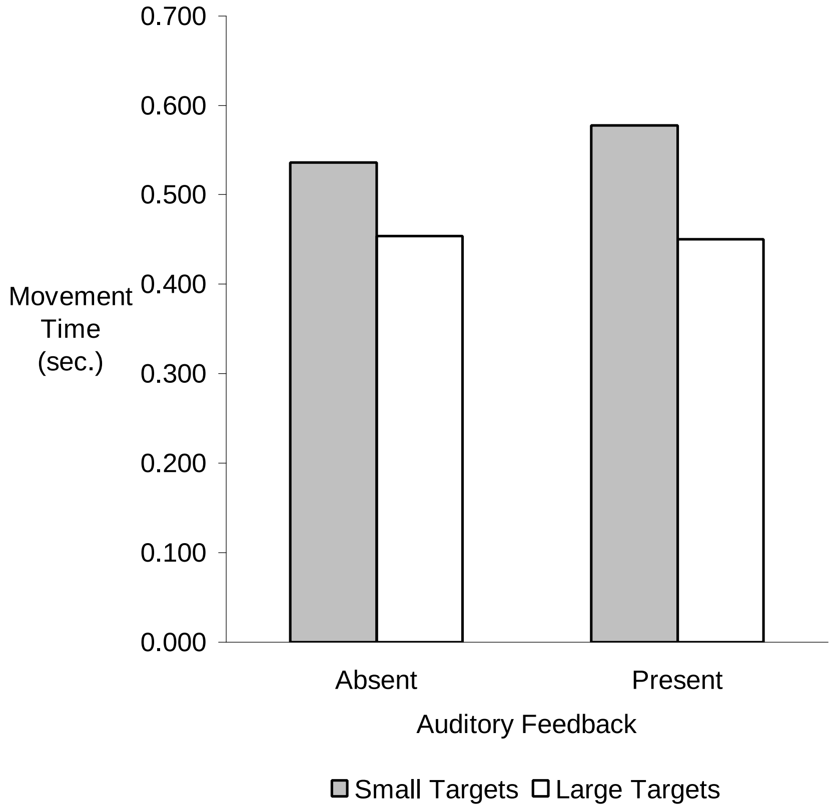
Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. Movement time data for each participant was averaged within each trial and across the last 40 trials, yielding a single score for each participant in each condition. Heterogeneity of variance was not significant, $F_{max} = 1.47$, $p > .05$ (Kirk, 1995). All analyses were evaluated using a significance level of $p = .05$.

A 2 x 2 randomized block factorial ANOVA was conducted (Kirk, 1995). The independent variables were feedback (no auditory feedback or 100 ms auditory feedback) and target size (10 x 10 mm or 30 x 30 mm). Mean movement times are presented in Figure 4. A significant interaction was observed, $F(1, 31) = 14.993$, $p < .001$; $eta^2 = .894$; $1 - ß = 1.000$. A significant main effect for feedback was observed, $F(1, 31) = 6.640$, $p < .01$; $eta^2 = .176$; $1 - ß = 0.704$. A significant main effect for target size was observed, $F(1, 31) = 260.108$, $p < .001$; $eta^2 = .326$; $1 - ß = 0.963$.

Simple effects tests were conducted on auditory feedback at each target size. A significant simple effect for feedback with small targets was observed, $F(1, 31) = 15.546$, $p < .001$. The simple effect for feedback with large targets was not significant, $F(1, 31) = 0.264$, $p > .05$.

Simple effects tests were conducted on target size at each level of auditory feedback. A significant simple effect for target size with no auditory feedback was observed, $F(1, 31) = 100.989$, $p < .001$. A significant simple effect for target size with 100 ms auditory feedback was observed, $F(1, 31) = 187.862$, $p < .001$.

Figure 4. Experiment 1 mean movement time as a function of auditory feedback and target size.



Mean Movement Time (sec.)

	Absent	Present
Small Targets	0.536	0.578
Large Targets	0.454	0.450

Contact Time

Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. Contact time data for each participant was averaged within each trial and across the last 40 trials, yielding a single score for each participant in each condition. Heterogeneity of variance was found to be significant, $F_{max} = 27.41$, $p < .01$ (Kirk, 1995). Heterogeneity of variance has been shown to increase Type I error (Keppel, 1991). In an attempt to reduce heterogeneity of variance, square root, logarithmic, reciprocal, and inverse sine transformations (see Appendix G) were conducted (Kirk, 1995). Each transformation failed to yield homogeneity of variance. Therefore, the variances of contact time were analyzed in addition to the means of contact time. The analyses of the variances of contact time were evaluated using a significance level of $p = .05$. The analyses of the means of contact time were evaluated using a significance level of $p = .01$, to compensate for the heterogeneity of variance (Keppel, 1991).

Analysis of the means of contact time. A 2 x 2 randomized block factorial ANOVA was conducted (Kirk, 1995). The independent variables were feedback (no auditory feedback or 100 ms auditory feedback) and target size (10 x 10 mm or 30 x 30 mm). Mean contact times are presented in Figure 5. The interaction was not significant, $F(1, 31) = 0.505$, $p > .05$; $eta^2 = .016$; $1 - ß = 0.106$. The main effect for feedback was not significant, $F(1, 31) = 0.117$, $p > .05$; $eta^2 = .004$; $1 - ß = 0.063$. A significant main effect for target size was observed, $F(1, 31) = 78.657$, $p < .001$; $eta^2 = .717$; $1 - ß = 1.000$.

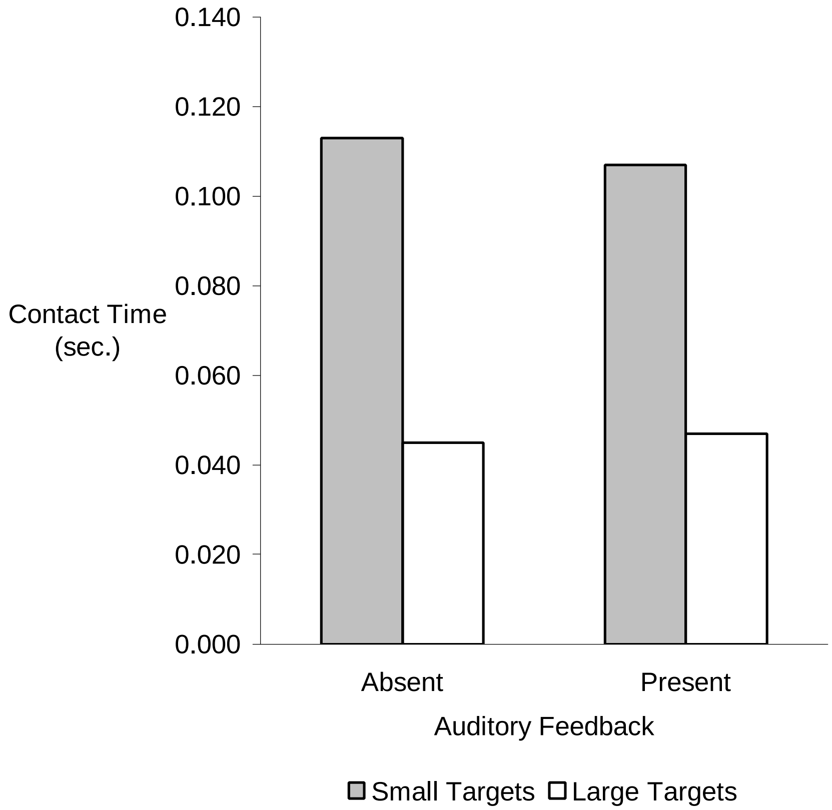
Simple effects tests were conducted on target size at each level of auditory feedback. A significant simple effect for target size with no auditory feedback was observed, $F(1, 31) = 40.344$, $p < .001$. A significant simple effect for target size with 100 ms auditory feedback was observed, $F(1, 31) = 55.004$, $p < .001$.

Analysis of the variances of contact time. A one-way ANOVA was conducted (Kirk, 1995). The independent variable was feedback (no auditory feedback or 100 ms auditory feedback). The variances of contact time are presented in Figure 6. The main effect for feedback was not significant, $F(31,31) = 1.554$, $p > .05$.

A one-way ANOVA was conducted (Kirk, 1995). The independent variable was target size (10 x 10 mm or 30 x 30 mm). The variances of contact time are presented in Figure 6. A significant main effect for target size was observed, $F(31,31) = 7.358$, $p < .001$.

Simple effects tests were conducted on target size at each level of auditory feedback. A significant simple effect for target size with no auditory feedback was observed, $F(31, 31) = 27.409$, $p < .001$. A significant simple effect for target size with 100 ms auditory feedback was observed, $F(31, 31) = 2.768$, $p < .01$.

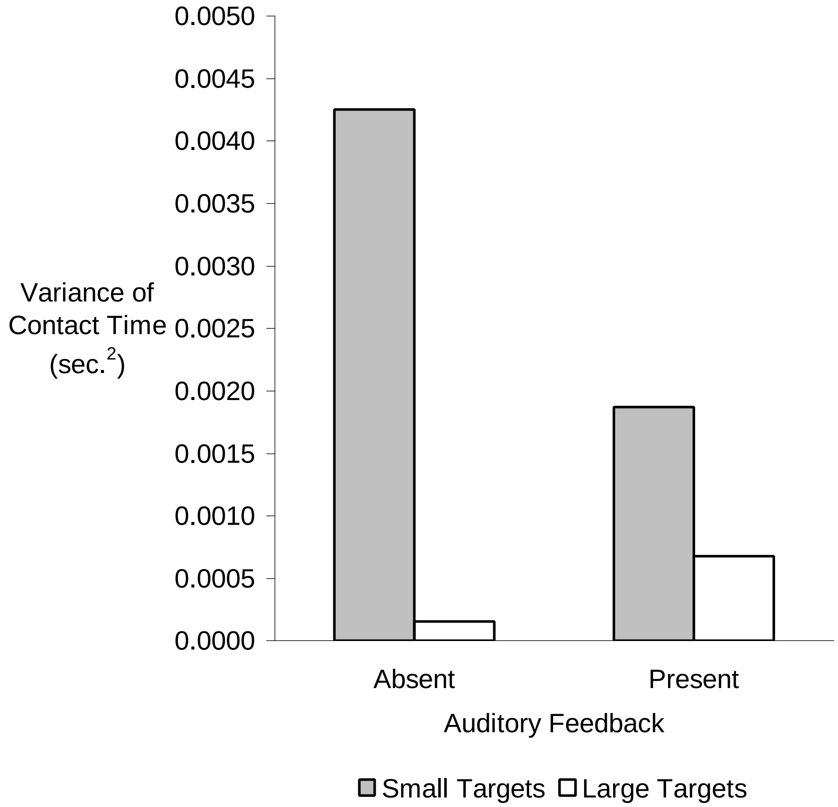
Figure 5. Experiment 1 mean contact time as a function of auditory feedback and target size.



Mean Contact Time (sec.)

	Absent	Present
Small Targets	0.113	0.107
Large Targets	0.045	0.047

Figure 6. Experiment 1 variance of contact time as a function of auditory feedback and target size.



Variance of Contact Time (sec.^{2})

	Absent	Present
Small Targets	0.0043	0.0019
Large Targets	0.0002	0.0007

Errors

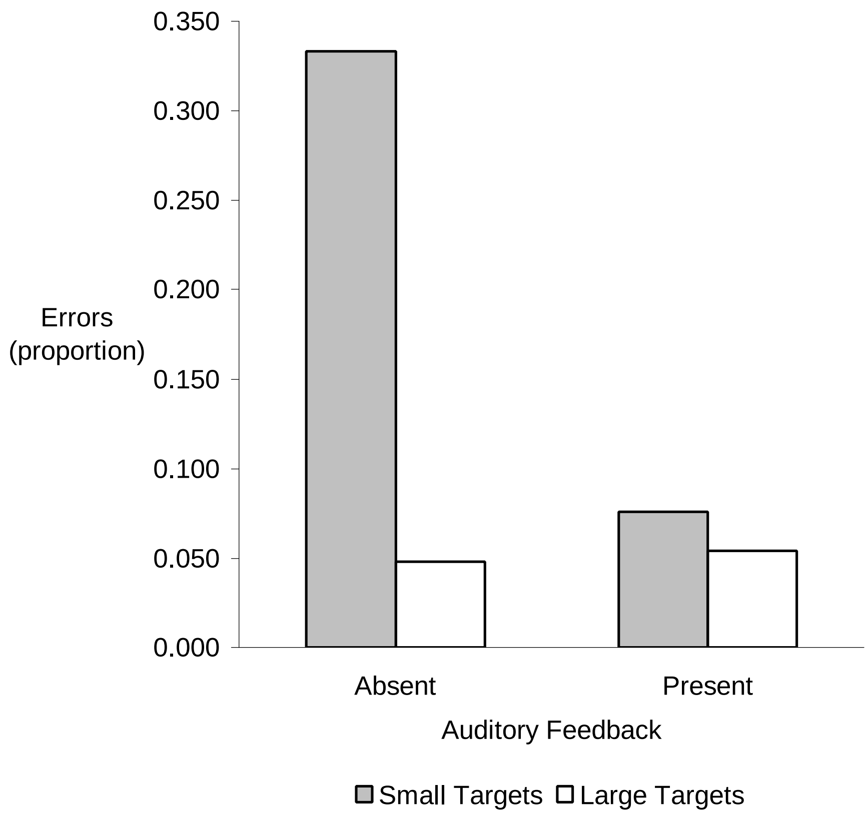
Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. The proportion of errors committed during the last 40 trials of each condition by each participant was calculated, yielding a single score for each participant in each condition. Heterogeneity of variance was found to be significant, $F_{max} = 14.24$, $p < .01$ (Kirk, 1995). Therefore, an inverse sine transformation (see Appendix G) was conducted (Kirk, 1995). Heterogeneity of variance of the transformed scores was not significant, $F_{max} = 2.64$, $p > .05$ (Kirk, 1995). All analyses were evaluated using a significance level of $p = .05$.

A 2 x 2 randomized block factorial ANOVA was conducted on the inverse sine transformed values (Kirk, 1995). The independent variables were feedback (no auditory feedback or 100 ms auditory feedback) and target size (10 x 10 mm or 30 x 30 mm). Non-transformed mean errors are presented in Figure 7. A significant interaction was observed, $F(1, 31) = 76.027$, $p < .001$; $eta^2 = .710$; 1 - ß = 1.000. A significant main effect for feedback was observed, $F(1, 31) = 65.412$, $p < .001$; $eta^2 = .678$; 1 - ß = 1.000. A significant main effect for target size was observed, $F(1, 31) = 115.206$, $p < .001$; $eta^2 = .788$; 1 - ß = 1.000.

Simple effects tests were conducted on auditory feedback at each target size. A significant simple effect for feedback with small targets was observed, $F(1, 31) = 86.319$, $p < .001$. The simple effect for feedback with large targets was not significant, $F(1, 31) = 1.122$, $p > .05$.

Simple effects tests were conducted on target size at each level of auditory feedback. A significant simple effect for target size with no auditory feedback was observed, $F(1, 31) = 169.907$, $p < .001$. The simple effect for target size with 100 ms auditory feedback was not significant, $F(1, 31) = 0.509$, $p > .05$.

Figure 7. Experiment 1 mean errors as a function of auditory feedback and target size.



Mean Errors (proportion)

	Absent	Present
Small Targets	0.333	0.076
Large Targets	0.048	0.054

Discussion

Experiment 1 revealed an important finding. The presence of auditory feedback greatly reduced the proportion of errors made with small targets in a ten-key entry task. This finding is important, as it justifies investigations into the specific nature of the auditory feedback signal. One possible interpretation of this finding is that auditory feedback becomes important as the difficulty of the task is increased, i.e., as target size decreases.

Movement Time

Both hypotheses regarding movement time were supported (see Table 1). Movement time differed as a function of auditory feedback and decreased as target size increased. The presence of auditory feedback slowed participants' movements with small targets. Participants may be waiting for the auditory feedback to signal that their touch was registered by the touch screen before moving to the next button. This effect was not observed with large targets, however, indicating that participants do not use the auditory feedback to signal that their touch was registered by the touch screen before moving to the next button. The observation that large target movement time was faster than small target movement time, regardless of feedback, supports previous research investigating the relationship between target size and movement time (Fitts, 1954; Plaisant & Sears, 1992; Sears, Revis, Swatski, Crittenden, & Shneiderman, 1993; Wilson et al., 1995).

Contact Time

One hypothesis regarding contact time was supported (see Table 1). Contact time decreased as target size increased. The observation that large target contact time was less than small target contact time, regardless of feedback, supports previous research investigating the relationship between target size and contact time (Adam & Paas, 1996). On the other hand, the results from the analyses of the variances of contact time are of greater interest. These analyses indicate that small targets cause greater variability in contact time than large targets, regardless of feedback. This finding provides additional empirical support for the use of large targets on touch screens.

Errors

Both hypotheses regarding errors were supported (see Table 1). Errors differed as a function of auditory feedback and decreased as target size increased. The presence of auditory feedback increases the accuracy of ten-key entry with small targets. Participants may be relying on the auditory feedback to signal that their touch was accurately registered by the touch screen. This effect was not observed with large targets, indicating that participants do not use the auditory feedback to signal that their touch was accurately registered by the touch screen.

The results from Experiment 1 justify further investigations into the specific nature of the auditory feedback signal. Therefore, Experiment 2 was conducted to determine if the duration of auditory feedback and target size impact movement time, contact time, and errors.

Table 1. Experiment 1 hypothesis support.

Hypothesis	Support (A significant difference was observed)
1. Touch screen ten-key entry movement time will be different in the presence of an auditory feedback signal than in the absence of an auditory feedback signal.	Yes
2. Touch screen ten-key entry contact time will be different in the presence of an auditory feedback signal than in the absence of an auditory feedback signal.	No
3. Touch screen ten-key entry errors will be different in the presence of an auditory feedback signal than in the absence of an auditory feedback signal.	Yes
4. Touch screen ten-key entry movement time will decrease as target size increases.	Yes
5. Touch screen ten-key entry contact time will decrease as target size increases.	Yes
6. Touch screen ten-key entry errors will decrease as target size increases.	Yes

CHAPTER IV

EXPERIMENT 2

The purpose of Experiment 2 was to determine if the duration of an auditory feedback signal differentially affects touch screen ten-key entry movement time, contact time, and/or errors.

Method

Apparatus & Materials

A 1000 Hz sine wave was used as the auditory feedback signal. The auditory feedback signal was presented at 65 dB(A) in a 55 dB(A) room (Deatherage, 1972). The center of each button on the ten-key pad was located 32 mm from the center of the nearest neighboring button (see Figures 1 and 2).

Design and Procedure

A 7 x 2 randomized block factorial design was used to test the effect of duration of auditory feedback and target size on touch screen ten-key entry performance. Duration of auditory feedback was manipulated within participants and contained seven levels: 12.5, 25, 50, 100, 200, 400, or 800 ms. Target size was manipulated within participants and contained two levels: 10 x 10 mm or 30 x 30 mm. Participants completed 14 blocks of 48 trials. The duration of the auditory feedback signal and target size were constant within blocks but randomized and counterbalanced across blocks.

Each trial began with the presentation of a pseudo-random sequence of four digits in the upper left-hand corner of the display. Upon completion of each trial, a new string of digits replaced the old string of digits and a new trial began. Participants required approximately 40 minutes to complete the experiment.

Results

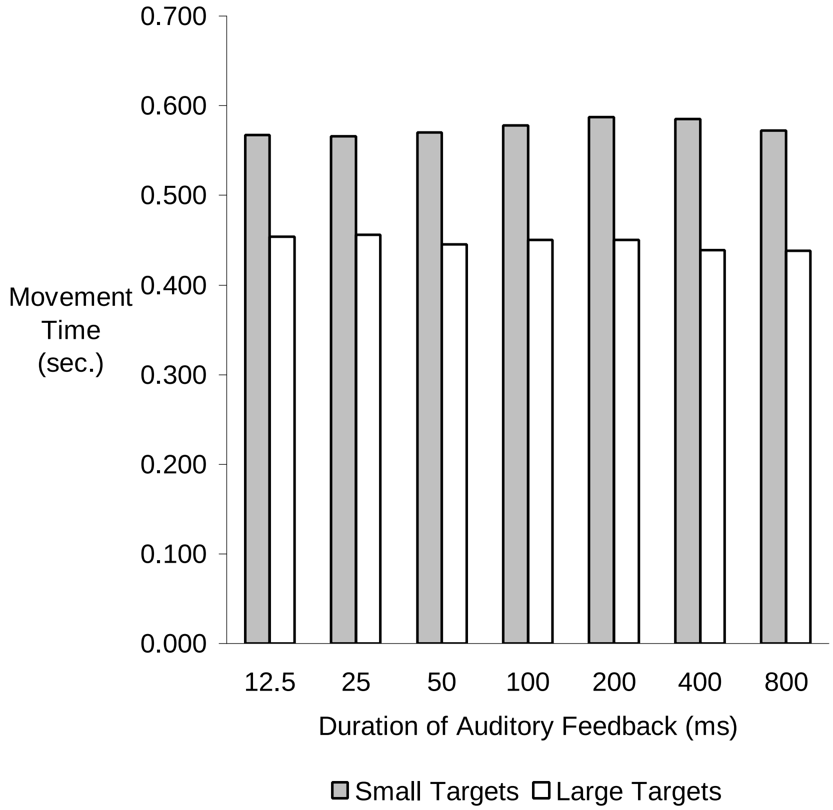
Movement Time

Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. Movement time data for each participant was averaged within each trial and across the last 40 trials, yielding a single score for each participant in each condition. Heterogeneity of variance was not significant, $F_{max} = 1.42$, $p > .05$ (Kirk, 1995). All analyses were evaluated using a significance level of $p = .05$.

A 7 x 2 randomized block factorial ANOVA was conducted (Kirk, 1995). The independent variables were the duration of auditory feedback (12.5, 25, 50, 100, 200, 400 or 800 ms) and target size (10 x 10 mm or 30 x 30 mm). Mean movement times are presented in Figure 8. A significant interaction was observed, $F(1, 31) = 2.162$, $p < .05$; $eta^2 = .065$; 1 - ß = 0.760. The main effect for duration of auditory feedback was not significant, $F(1, 31) = 1.182$, $p > .05$; $eta^2 = .037$; 1 - ß = 0.459. A significant main effect for target size was observed, $F(1, 31) = 307.152$, $p < .001$; $eta^2 = .908$; 1 - ß = 1.000.

Simple effects tests were conducted on target size at each duration of auditory feedback (see Table 2). At each duration of auditory feedback, large targets yielded significantly faster movement times than small targets.

Figure 8. Experiment 2 mean movement time as a function of the duration of auditory feedback and target size.



Mean Movement Time (sec.)

	12.5 ms	25 ms	50 ms	100 ms	200 ms	400 ms	800 ms
Small Targets	0.567	0.566	0.570	0.578	0.587	0.585	0.572
Large Targets	0.454	0.456	0.445	0.450	0.450	0.439	0.438

Table 2. Experiment 2 movement time simple effects F-test values conducted on target size at each duration of auditory feedback.

Duration of Auditory Feedback (ms)						
12.5	25	50	100	200	400	800
73.270***	131.709***	178.448***	187.862***	127.386***	161.982***	139.426***

*** indicates F-test values significant at $p < .001$

Contact Time

Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. Contact time data for each participant was averaged within each trial and across the last 40 trials, yielding a single score for each participant in each condition. Heterogeneity of variance was found to be significant, $F_{max} = 26.66$, $p < .01$ (Kirk, 1995). In an attempt to reduce heterogeneity of variance, square root, logarithmic, reciprocal, and inverse sine transformations (see Appendix G) were conducted (Kirk, 1995). Each transformation failed to yield homogeneity of variance. Therefore, the variances of contact time were analyzed in addition to the means of contact time. The analyses of the variances of contact time were evaluated using a significance level of $p = .05$. The analyses of the means of contact time were evaluated using a significance level of $p = .01$, to compensate for the heterogeneity of variance (Keppel, 1991).

Analysis of the means of contact time. A 7 x 2 randomized block factorial ANOVA was conducted (Kirk, 1995). The independent variables were the duration of auditory feedback (12.5, 25, 50, 100, 200, 400 or 800 ms) and target size (10 x 10 mm or 30 x 30 mm). Mean contact times are presented in Figure 9. The interaction was not significant, $F(1, 31) = 0.378$, $p > .05$; $eta^2 = .012$; $1 - ß = 0.157$. A significant main effect for duration of auditory feedback was observed, $F(1, 31) = 4.185$, $p < .001$; $eta^2 = .119$; $1 - ß = 0.976$. A significant main effect for target size was observed, $F(1, 31) = 126.501$, $p < .001$; $eta^2 = .803$; $1 - ß = 1.000$.

Simple effects tests were conducted on the duration of auditory feedback at each target size. The simple effect for feedback with small targets was not significant, $F(6, 186) = .877$, $p > .05$. A significant simple effect for feedback with large targets was observed, $F(6, 186) = 8.469$, $p < .001$.

Simple comparisons tests were conducted on feedback with large targets (see Table 3). Auditory feedback of 12.5, 25, 50, 100, 200, and 400 ms yielded significantly less contact time than 800 ms auditory feedback. Auditory feedback of 12.5, 25, and 50 ms yielded significantly less contact time than 400 ms auditory feedback. Auditory feedback of 50 ms yielded significantly less contact time than 200 ms auditory feedback.

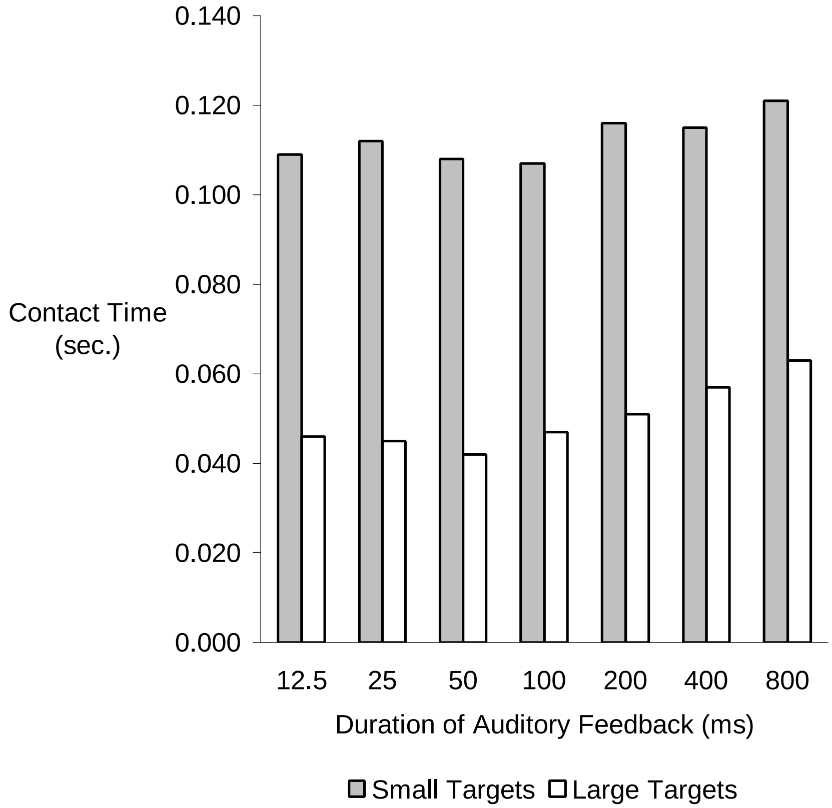
Simple effects tests were conducted on target size at each duration of auditory feedback (see Table 4). At each duration of auditory feedback, large targets yielded significantly less contact time than small targets.

Analysis of the variances of contact time. A one-way ANOVA was conducted (Kirk, 1995). The independent variable was the duration of auditory feedback (12.5, 25, 50, 100, 200, 400 or 800 ms). The variances of contact time are presented in Figure 10. The main effect for duration of auditory feedback was not significant, $F(31,31) = 1.328$, $p > .05$.

A one-way ANOVA was conducted (Kirk, 1995). The independent variable was target size (10 x 10 mm or 30 x 30 mm). The variances of contact time are presented in Figure 10. A significant main effect for target size was observed, $F(31,31) = 5.847$, $p < .001$.

Simple effects tests were conducted on target size at each duration of auditory feedback (see Table 5). At each duration of auditory feedback, large targets yielded significantly less contact time than small targets.

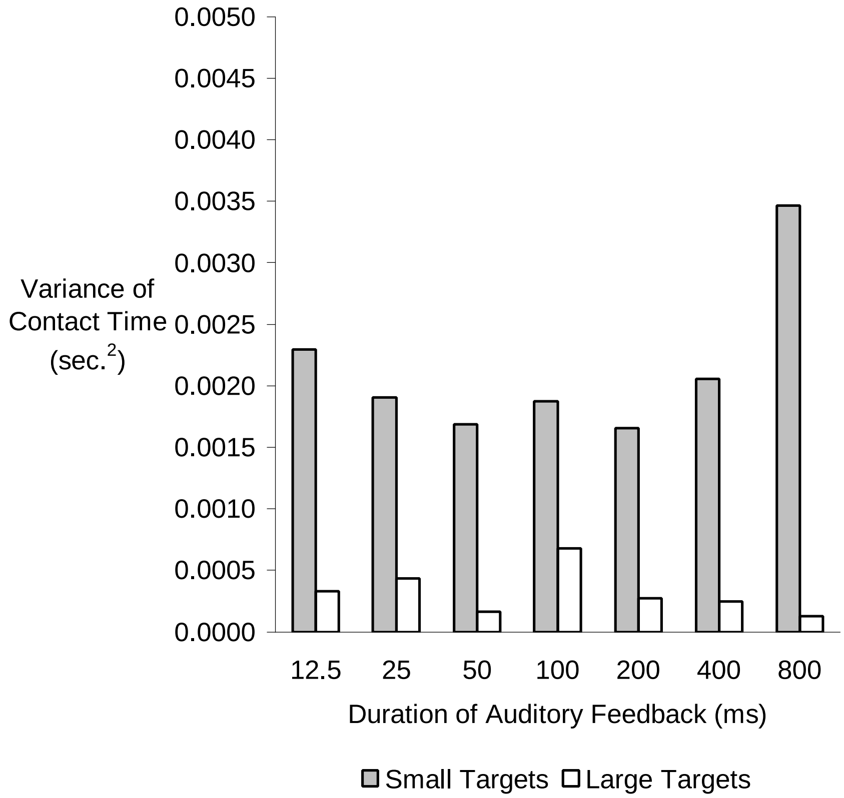
Figure 9. Experiment 2 mean contact time as a function of the duration of auditory feedback and target size.



Mean Contact Time (sec.)

	12.5 ms	25 ms	50 ms	100 ms	200 ms	400 ms	800 ms
Small Targets	0.109	0.112	0.108	0.107	0.116	0.115	0.121
Large Targets	0.046	0.045	0.042	0.047	0.051	0.057	0.063

Figure 10. Experiment 2 variance of contact time as a function of the duration of auditory feedback and target size.



Variance of Contact Time (sec.^{2})

	12.5 ms	25 ms	50 ms	100 ms	200 ms	400 ms	800 ms
Small Targets	0.0023	0.0019	0.0017	0.0019	0.0017	0.0021	0.0035
Large Targets	0.0003	0.0004	0.0002	0.0007	0.0003	0.0002	0.0001

Table 3. Experiment 2 contact time simple pairwise comparisons F-test values conducted on duration of auditory feedback with large targets.

		Duration of Auditory Feedback (ms)					
		25	50	100	200	400	800
	12.5	0.039	3.053	0.068	2.846	9.199**	27.385***
Duration of	25		1.330	0.123	1.871	17.825***	33.133***
Auditory	50			1.520	17.180***	38.493***	103.544***
Feedback	100				0.534	3.905	16.522***
(ms)	200					3.712	14.889***
	400						6.002*

* indicates F-test values significant at $p < .05$

** indicates F-test values significant at $p < .01$

*** indicates F-test values significant at $p < .001$

Table 4. Experiment 2 contact time simple comparisons F-test values conducted on target size at each duration of auditory feedback.

Duration of Auditory Feedback (ms)						
12.5	25	50	100	200	400	800
68.297***	79.931***	104.501***	55.004***	78.292***	54.232***	37.779***

*** indicates F-test values significant at $p < .001$

Table 5. Experiment 2 contact time variance simple effects F-test values conducted on target size at each duration of auditory feedback.

Duration of Auditory Feedback (ms)						
12.5	25	50	100	200	400	800
7.004***	4.378***	10.230***	2.768**	6.014***	8.244***	26.656***

** indicates F-test values significant at $p < .01$

*** indicates F-test values significant at $p < .001$

Errors

Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. The proportion of errors committed during the last 40 trials of each condition by each participant was calculated, yielding a single score for each participant in each condition. Heterogeneity of variance was found to be significant, $F_{max} = 15.94$, $p < .01$ (Kirk, 1995). Therefore, an inverse sine transformation (see Appendix G) was conducted (Kirk, 1995). Heterogeneity of variance of the transformed scores was not significant, $F_{max} = 5.29$, $p > .05$ (Kirk, 1995). All analyses were evaluated using a significance level of $p = .05$.

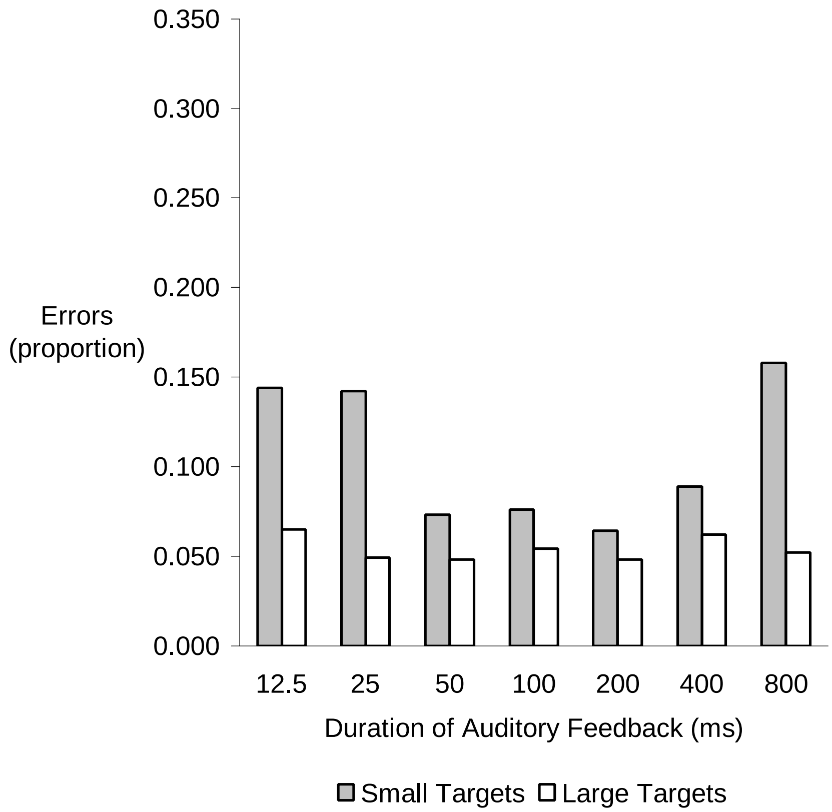
A 7 x 2 randomized block factorial ANOVA was conducted on the inverse sine transformed values (Kirk, 1995). The independent variables were the duration of auditory feedback (12.5, 25, 50, 100, 200, 400 or 800 ms) and target size (10 x 10 mm or 30 x 30 mm). Non-transformed mean errors are presented in Figure 11. A significant interaction was observed, $F(1, 31) = 5.013$, $p < .001$; $eta^2 = .139$; 1 - ß = 0.992. A significant main effect for duration of auditory feedback was observed, $F(1, 31) = 5.919$, $p < .001$; $eta^2 = .160$; 1 - ß = 0.998. A significant main effect for target size was observed, $F(1, 31) = 21.540$, $p < .001$; $eta^2 = .410$; 1 - ß = 0.994.

Simple effects tests were conducted on the duration of auditory feedback at each target size. A significant simple effect for feedback with small targets was observed, $F(6, 186) = 7.497$, $p < .001$. The simple effect for feedback with large targets was not significant, $F(6, 186) = .869$, $p > .05$.

Simple comparisons tests were conducted on feedback with small targets (see Table 6). Auditory feedback of 50, 100, 200, and 400 ms yielded significantly fewer errors than 12.5, 25, and 800 ms auditory feedback.

Simple effects tests were conducted on target size at each duration of auditory feedback (see Table 7). With 12.5, 25, and 800 ms auditory feedback, large targets yielded significantly fewer errors than small targets.

Figure 11. Experiment 2 mean errors as a function of the duration of auditory feedback and target size.



Mean Errors (proportion)

	12.5 ms	25 ms	50 ms	100 ms	200 ms	400 ms	800 ms
Small Targets	0.144	0.142	0.073	0.076	0.064	0.089	0.158
Large Targets	0.065	0.049	0.048	0.054	0.048	0.062	0.052

Table 6. Experiment 2 error simple pairwise comparisons F-test values conducted on duration of auditory feedback with small targets.

		Duration of Auditory Feedback (ms)					
		25	50	100	200	400	800
	12.5	0.413	12.142***	21.261***	29.532***	10.486**	0.000
Duration of	25		7.714**	13.169***	14.471***	4.530*	0.674
Auditory	50			0.007	0.159	0.405	12.093**
Feedback	100				0.265	0.439	18.080***
(ms)	200					1.271	18.815***
	400						8.781**

* indicates F-test values significant at $p < .05$

** indicates F-test values significant at $p < .01$

*** indicates F-test values significant at $p < .001$

Table 7. Experiment 2 error simple comparisons F-test values conducted on target size at each duration of auditory feedback.

Duration of Auditory Feedback (ms)						
12.5	25	50	100	200	400	800
23.293***	13.193***	1.787	0.509	0.928	0.647	23.756***

*** indicates F-test values significant at p < .001

Discussion

Experiment 2 revealed an important finding. The optimal range for the duration of auditory feedback within which ten-key entry performance with small targets is superior is between 50 and 400 ms. Specifically, auditory feedback within this range greatly reduces the proportion of errors committed in a ten-key entry task. This finding, that human performance is optimal across a range of values, is consistent with a substantial portion of the human factors literature (Boff & Lincoln, 1988; Helander, Landauer, & Prabhu, 1997; Salvendy, 1997; Sanders & McCormick, 1993). One possible interpretation of this finding is that the duration of auditory feedback becomes important as the difficulty of the task is increased, i.e., as target size decreases.

Movement Time

One hypothesis regarding movement time was supported (see Table 8). Movement time decreased as target size increased. The observation that large target movement time was faster than small target movement time, regardless of the duration of auditory feedback, supports previous research investigating the relationship between target size and movement time (Fitts, 1954; Plaisant & Sears, 1992; Sears et al., 1993; Wilson et al., 1995).

Contact Time

Both hypotheses regarding contact time were supported (see Table 8). Contact time differed as a function of the duration of auditory feedback and contact time decreased as target size increased. With large targets, contact time increased as the duration of auditory feedback increased. The long durations of auditory feedback overlapped one another. Participants may have maintained contact with the screen longer in order to confirm that their touch was registered by the touch screen. This effect was not observed with small targets, possibly due to the greater variance associated with small targets. The observation that large target contact time was less than small target contact time, regardless of the duration of auditory feedback, supports previous research investigating the relationship between target size and contact time (Adam & Paas, 1996). The results from the analyses of the variances of contact time are also interesting. These analyses indicate that small targets cause greater variability in contact time than large targets, regardless of the duration of auditory feedback. This finding provides additional empirical support for the use of large targets on touch screens.

Errors

Both hypotheses regarding errors were supported (see Table 8). Errors differed as a function of the duration of auditory feedback and errors decreased as target size increased. With small targets, error rates were reduced when 50, 100, 200, or 400 ms auditory feedback was used. Auditory feedback outside of this range, either less than 50 ms or greater than 400 ms, increased errors substantially. This effect was not observed with large targets, indicating that participants do not use the auditory feedback to signal that their touch was accurately registered by the touch screen.

The results from Experiment 2 are encouraging. Error rates were dependent on the duration of auditory feedback. However, Experiment 2 took place in a somewhat unrealistic laboratory setting. Therefore, Experiment 3 was conducted to determine if the duration of the auditory feedback signal and target size impact movement time, contact time, and errors in a setting with higher fidelity.

Table 8. Experiment 2 hypothesis support.

Hypothesis	Support (A significant difference was observed)
1. Touch screen ten-key entry movement time will differ as a function of the duration of the auditory feedback signal.	No
2. Touch screen ten-key entry contact time will differ as a function of the duration of the auditory feedback signal.	Yes
3. Touch screen ten-key entry errors will differ as a function of the duration of the auditory feedback signal.	Yes
4. Touch screen ten-key entry movement time will decrease as target size increases.	Yes
5. Touch screen ten-key entry contact time will decrease as target size increases.	Yes
6. Touch screen ten-key entry errors will decrease as target size increases.	Yes

CHAPTER V

EXPERIMENT 3

The purpose of Experiment 3 was to validate the differences observed in Experiment 2 in a setting with higher fidelity. Higher fidelity was achieved by requiring participants to handle packages, listen to recorded store noise, and use a ten-key pad with small targets located close together.

Method

Apparatus & Materials

A 1000 Hz sine wave was used as the auditory feedback signal. The auditory feedback signal was presented at 80 dB(A) (Deatherage, 1972). Recorded store noise was reproduced at 70 dB(A) (Bender, 1998a) using a AIWA CA-DW530 portable stereo (see Appendix D). The center of each button on the ten-key pad with small targets (10 x 10 mm) was located 12 mm from the center of the nearest neighboring button (see Figure 3). The center of each button on the ten-key pad with large targets (30 x 30 mm) was located 32 mm from the center of the nearest neighboring button (see Figure 1).

Design and Procedure

A 2 x 2 randomized block factorial design was used to test the effect of duration of auditory feedback and target size on touch screen ten-key entry performance. Duration of auditory feedback was manipulated within participants and contained two levels: 200 or 800 ms. These values were chosen based on the results from Experiment 2 and previous research (Stevens & Davis, 1938). The results from Experiment 2 suggest that the duration of auditory feedback that results in the fewest errors is 200 ms. Likewise, the results from Experiment 2 suggest that the duration of auditory feedback that results in the most errors is 800 ms. Target size was manipulated within participants and contained two levels: 10 x 10 mm or 30 x 30 mm.

Participants completed 4 blocks of 48 trials. The duration of the auditory feedback signal and target size were constant within blocks but randomized and counterbalanced across blocks.

Each trial began with the participant picking up a videotape labeled with a pseudo-random sequence of four digits on the face of the video tape. Upon completion of each trial, participants set the video tape aside and began a new trial by picking up a another video tape. Participants required approximately 15 minutes to complete the experiment.

Results

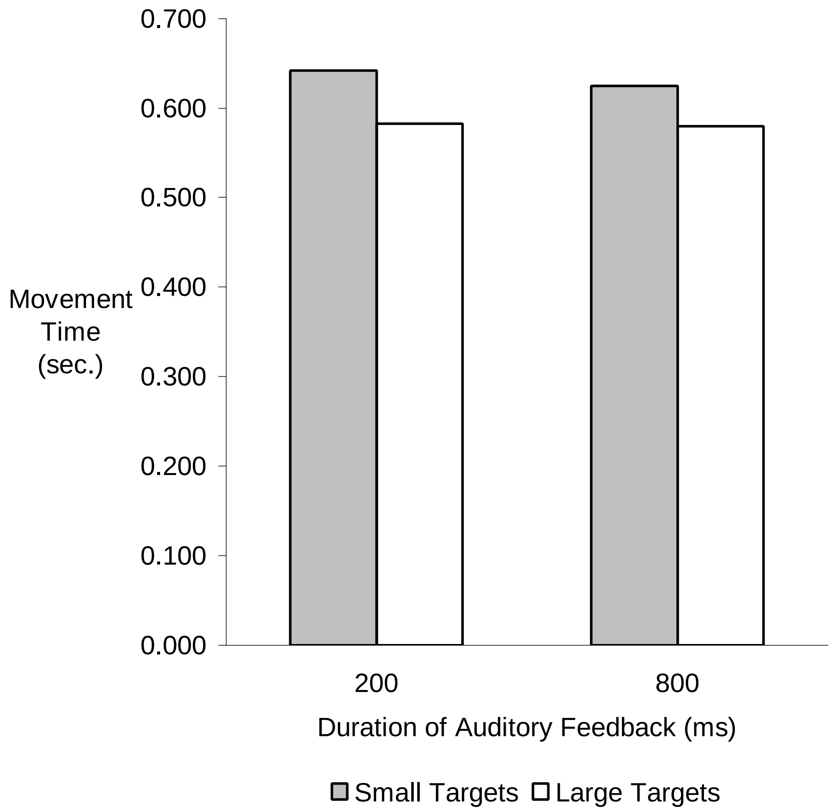
Movement Time

Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. Movement time data for each participant was averaged within each trial and across the last 40 trials, yielding a single score for each participant in each condition. Heterogeneity of variance was not significant, $F_{max} = 1.26$, $p > .05$ (Kirk, 1995). All analyses were evaluated using a significance level of $p = .05$.

A 2 x 2 randomized block factorial ANOVA was conducted (Kirk, 1995). The independent variables were the duration of auditory feedback (200 or 800 ms) and target size (10 x 10 mm or 30 x 30 mm). Mean movement times are presented in Figure 12. The interaction was not significant, $F(1, 30) = 1.297$, $p > .05$; $eta^2 = .041$; $1 - ß = 0.197$. The main effect for duration of auditory feedback was not significant, $F(1, 30) = 1.530$, $p > .05$; $eta^2 = .049$; $1 - ß = 0.224$. A significant main effect for target size was observed, $F(1, 30) = 28.439$, $p < .001$; $eta^2 = .487$; $1 - ß = 0.999$.

Simple effects tests were conducted on target size at each duration of auditory feedback. A significant simple effect for target size with 200 ms auditory feedback was observed, $F(1, 31) = 19.134$, $p < .001$. A significant simple effect for target size with 800 ms auditory feedback was observed, $F(1, 31) = 22.880$, $p < .001$.

Figure 12. Experiment 3 mean movement time as a function of the duration of auditory feedback and target size.



Mean Movement Time (sec.)

	200 ms	800 ms
Small Targets	0.642	0.625
Large Targets	0.583	0.580

Contact Time

Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. Contact time data for each participant was averaged within each trial and across the last 40 trials, yielding a single score for each participant in each condition. Heterogeneity of variance was found to be significant, $F_{max} = 37.89$, $p < .01$ (Kirk, 1995). In an attempt to reduce heterogeneity of variance, square root, logarithmic, reciprocal, and inverse sine transformations (see Appendix G) were conducted (Kirk, 1995). Each transformation failed to yield homogeneity of variance. Therefore, the variances of contact time were analyzed in addition to the means of contact time. The analyses of the variances of contact time were evaluated using a significance level of $p = .05$. The analyses of the means of contact time were evaluated using a significance level of $p = .01$, to compensate for the heterogeneity of variance (Keppel, 1991).

Analysis of the means of contact time. A 2 x 2 randomized block factorial ANOVA was conducted (Kirk, 1995). The independent variables were the duration of auditory feedback (200 or 800 ms) and target size (10 x 10 mm or 30 x 30 mm). Mean contact times are presented in Figure 13. A significant interaction was observed, $F(1, 30) = 5.903$, $p < .05$; $eta^2 = .164$; $1 - ß = 0.652$. The main effect for duration of auditory feedback was not significant, $F(1, 30) = 0.837$, $p > .05$; $eta^2 = .027$; $1 - ß = 0.144$. A significant main effect for target size was observed, $F(1, 30) = 29.462$, $p < .001$; $eta^2 = .495$; $1 - ß = 0.999$.

Simple effects tests were conducted on target size at each duration of auditory feedback. A significant simple effect for target size with 200 ms auditory feedback was observed, $F(1, 31) = 23.407$, $p < .001$. A significant simple effect for target size with 800 ms auditory feedback was observed, $F(1, 31) = 20.685$, $p < .001$.

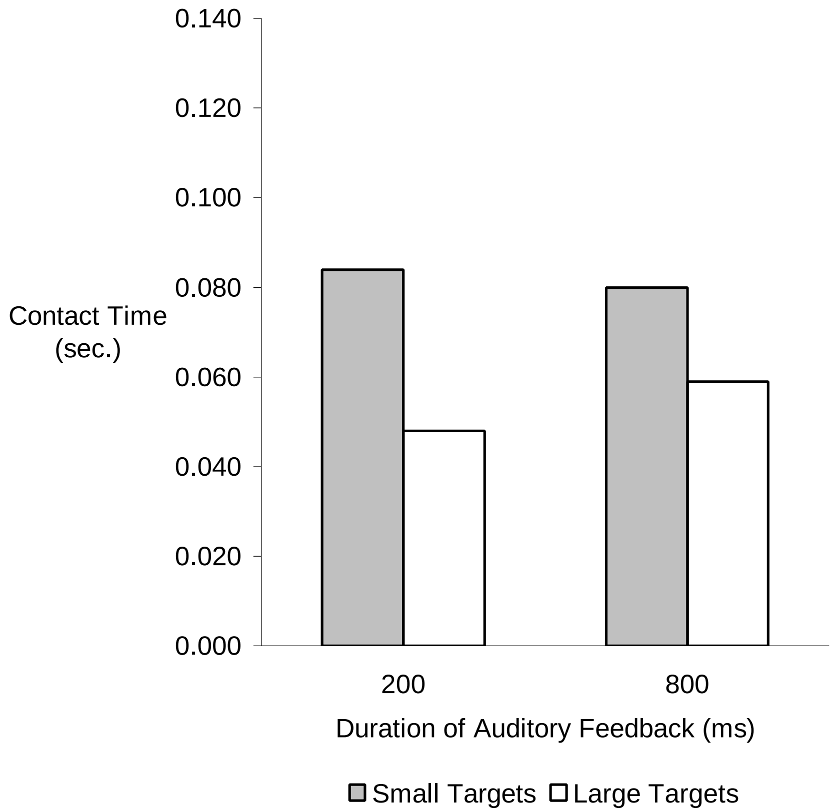
Analysis of the variances of contact time. A one-way ANOVA was conducted (Kirk, 1995). The independent variable was the duration of auditory feedback (200 or 800 ms). The variances of contact time are presented in Figure 14. A significant main effect for duration of auditory feedback was observed, $F(31,31) = 2.152$, $p < .05$.

Simple effects tests were conducted on the duration of auditory feedback at each target size. A significant simple effect for duration of auditory feedback with small targets was observed, $F(31, 31) = 2.012$, $p < .05$. The simple effect for duration of auditory feedback with large targets was not significant, $F(31, 31) = 1.060$, $p > .05$.

A one-way ANOVA was conducted (Kirk, 1995). The independent variable was target size (10 x 10 mm or 30 x 30 mm). The variances of contact time are presented in Figure 14. A significant main effect for target size was observed, $F(31,31) = 17.763$, $p < .001$.

Simple effects tests were conducted on target size at each duration of auditory feedback. A significant simple effect for target size with 200 ms auditory feedback was observed, $F(31, 31) = 35.739$, $p < .001$. A significant simple effect for target size with 800 ms auditory feedback was observed, $F(31, 31) = 18.834$, $p < .001$.

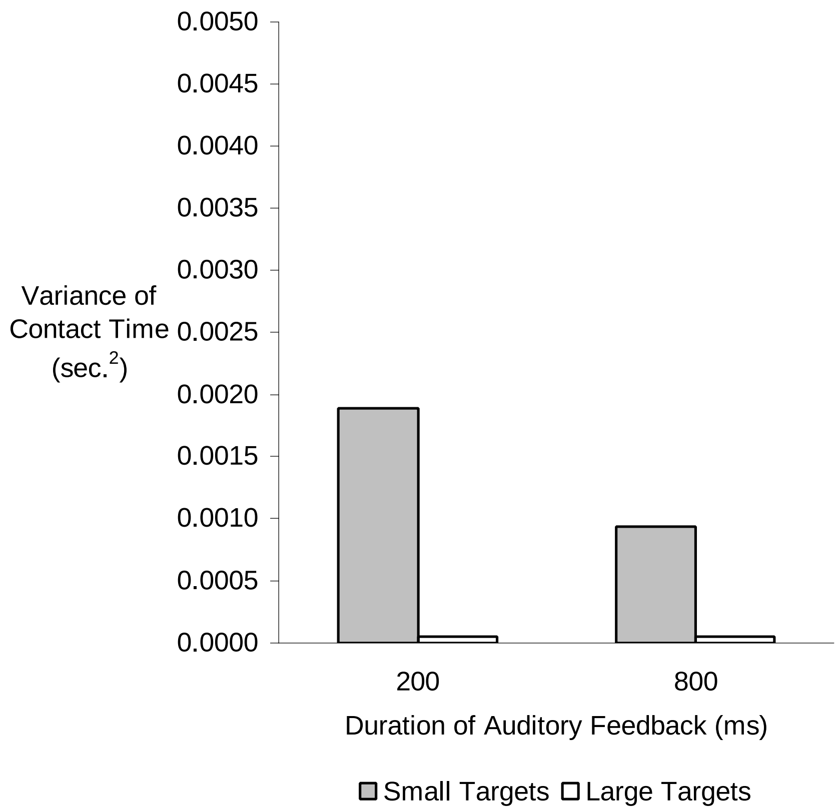
Figure 13. Experiment 3 mean contact time as a function of the duration of auditory feedback and target size.



Mean Contact Time (sec.)

	200 ms	800 ms
Small Targets	0.084	0.080
Large Targets	0.048	0.059

Figure 14. Experiment 3 variance of contact time as a function of the duration of auditory feedback and target size.



Variance of Contact Time (sec.^{2})

	200 ms	800 ms
Small Targets	0.0019	0.0009
Large Targets	0.0001	0.0001

Errors

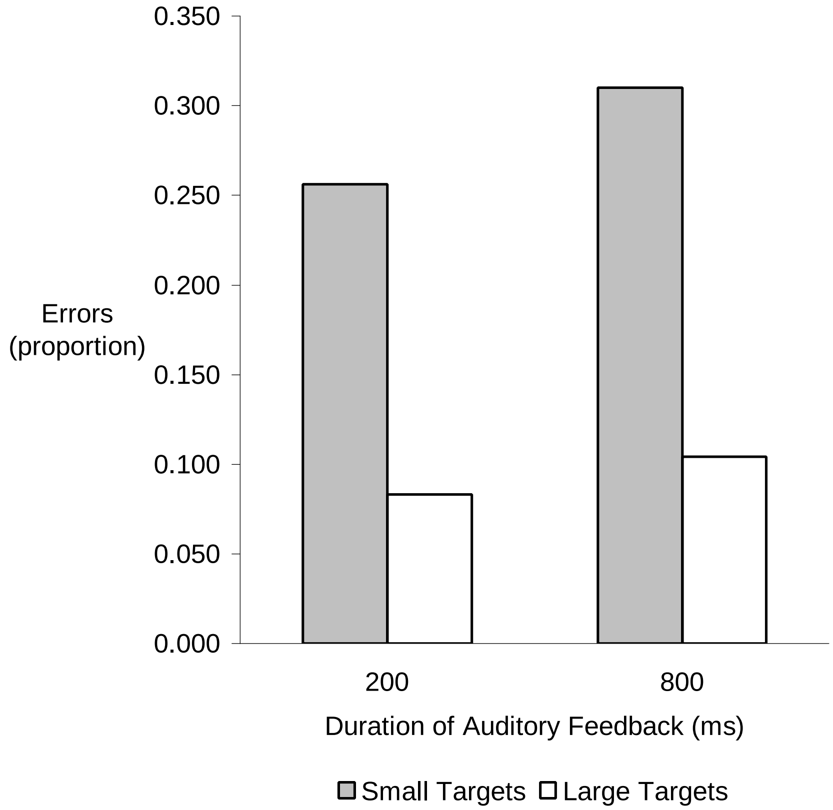
Examination of the 48 trials within each condition revealed that participants reached asymptotic performance after eight trials. Therefore, the first eight trials of each condition were considered practice and removed prior to data analysis. No outliers were detected. The proportion of errors committed during the last 40 trials of each condition by each participant was calculated, yielding a single score for each participant in each condition. Heterogeneity of variance was found to be significant, $F_{max} = 7.85$, $p < .01$ (Kirk, 1995). Therefore, an inverse sine transformation (see Appendix G) was conducted (Kirk, 1995). Heterogeneity of variance of the transformed scores was not significant, $F_{max} = 3.52$, $p > .05$ (Kirk, 1995). All analyses were evaluated using a significance level of $p = .05$.

A 2 x 2 randomized block factorial ANOVA was conducted on the inverse sine transformed values (Kirk, 1995). The independent variables were the duration of auditory feedback (200 or 800 ms) and target size (10 x 10 mm or 30 x 30 mm). Non-transformed mean errors are presented in Figure 15. The interaction was not significant, $F(1, 30) = 1.919$, $p > .05$; $eta^2 = .060$; 1 - ß = 0.268. A significant main effect for duration of auditory feedback was observed, $F(1, 30) = 8.115$, $p < .01$; $eta^2 = .213$; 1 - ß = 0.787. A significant main effect for target size was observed, $F(1, 30) = 114.033$, $p < .001$; $eta^2 = .792$; 1 - ß = 1.000.

Simple effects tests were conducted on the duration of auditory feedback at each target size. A significant simple effect for feedback with small targets was observed, $F(1, 31) = 8.402$, $p < .01$. The simple effect for feedback with large targets was not significant, $F(1, 31) = 0.366$, $p > .05$.

Simple effects tests were conducted on target size at each duration of auditory feedback. A significant simple effect for target size with 200 ms auditory feedback was observed, $F(1, 31) = 50.635$, $p < .001$. A significant simple effect for target size with 800 ms auditory feedback was observed, $F(1, 31) = 83.044$, $p < .001$.

Figure 15. Experiment 3 mean errors as a function of the duration of auditory feedback and target size.



Mean Errors (proportion)

	200 ms	800 ms
Small Targets	0.256	0.310
Large Targets	0.083	0.104

Discussion

Experiment 3 revealed an important finding. With small targets, 200 ms auditory feedback resulted in fewer errors than 800 ms auditory feedback. This finding replicates the findings from Experiment 2 in a setting with higher fidelity. One possible interpretation of this finding is that auditory feedback becomes important as the difficulty of the task is increased, i.e., as target size decreases.

Movement Time

One hypothesis regarding movement time was supported (see Table 9). Movement time decreased as target size increased. The observation that large target movement time was faster than small target movement time, regardless of the duration of auditory feedback, supports previous research investigating the relationship between target size and movement time (Fitts, 1954; Plaisant & Sears, 1992; Sears et al., 1993; Wilson et al., 1995).

Contact Time

One hypothesis regarding contact time was supported (see Table 9). Contact time decreased as target size increased. The observation that large target contact time was less than small target contact time, regardless of the duration of auditory feedback, supports previous research investigating the relationship between target size and contact time (Adam & Paas, 1996). The results from the analysis of the variances of contact time are also interesting. These analyses indicate that small targets cause greater variability in contact time than large targets, regardless of the duration of auditory feedback. This finding provides additional empirical support for the use of large targets on touch screens.

Errors

Both hypotheses regarding errors were supported (see Table 9). Errors differed as a function of the duration of auditory feedback and errors decreased as target size increased. The observation that small target errors were fewer with 200 ms auditory feedback is interesting. The duration of auditory feedback affects the accuracy with which participants perform ten-key entry.

This effect was not observed with large targets, indicating that participants do not use the auditory feedback to signal that their touch was accurately registered by the touch screen. The observation that large target errors were less than small target errors, regardless of the duration of auditory feedback, supports previous research investigating the relationship between target size and errors (Fitts, 1954; Plaisant & Sears, 1992; Sears et al., 1993; Wilson et al., 1995).

Table 9. Experiment 3 hypothesis support.

Hypothesis	Support (A significant difference was observed)
1. Touch screen ten-key entry movement time will be different in the presence of the 200 ms auditory feedback signal than the 800 ms auditory feedback signal.	No
2. Touch screen ten-key entry contact time will be different in the presence of the 200 ms auditory feedback signal than the 800 ms auditory feedback signal.	No
3. Touch screen ten-key entry errors will be different in the presence of the 200 ms auditory feedback signal than the 800 ms auditory feedback signal.	Yes
4. Touch screen ten-key entry movement time will decrease as target size increases.	Yes
5. Touch screen ten-key entry contact time will decrease as target size increases.	Yes
6. Touch screen ten-key entry errors will decrease as target size increases.	Yes

CHAPTER VI

GENERAL DISCUSSION

An interesting pattern of results emerges from these experiments with important implications for software design. In the discussion that follows, the effect of the auditory feedback and target size manipulations on each dependent variable are examined.

Movement Time

Movement time was mostly unaffected by the auditory feedback manipulations. The only exception to this pattern occurred with small targets in Experiment 1. In this situation, movement time increased in the presence of auditory feedback. The effect was small, but may indicate that auditory feedback disrupts movements to small targets. Participants may have been waiting for the auditory feedback signal to confirm that their touch was registered by the computer prior to moving to a subsequent target.

The target size results, as expected, are consistent with the predictions of Fitts Law (Fitts, 1954; Fitts & Peterson, 1964). Across all three experiments, large targets were associated with shorter movement times than small targets. When moving to large targets, participants are not required to constrain the final position of their finger to the same degree as with small targets. Constraining the final position of the finger requires a certain amount of time. Therefore, large targets can be acquired quicker than small targets. This effect emphasizes the speed benefit of using large targets in a touch screen environment.

In summary, the auditory feedback manipulations had little impact on touch screen ten-key entry movement time. Target size, however, is critical to touch screen ten-key entry movement time (Sears et al., 1993; Wilson et al., 1995). Therefore, the use of large targets on touch screens is recommended.

Contact Time

Contact time was mostly unaffected by the auditory feedback manipulations. The only exception to this pattern occurred with large targets in Experiment 2. In this situation, contact time increased as the duration of auditory feedback increased. One possible interpretation of this finding is that participants kept their fingers in contact with the screen longer in order to rely on the tactile feedback from the screen. The tactile feedback may be necessary because lengthy auditory feedback signals overlap one another. That is, the feedback signal initiated by acquiring one target may still be audible when acquiring a subsequent target. Under these circumstances, the auditory signal is not feedback. Thus, another form of feedback (e.g., tactile) may be needed. Except for this one effect, however, contact time was unaffected by the auditory feedback manipulations.

The target size results, as expected, replicate studies investigating dwell time (Adam, 1992; Adam & Paas, 1996; Guiard, 1993). That is, participants spent less time in contact with large targets than small targets. One possible interpretation of this finding is that the amount of time spent in contact with a touch screen may be an indication of the difficulty of the task. That is, participants may be remaining in contact with the touch screen longer in order to visually verify that their finger has acquired the target or to program their movement to a subsequent target (Adam, 1992; Adam & Paas, 1996; Guiard, 1993). When acquiring targets, participants rely on the tactile feedback they receive from touching the screen, the auditory feedback provided by the computer, and/or the visual feedback they receive when their finger is inside the boundaries of a target. One possible reason performance with large targets was better than performance with small targets is that participants can more easily visually verify that their finger is inside the boundaries of large targets. Large targets afford quick visual verification of target acquisition and participants may not need to remain in contact with them very long in order to confirm that the target has been acquired. Small targets do not afford quick visual verification of target acquisition and participants may need to remain in contact with the screen longer in order to confirm that the target was successfully acquired.

Yet another finding is that contact time with small targets was characterized by more variability than large targets. This finding provides additional support for the argument that contact time is an indication of the difficulty of the target acquisition task because one characteristic of difficult tasks is greater variability. These experiments were not designed to directly address this idea and future research is certainly necessary.

In summary, it may be tempting to disregard contact time as an important variable due to its brief nature. However, contact time may be an indicator of task difficulty. Therefore, if it is important to minimize the length of time spent in contact with a touch screen in a ten-key entry task, then large targets should be used because large targets allow faster judgement of target acquisition than small targets. Additionally, avoiding auditory feedback longer than 100 ms may also minimize contact time with the touch screen.

Errors

Errors were dependent on the auditory feedback manipulations, but only for small targets. The pattern of results that emerged across the three experiments for errors associated with small targets is quite interesting. First, Experiment 1 showed that errors were reduced by providing auditory feedback. Second, Experiment 2 demonstrated that there is an optimal range (50 to 400 ms) for the duration of auditory feedback. Third, the differences observed in Experiment 2 were replicated in Experiment 3 under higher fidelity conditions. These results are important and raise further questions. First, why did 12.5 and 25 ms auditory feedback result in poorer error performance than 50 to 400 ms auditory feedback? Second, why did 800 ms auditory feedback result in poorer error performance than 50 to 400 ms auditory feedback? Third, why did the error rates escalate from Experiment 2 to Experiment 3?

First, was the poor error performance associated with 12.5 and 25 ms auditory feedback an audibility or a duration effect? That is, were participants able to hear 12.5 and 25 ms auditory feedback signals? All auditory feedback signals were presented at the same decibel level. However, the law of reciprocity indicates that the loudness of two sounds, one with a longer duration and a lower intensity and one with a shorter duration and a higher intensity, will be perceived as equivalent. Therefore, since the intensity of the brief sounds were not increased to compensate for this effect, it is possible that the brief sounds were not audible. A post hoc study was conducted to evaluate this idea.[1] All participants indicated that they heard all of the auditory feedback signals. Therefore, the fact that error rates were higher with 12.5 and 25 ms auditory feedback appears to be due to a duration effect rather than and audibility effect. Although the 12.5 and 25 ms auditory feedback signals were audible, it is possible that participants may not have believed that these signals were feedback because they were extremely brief.

Second, why did 800 ms auditory feedback result in poorer error performance than 50 to 400 ms auditory feedback? The likely explanation is that the 800 ms auditory feedback overlapped participants' movement and contact times. That is, the 800 ms feedback from the acquisition of a target is so long that it is still audible when acquiring a subsequent target. As one auditory signal is immediately followed by another auditory signal, participants are essentially in a no feedback condition and may ignore the auditory feedback altogether. Even though error rates were higher with 800 ms feedback than 50 to 400 ms feedback, post hoc dependent samples t-tests confirm that error rates for 800 ms feedback in Experiment 2 (Coefficient of Variation = 92.1%) were less than the error rates with the absence of feedback in Experiment 1 (Coefficient

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[1] Six participants took part in an auditory threshold study using the method of constant stimuli. Each auditory feedback signal was presented three times in random order. Participants indicated that they heard a sound by raising their hand. The auditory feedback signals were presented at the same intensity and in the same environmental conditions as those present during Experiment 2. All participants indicated that they heard each auditory feedback signal on each presentation of the signal.

of Variation = 46.2%), t(32) = 5.438, $p < .001$. This indicates that even the longest duration of auditory feedback tested is still better than providing no feedback with regard to error rates. So, if the 800 ms auditory signal condition is providing no feedback, then why were fewer errors committed in this condition than in the no feedback condition present in Experiment 1? At least two explanations are apparent. First, although participants movement times averaged less than 800 ms, there were certainly movements that exceeded 800 ms. Therefore, during these longer movements, participants were receiving feedback. Second, slight speaker noise was present when one signal was interrupted by the presentation of another signal. This is due to the nature of sound, the method by which computers generate sound, and the point along the sine wave where the signal was interrupted. Participants may have received feedback from the speaker noise during the 800 ms condition.

Third, why did error rates escalate between Experiments 2 and 3. In Experiment 2, the proportion of errors for 200 and 800 ms feedback was 0.064 and 0.158, respectively. However, in Experiment 3, the proportion of errors for 200 and 800 ms feedback was 0.256 and 0.310, respectively. A post hoc dependent samples t-test confirms that error rates for 200 ms feedback were higher in Experiment 3 (Coefficient of Variation = 67.6%) than in Experiment 2 (Coefficient of Variation = 99.6%), t(30) = 11.218, $p < .001$. Likewise, a post hoc dependent samples t-test confirms that error rates for 800 ms feedback were higher in Experiment 3 (Coefficient of Variation = 52.6%) than in Experiment 2 (Coefficient of Variation = 92.1%), t(30) = 6.465, $p < .001$. There are at least three potential explanations for why the error rate differences were observed. First, the layout of the ten-key pad for small targets differed between Experiments 2 and 3. In Experiment 2, the center of each small target on the ten-key pad was located 32 mm from the center of the nearest neighboring target. However, in Experiment 3, the center of each small target on the ten-key pad was located 12 mm from the center of the nearest neighboring target. This difference may have induced fingerprint errors. That is, with less dead space between buttons, participants may have inadvertently acquired neighboring targets. Second, Experiment 3 was characterized by the presence of store background noise that was not present during Experiment 2. The store background noise may have distracted participants or partially masked the auditory feedback, leading to decreased accuracy. Third, participants were required to handle packages during Experiment 3 while needing only to read information off the screen during Experiment 2. The requirement to handle packages is more realistic, but transferring information from the package to the touch screen may have disrupted ten-key entry error performance.

Perhaps a more important consideration is the correspondence of the observed error rates in the experimental conditions and actual error rates in the real world. That is, do cashiers make as many errors as were observed in Experiment 3? There are a several reasons why the error rates observed in Experiment 3 are probably higher than actual error rates in the real world. First, in the present experiment, errors could not be corrected and no customers were present to influence the accuracy of the participants. The presence of customers at a point-of-sale may serve to motivate cashiers to be accurate as inaccurately entered information would likely have to be re-entered. Second, although the realism of the experimental conditions was increased from Experiment 2 to Experiment 3, the experimental conditions still did not parallel an actual retail POS environment. That is, all three experiments were conducted in an artificial environment lacking realism that may be essential for accurate performance. Third, and perhaps most importantly, the participants were not trained data entry personnel. Without training, the participants could not be expected to perform at high levels of accuracy. Although the absolute error rates observed in these studies are probably inflated, the pattern of results that emerges from these studies is important. That is, if small targets are used for a ten-key entry task, then errors can be reduced by providing auditory feedback between 50 and 400 ms.

Large target error performance followed the same pattern observed with movement time and contact time. That is, large targets were unaffected by the auditory feedback manipulations. One possible interpretation of this finding is that large targets make the ten-key entry task easier than the small targets. Therefore, additional auditory feedback is an unnecessary addition to the use of large targets. Also, large target error rates were superior to small target error rates, reinforcing the need to use large targets on touch screens.

Design Principles

Several interface design principles can be gleaned from this study. First, large targets should be used whenever possible. The benefits of using large targets include reduced movement time, contact time, and errors. Second, if small targets are used, then auditory feedback between 50 and 400 ms should be used. Using feedback within this range significantly reduces error rates. This pattern of results seems to indicate that large targets should be used to the exclusion of small targets. However, large targets can also be problematic. Specifically, screen real estate is a limited resource. So, fewer large targets can be placed on a display than small targets. Point-of-sale software applications often require cashiers to select from many targets. If fewer targets are placed on a screen (i.e., with the use of large targets), then the cashier will have to navigate to other screens in order to view the targets that cannot be placed on the current screen. Therefore, a tradeoff exists between the use of small and large targets. More small targets can be placed on a screen, but a cashier will make more errors and take more time. With large targets, cashiers will make fewer errors and take less time, but fewer large targets can be placed on a display and screen navigation time will increase.

Fortunately, the results of this series of experiments can assist human factors psychologists in deciding what size of targets to place on the screen. Specifically, these experiments show that the careful implementation of auditory feedback can reduce the proportion of errors cashiers will commit with small targets. Using 50 and 400 ms auditory feedback substantially reduces error rates with small targets. Thus, although movement time and contact time with small targets remain longer than large targets, error rates are reduced. Therefore, if cashiers need to be fast and accurate, and/or screen real estate is not severely limited, then large targets should be used. However, if cashiers need to be accurate and screen real estate is more limited, then small targets with 50 to 400 ms auditory feedback should be used. Moreover, Experiment 3 investigated the duration of auditory feedback and target size in a setting with higher fidelity. Although still an unrealistic setting, the results from Experiment 3 demonstrate that the principles gleaned from Experiment 2 are robust and do not disappear with the addition of extraneous variables.

Future Research

Future research should investigate the effect of other variables on the relationship between the duration of auditory feedback and target size on movement time, contact time, and errors. Within the laboratory environment, the effect of visual feedback should be explored. Visual feedback can be provided with buttons changing color or the impression of 3-dimensional depression when touched. Visual feedback can also be enhanced by having numbers appear on-screen as they are typed. Additionally, more complex situations can be investigated where participants are performing a combination of tasks such as scanning, weighing, bagging, tendering payment, etc. Outside the laboratory, the results should be replicated in a real store environment. The presence of customers, the use of trained cashiers, and the realism of the retail atmosphere may impact the effect that duration of auditory feedback and target size have on ten-key entry performance.

Summary

In sum, the knowledge gleaned from this research can be leveraged by the human factors psychologist to help meet the challenges of designing POS interfaces for retail tasks. Incorporating proper auditory feedback and target sizes in touch screen ten-key entry applications can help satisfy the goals of three users: the shopper who is purchasing the product at the interface, the cashier who directly interacts with the interface, and the corporation that purchases the interface. The shopper will be able to purchase products quicker. The cashier will commit fewer errors and perform a more enjoyable task. The corporation will benefit from more return visits to the store. With these objectives met, all three users will increase efficiency and maximize productivity, which is the goal of any properly designed POS.

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APPENDICES

APPENDIX A

Review of Touch Screen Literature

Overview

Pointing is such an intuitive method of communication that it seems only natural to utilize this ability to improve the interaction between humans and computers. Indeed, many pointing devices have been created to aid computer users. These pointing devices may be categorized along two continuums: on-display vs. off-display and direct vs. indirect. On-display pointing devices are characterized by an interaction with the computer on the computer screen. Examples of such devices include light pens and touch screens. Off-display pointing devices are characterized by interactions with the computer that occur at any location other than the computer screen. Examples include mice, trackballs, and touch pads. Direct pointing devices are characterized by an interaction with the computer in the same three-dimensional plane as the computer screen. Examples include light pens, styli, and touch screens where the cursor is located directly beneath the device. Indirect pointing devices are characterized by an interaction with the computer in some other three-dimensional plane than the computer screen. Examples include trackballs, mice, light pens, styli, and touch screens where the cursor is offset from the point directly beneath the device.

Although the touch screen is an on-display device, and can be a direct pointing device, it is unique because it does not require the user to manipulate a foreign device. Due to the inherently natural mode of interaction, the touch screen is heralded as a superior pointing device by many researchers (Buxton, Hill, & Rowley 1985; Pickering, 1986; Shneiderman, 1991; Whitefield, Ball, & Bird, 1983).

Advantages and disadvantages of touch screens. Touch screens have certain advantages over alternative input devices. Shneiderman (1991, p. 93) presents the following advantages of touch screens:

g) Touching a visual display of choices requires little thinking and is a form of direct manipulation that is easy to learn.

h) Touch screens are the fastest pointing device.

i) Touch screens have easier hand-eye coordination than mice or keyboards.

j) No extra workspace is required as with other pointing devices.

k) Touch screens are durable in public-access and in high-volume usage.

As with any input device, however, touch screens also have certain disadvantages. Shneiderman (1991, p. 93) presents the following disadvantages of touch screens:

g) Users' hands may obscure the screen.

h) Screens need to be installed at a lower position and tilted to reduce arm fatigue.

i) Some reduction in image brightness may occur.

j) They cost more than alternative devices.

Touch screen technologies

Many different touch technologies have been developed to facilitate the ability of the finger to interact with a touch screen. Five common technologies include capacitive, resistive, acoustic, infra-red, and displacement.

Capacitive. Capacitive touch technologies use a glass overlay that is coated with a transparent film of metallic material (Meko Ltd, 1998). Very low AC voltages are applied to all four corners of the metallic material, creating an even electric field across the entire surface of the overlay. When a finger touches the screen, the capacitance of the finger draws a small amount of current from each corner of the overlay. The position at which the finger touched the screen is calculated based on the amount of current drawn from each corner. Capacitive touch technologies have several advantages: (a) only a 3 ms contact time is needed to register a touch,

(b) the overlay protects the display and can be sealed within the bezel, (c) capacitive overlays are very reliable, lasting for more than 20 million touches, (d) the overlay is unaffected by contaminants, and (e) capacitive overlays have a high resolution of at least 1024 x 1024 points. Correspondingly, capacitive overlays have certain disadvantages: (a) the overlay only permits transmission of 85% to 90% of the display's light, (b) the overlay can be programmed to work with either a bare finger or a thin glove, but not both, and (c) capacitive overlays are more expensive than other touch technologies.

Resistive. Resistive touch technologies use an overlay of front and rear polyester layers with conductive coatings separated by tiny spacers (Meko Ltd, 1998). Like the capacitive overlay, voltages are applied to all four corners of the rear layer. When a finger touches the screen, the front layer comes into contact with the rear layer and completes the circuit. The position at which the finger touched the screen is calculated based on the amount of current drawn from each corner. Resistive touch technologies have several advantages: (a) only a 3 ms contact time is needed to register a touch, (b) resistive overlays can accept input from a stylus, bare finger, or gloved finger, (c) resistive overlays have a high resolution of at least 1024 x 1024 points, and (d) resistive touch technology is relative inexpensive. Correspondingly, resistive overlays have certain disadvantages: (a) the overlay only permits transmission of 55% to 80% of the display's light, (b) the spacers can be visible, and (c) the overlay can be effected by certain chemicals.

Acoustic. Acoustic touch technologies generate a ultrasonic acoustic wave across the front of an overlay (Meko Ltd, 1998). When a finger touches the screen, the waves are absorbed. The position of contact is calculated by measuring the amount of time required until the electronics detect that the wave was absorbed. In addition to determining the x and y coordinates, acoustic overlays can provide a z axis by measuring the amount of energy absorbed by the finger and translating this into pressure. Acoustic touch technologies have several advantages: (a) more than 90% of the display’s light is transmitted through the clear glass overlay, (b) acoustic overlays can measure pressure via the z axis, and (c) the overlay is very stable in terms of its calibration.

Correspondingly, acoustic overlays have certain disadvantages: (a) hard objects cannot be used to activate the screen because the acoustic waves must be absorbed, (b) acoustic overlays are more expensive than other touch technologies, and (c) the overlay can be affected by contaminants and foreign objects.

Infra-red. Infra-red touch technologies use an array of Light Emitting Diodes (LED's) embedded within the top and side of a bezel (Meko Ltd, 1998). An array of photo transistors embedded within the opposite sides of the bezel detect the light from the LED's. When a finger touches the display, beams of light are obstructed and the point of contact can be calculated. Infra-red touch technologies have several advantages: (a) since there is no overlay, 100% of the display's light is transmitted, and (b) any stylus can be used. Correspondingly, infra-red touch screens have certain disadvantages: (a) infra-red touch screens have a low resolution of about 8 points per square inch, (b) infra-red touch screens can be affected by ambient light sources, (c) parallax is often a problem as the LED's are some distance from the surface of the display, and (d) touches can be detected without ever contacting the display.

Displacement. Displacement touch technologies (force vector systems) use a spring loaded base upon which a monitor is placed (Meko Ltd, 1998). When a finger touches the display, the point of contact is calculated by measuring the amount of force at the base. Displacement touch technologies have several advantages: (a) since there is no overlay, 100% of the display's light is transmitted, and (b) displacement touch screens can measure pressure in the z axis. Correspondingly, displacement touch screens have certain disadvantages: (a) displacement touch screens are susceptible to drift and require frequent calibration, (b) the calculations required to determine the touch location are complicated and slow, (c) any physical disturbance of the workstation affects the calibration, and (d) displacement touch screens are inaccurate and unreliable.

Given the characteristics of each touch technology, capacitive and resistive technologies are the most commonly implemented technologies. The preference for these two technologies is largely due to the superior precision, reliability, and resolution capabilities of these two technologies.

Target Characteristics

The characteristics of the targets used on touch screens can have a dramatic effect on both the speed and accuracy with which users accomplish tasks. Three important characteristics include the size, shape and location of the targets on the touch screen.

Size. A limited number of studies have investigated the effect of touch screen target size on performance. Touch screen real estate, like any screen real estate, is a limited resource. Using small targets allows more options to be placed on the touch screen, but may hinder target acquisition performance. Using targets that are too big may positively impact target acquisition performance but waste screen real estate. Therefore, target size is an important issue.

Wilson et al. (1995) compared two touch screen target sizes on four tasks designed to simulate typical retail POS tasks. The four tasks included (a) ten-key entry, (b) item modification, (c) a combination of item modification and scanning, and (d) a combination of item modification, scanning, and a secondary monitoring task. Results indicated that across all tasks, large targets (20 x 20 mm) facilitated faster and more accurate performance than small targets (14 x 14 mm).

Sears et al. (1993) compared four touch screen target sizes in a typing task. The typing task involved the use of a QWERTY key layout and required entry of single words, brief phrases, and longer sentences. The four target sizes were 22.7 x 22.7 mm, 11.4 x 11.4 mm, 7.6 x 7.6 mm, and 5.7 x 5.7 mm. Results indicated that large target sizes permitted faster performance and were more preferred by participants than small targets. Significant differences were observed between all target sizes on speed.

Plaisant and Sears (1992) examined the effect of practice on touch screen typing. Participants used a QWERTY key layout with target sizes at 11.4 x 11.4 mm. After 25 minutes of practice, performance increased from 9.5 to 13.8 words per minute. The authors comment that for limited text entry, touch screens with small targets can be a viable alternative to mechanical devices.

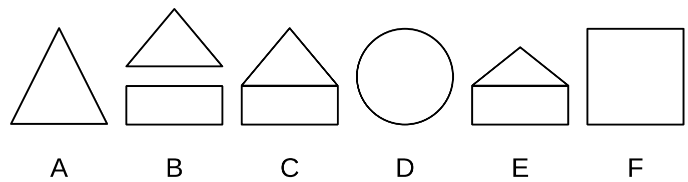
Leahy and Hix (1990) compared touch screen target sizes of 7.5 x 7.5 mm, 12.2 x 12.2 mm, and 20 x 20 mm in a simple target acquisition task emphasizing accuracy. No significant differences in target acquisition accuracy were observed. Target acquisition speed was not reported.

The results from these experiments clearly indicate the impact of target size on performance. Large targets are generally responded to more quickly, more accurately, and are preferred over small targets. Unfortunately, large target sizes require comparably more screen real estate than small target sizes. Interface designers must weigh the tradeoff between performance and aesthetics to find an acceptable compromise in the design of touch screen interfaces.

Shape. Touch screens permit flexibility in designing targets of different shapes. Using different shapes can enhance the appearance of an interface and increase corporate identity with a particular product. Unfortunately, very little research has investigated the effect of target shape on touch screen performance.

Breinholt and Krueger (1996) compared six target shapes in a simple target acquisition task. The six target shapes are shown in Figure 16. Results indicated no significant differences between the target shapes for target acquisition speed. However, shape B produced significantly more errors than any of the other designs. Apparently, participants pressed shape B as if the target areas were contiguous, rather than separated. These results suggest that target shape is a relatively unimportant factor given that the shape is contiguous.

Figure 16. Target shapes used in the Breinholt and Krueger (1996) study.



Location. The flexibility of touch screen design also affords the opportunity to place targets at different locations on the touch screen. Once again, locating targets at different locations can improve interface appearance and enhance corporate identity. A few studies have investigated the effect of touch screen target location on performance.

Leahy and Hix (1990) placed targets at nine locations and measured touch screen target acquisition performance. Touch accuracy was emphasized over speed. The display was located 1318 mm above the floor and declinated 15°. Participants stood while performing the task. The results suggest that the top-center area of the screen produced the most accurate target acquisition performance. As targets moved from the top to the bottom of the screen, touches were more likely to be below the center of the target (mean offset of 5.28 mm). As targets moved from the center to the outside of the screen, touches were more likely to be located away from the center of the screen, outside the center of the target (mean offset of 0.29 mm).

Beringer (1990) placed targets at nine locations and measured target acquisition performance. Touch accuracy and speed were emphasized. Participants were positioned so that their line of sight was orthogonal to the center of the display. Participants were seated while performing the task. Results indicated that right-handed users were more quick and most accurate when targets were located in the lower-right portion of the display. Left-handed users were more quick and most accurate when targets were located in lower-left portion of the display. The deviation of touches from the center of the target was approximately 1.5 mm.

The differences in obtained results in the Leahy and Hix (1990) and Beringer (1990) studies may be due to the difference in the instructional set (accuracy vs. speed and accuracy), viewing angle (fixed angle vs. orthogonal angle), and/or interaction position (standing vs. seated). In any case, the absolute deviation from the center of the targets was minimal.

Display Characteristics

Touch screens are unique in that the output the user receives and the input the user communicates to the computer occur in the same plane. This feature offers the unique advantage of providing users a direct, on-display method of interaction. However, certain unique problems are inherent with this feature as well.

Angle. The surface of the touch screen is separated from the surface of the display by some distance. This separation generates a parallax between where a target appears to be and where the target is actually located. The extent of the parallax problem is dependent upon the angle at which the display is located and the distance the display surface and touch screen overlay are separated.

Leahy and Hix (1990) had participants perform a simple target acquisition task with three viewing locations: perpendicular to the display, 20° to the left of perpendicular, and 20° to the right of perpendicular. The side viewing locations were selected to represent two 50% U.S. adults standing side by side and jointly interacting with the display. The display was located 1318 mm above the floor and was declinated 15°. Participants stood while performing the task. Results indicated that participants selected targets less accurately (in both the horizontal and vertical axes) when standing either to the left or to the right of the display.

Beringer and Bowman (1989) and James-Bowman and Beringer (1989) had participants perform a simple target acquisition task with the angle of the display orthogonal to the line of sight and declinated 17° from the line of sight. Participants consistently touched too high (9 pixels or about 0.75 mm) under the 17° declination condition. Maintaining an orthogonal viewing angle nearly eliminated any touch bias.

Hall, Cunningham, Roache, and Cox (1988) conducted two experiments investigating the effects of horizontal and vertical angle of regard between the user and the display. In experiment one, participants completed a simple target acquisition task while seated with three viewing locations: perpendicular to the display, 21° to the left of perpendicular, and 21° to the right of perpendicular. Results indicated that horizontal axis errors were greater under both 21° left and 21° right of perpendicular than under the perpendicular orientation. No significant vertical axis errors were observed. In experiment two, participants completed a simple target acquisition task while standing with three viewing locations: perpendicular to the display, 21° to the left of perpendicular, and 21° to the right of perpendicular and display declinations of 7°, 30°, and 45°. Results indicated no significant differences between the 7° and 30° inclinations. However, in both the 7° and 30° inclination conditions, performance was more accurate than in the 45° inclination condition.

These studies (Beringer & Bowman, 1989; Hall et al., 1988; James-Bowman & Beringer, 1989; and Leahy & Hix, 1990) emphasize the importance of maintaining a perpendicular, orthogonal line of sight between the user and the display. However, simply positioning a touch screen for optimum viewing does not ensure proper anthropometric design. Because touch screens integrate display output and user input in the same plane, unique anthropometric problems arise. Specifically, touch screens cannot be simultaneously positioned for optimal input and output. Therefore, certain compromises must be made.

Lehman and Sutarno (1995) present ergonomic guidelines for devices that combine input and output in a single plane and require standing operation. The display should be positioned directly in front of (perpendicular to) the user. The display should be adjustable in height between 1040 mm and 1397 mm from the floor to the center of the display. The display should be reachable within 255 mm to 460 mm. Additionally, there should be no obstacles between the user and the display to hinder operation. Specific height, distance, and angle adjustments must be made for individual users. The height of the display should be adjusted so that the shoulder angle is no greater than a 30° angle from the chest, the neck is not bent more than 15° forward, and the viewing angle is no greater than 30° from eye level. The distance of the display should be adjusted so that it can be reached with an elbow angle between 90° and 135°. The angle of the display should be adjusted so that it can be operated with the wrist in a neutral position, all points of interaction can be easily reached, and glare is minimized.

Touch selection strategy. In addition to adjusting the angle for optimal accuracy and anthropometrics, touch screens offer the ability to detect touches at different times while the finger is in contact with the display. Several studies have investigated different techniques for registering touches.

Potter, Weldon, and Shneiderman (1988) had participants select 1/4 inch square targets using one of three strategies: land-on, first-contact, and take-off. The land-on strategy is characterized by the cursor being placed directly under the finger, only the first contact with the screen is registered, and a target is selected only if the first contact is on a target. The first-contact strategy is characterized by the cursor being placed directly under the finger, all contact with the screen is registered, and the first target that is touched is selected. This strategy allows the user to move his/her finger on the screen until the target is contacted. The take-off strategy is characterized by the cursor being placed 1/2 inch above the finger, all contact with the screen is registered, and a target is selected when the user removes his/her finger from the display while the cursor is located over a target. This strategy allows the user to move his/her finger anywhere on the screen until he/she lifts his/her finger from the screen. Additionally, for the take-off strategy, Potter et al. (1988) highlighted the target item when the cursor was over it and added jitter stabilization to smooth cursor movements over target boundaries. Results indicated that the first-contact strategy was significantly faster than the take-off strategy, the take-off strategy produced fewer errors than either the land-on or first-contact strategies, and participants preferred the take-off strategy to the land-on strategy. Although these results are interesting, Potter et al. (1988) failed to control for the introduction of jitter reduction techniques and target highlighting. This confounding of independent variables prevents the inference of conclusions regarding the effect of the touch selection strategies.

Potter, Berman, and Shneiderman (1989) had participants select small closely spaced hypertext targets using one of three strategies: land-on, first-contact, and take-off. Results indicated no speed differences between the three strategies. The land-on strategy, however, produced significantly more errors than either the first-contact or take-off strategy. The observed error differences are easily understood when considering the size of the targets. Potter et al. (1989) used targets smaller than the average size human finger-tip. It is neither surprising nor interesting that the first-contact and take-off strategies would be superior to the land-on strategy under these circumstances.

Beringer and Lee (1988) and Beringer (1989) had participants complete a simple target acquisition task and recorded the points at which the participant’s finger came into contact with the screen relative to target location. Resistive and infra-red touch screens were used with 1/8 inch square targets. Results indicated that the initial and final points of contact were less accurate than the points in between. Furthermore, the resistive touch screen was most accurately sampled 50 ms prior to the finger being removed from the screen. The infra-red touch screen was most accurately sampled between 25% and 75% of the duration of touch contact. Waiting for the user to remove his/her finger before calculating the touch requires more processing time from the computer and may not provide the user with the most intuitive interface.

Two important points must be emphasized regarding the Potter et al. (1988), Potter et al. (1989), Beringer and Lee (1988), and Beringer (1989) studies. These studies were designed to test touch screen selection strategies with small, high resolution targets. This type of interaction is advantageous under certain circumstances. However, previous research investigating target size argues that large targets are acquired faster and more accurately than small targets (Fitts, 1954; Plaisant & Sears, 1992; Sears et al., 1993; Wilson et al., 1995). With this in mind, it is possible that large targets would be best acquired using a land-on touch selection strategy. The land-on strategy acts much like a physical button. That is, an action occurs when the user touches, or presses, the screen, not when the finger is removed from the screen. Further research should investigate this hypothesis.

Interface Design Characteristics

A variety of touch screen design characteristics have been investigated, including interaction techniques and forms of feedback.

Interaction techniques. Beringer (1990) manipulated the instructions given to participants in a simple target acquisition task. Participants were instructed to: "touch the square," "touch inside the square," or "touch the center of the square." The instructions affected the accuracy and speed with which participants acquired the targets. Participants were more accurate and took more time to acquire targets with more explicit instructions. Specifically, "touch the square" instructions resulted in 3 mm errors and 729 ms reaction times while "touch the center of the square" instructions resulted in 2 mm errors and 1048 ms reaction times. The implications of instructions have the most meaningful effect on reaction time, as errors on the order of 2 or 3 mm are fairly meaningless with targets of adequate size.

Landauer and Nachbar (1985) manipulated the breadth and depth of touch screen menu trees and measured the time required by participants to navigate the menus to find a target. Two, four, eight, or 16 menu items were presented on screen. Although response time per touch was faster for menu trees with fewer alternatives, cumulative response was faster for menu trees with more alternatives. Since cumulative response time to complete a task is usually the variable of greater meaningfulness, these results suggest that menus of eight or 16 items should be used.

Long, Whitefield, and Dennett (1984) compared three numeric layouts for digit entry tasks: a telephone keypad matrix, a linear array, and cash register layout. The telephone keypad matrix is characterized by four rows of buttons. The top (first) row contains digits 1 through 3, the second row, digits 4 through 6, the third row, digits 7 through 9, and the bottom (fourth) row, digit 0 centered horizontally on the keypad. The linear array is characterized by a horizontal row of digits; from left to right, the digits are 1, 2, 3, 4, 5, 6, 7, 8, 9, and 0. The cash register layout is characterized by a variable number of vertical columns each containing the digits are 1 through 9. Each column represents one digit place in a number. Zero is represented by not selecting any number in a particular column. Participants entered numbers containing either 10% or 50% zeros. With 10% zeros, participants were slowest with the cash register format and fastest with the telephone matrix layout. With 50% zeros, however, participants were fastest with the cash register layout and slowest with the linear layout. For the majority of situations, a matrix layout will produce the quickest data entry. However, in unique situations where a large proportion of digits are zeros, then a cash register format can be significantly faster.

Beringer (1979) compared three devices for aerial navigation: keyboard entry with a static map, keyboard entry with a dynamic map, and touch screen entry with a dynamic map. Participants using the touch screen with the dynamic map completed the aerial navigation task most quickly and with the fewest errors while the keyboard entry with the static map resulted in the slowest performance and the most errors. Beringer (1979) demonstrated that touch screens can be very useful for certain tasks and outperform conventional interaction techniques.

Mack and Montaniz (1991) compared mouse, stylus and finger speed and accuracy on several representative desktop application tasks. Tasks included (a) opening two memos, comparing the contents, and deleting one, (b) comparing the contents of a memo with a schedule from a calendar application, confirming meeting times and agendas, (c) opening a memo, summing a list of expenses using a calculator application, and then pasting the total in a memo, and (d) revising spreadsheet entries, adding a row of data, and saving the spreadsheet. The mouse facilitated faster and more accurate performance while the finger was the slowest and least accurate interaction technique.

Montaniz and Mack (1991) compared styli and finger interaction techniques on several representative desktop application tasks using two touch control methods. Tasks included (a) opening a memo, summing a list of expenses using a calculator application, and then pasting the total in a memo, (b) revising spreadsheet entries, adding a row of data, and saving the spreadsheet, (c) creating a bar chart, adding a title and legend, and naming and saving the chart, (d) opening a chart, pasting it into a memo, and naming and saving the memo, and (e) copying the contents of two memos into a new document, editing the header, naming and saving the document, and deleting the original memos. The two touch control methods were different methods of selecting and manipulating icons: the 1-2-3 and pause methods. The 1-2-3 method was characterized by (a) touching an icon once to select it, (b) touching an icon twice to open a window, and (c) touching an icon once and then touching and dragging the icon on the screen. The pause method was characterized by (a) a brief touch interpreted as a double-click and (b) a longer touch interpreted as a single click. The stylus outperformed the finger in terms of speed when using the 1-2-3 method of touch control. No differences were observed between the stylus and the finger on the pause touch control method. Performance using the stylus was equally fast under the 1-2-3 and pause touch control method. The finger performed faster under the pause touch control method than the 1-2-3 touch control method.

Karat, McDonald, and Anderson (1986) compared a touch screen, mouse, and keyboard on a menu selection task. Results indicated that the touch screen outperforms both the keyboard and the mouse and that participants prefer either the touch screen or the keyboard to the mouse. However, the meaningfulness of these results are severely attenuated by the control gain used on the mouse. In one experiment, the gain was 1:1 while in another, the gain was 1:2. These gains are extremely low and may have frustrated users considerably, requiring greater mouse movements and longer menu navigation times.

Feedback. Any interaction with a machine necessitates feedback for adequate performance. This feedback can be of several forms. The most common types of feedback are visual, auditory, and proprioceptic. By their very nature, touch screens do not provide proprioceptic feedback. Therefore, some combination of visual and auditory feedback is the only viable method of providing feedback with touch screens. Several studies have investigated the effect of feedback on keying performance with touch screens and standard mechanical keyboards.

Nakatani and O'Connor (1980) investigated the use of speech feedback in keying telephone numbers where the keyboard is unseen. Specifically, Nakatani and O'Connor (1980) compared standard Dual Tone Multi-Frequency (DTMF) touch tones with speech feedback for keying telephone numbers. Participant's keying hand and the telephone keypad were blocked from view. Results indicated that participants are faster and more likely to catch and correct their errors with the speech feedback than with the touch tone feedback.

Boyle and Lanzetta (1984) measured the perceived delay of single and multiple keystrokes appearing on a display. For single keystrokes, participants pressed the "H" key while attending to the screen and reported whether a delay could or could not be perceived. For multiple keystrokes, typists keyed brief sentences and phrases and reported whether a delay could or could not be perceived. Results indicated a threshold of 165 ms for single keystrokes and 100 ms for multiple keystrokes.

Review of Audition Literature

Hearing

Auditory stimuli are created by the displacement of some elastic medium such as air (Goldstein, 1996; Matlin & Foley, 1992). As molecules in the air are displaced, the molecules collide with one another and produce sound waves. These sound waves travel outward from a source of displacement, such as a stereo speaker. As a speaker vibrates, its diaphragm moves forward and back. When a speaker moves forward, the air molecules in front of the speaker move closer together. When a speaker moves back, the air molecules in front of the speaker move further apart. Thus, by alternating back and forth movements, a speaker produces areas of high and low atmospheric pressure. This pattern of alternating atmospheric pressures is referred to as a cycle, where one cycle represents one low and one high atmospheric pressure area.

Frequency. The number of cycles that are produced in a second determines the frequency, or hertz (Hz), of the sound (Goldstein, 1996; Matlin & Foley, 1992). For example, middle C on a piano has a frequency of 256 Hz because it cycles 256 times per second. The human ear is sensitive to frequencies between 20 and 20,000 Hz. Frequency corresponds with the perception of pitch, the highness or lowness of a sound. However, the relationship between frequency and pitch is not perfect. Intensity, for example, can affect pitch. Tones with frequencies less than 1000 Hz become lower in pitch as intensity is increased, whereas tones with frequencies greater than 3000 Hz become higher in pitch as intensity is increased.

Intensity. As sound frequency is related to the perception of pitch, sound intensity, or amplitude, is related to the perception of loudness and represents the maximum change in atmospheric pressure from normal (Goldstein, 1996; Matlin & Foley, 1992). Sound pressure is measured in dynes per square centimeter. In ideal conditions, a 1000 Hz tone with an amplitude of 0.0002 dynes/cm^2 can just be detected. At the other end of the spectrum, a 1000 Hz tone with an amplitude of 2000 dynes/cm^2 produces pain in humans. Thus, the range from just being able to detect a sound to the sound producing pain is larger than 1 to 10,000,000. Instead of referencing intensity in dynes/cm^2, an easier scale, referred to as sound pressure level (SPL) with measurement units in decibels (dB), has been adopted. Decibels are computed using the following equation:

$$decibels = 20 \log_{10}(P_1 / P_0),$$

where P_1 is the sound pressure level of the sound that needs to be converted to decibels and P_0 is the reference level of 0.0002 dynes/cm^2. Therefore, a sound pressure level of 1000 dynes/cm^2 would become 134 dB(SPL). Just as the pitch of certain frequency sounds changes with intensity, the loudness of certain frequency sounds changes with intensity. In general, sounds less than about 500 Hz are perceived as less loud than sounds greater than about 500 Hz with identical intensities.

Duration. Another characteristic of sound is the duration, or length of time, that the sound lasts (Goldstein, 1996; Matlin & Foley, 1992). Humans are able to detect sounds that are very brief (less than 1 ms) in duration. The loudness of sounds also depends on the duration of the sounds. Sounds briefer than about 80 ms are perceived less loud than sounds longer than about 80 ms in duration. To compensate for this effect, the amplitude of shorter duration sounds must be increased using the following equation:

$$It = K,$$

where I is the intensity of the sound in decibels, t is the duration of the sound in seconds, and K is a constant.

Outer ear. The ear is comprised of three main components, the outer ear, the middle ear, and the inner ear (Goldstein, 1996; Matlin & Foley, 1992). The outer ear contains the pinna, the external auditory canal, and the tympanic membrane. The pinna is the outer tissue of the ear and can amplify sounds and aid in sound localization. The external auditory canal is the tube that goes inward from the pinna. The external auditory canal amplifies certain frequencies and helps protect the tympanic membrane from foreign objects. The tympanic membrane is a thin piece of membrane that vibrates in response to sound waves and forms the boundary between the outer and middle ear.

Middle ear. The middle ear contains the three ossicles: the malleus, the incus, and the stapes (Goldstein, 1996; Matlin & Foley, 1992). These tiny bones connect the tympanic membrane to the oval window of the inner ear. The malleus is connected to the tympanic membrane. The incus connects the malleus to the stapes. The stapes is connected to the oval window. The purpose of the middle ear is to amplify the sound waves and transmit them to the inner ear. The amplification is necessary because the sound waves, which are traveling through air with very little impedance, will be traveling through liquid in the inner ear with much greater impedance. This purpose is realized in three ways. First, the tympanic membrane is much larger than the oval window. Therefore, any vibration of the tympanic membrane will be much larger at the oval window. Second, the ossicles act as a lever to increase the force on the oval window. Third, the tympanic membrane is cone-shaped and responds more efficiently than a simple flat membrane.

Inner ear. The inner ear contains the semicircular canals and the cochlea (Goldstein, 1996; Matlin & Foley, 1992). The semicircular canals affect the sense of orientation. The cochlea contains the oval window, the vestibular canal, the tympanic canal, the round window, the cochlear duct, and the organ of Corti. As the oval window moves to the vibrations of the stapes, fluid is forced down the vestibular canal. When the fluid reaches the end of the vestibular canal, it passes through a small hole, called the helicotrema, and into the tympanic canal. Since fluid is very difficult to compress, the round window at the end of the tympanic canal allows the fluid someplace to go. Thus, the round window and the oval window move in opposite directions. The cochlear duct separates the vestibular canal via Reissner's membrane and the tympanic canal by the basilar membrane. As the oval window vibrates, the vibration is transmitted to the basilar membrane, which contains the auditory receptors. The vibration is transmitted down the length of the basilar membrane to the organ of Corti. The organ of Corti contains the hair cells which transduce the pressure energy from the sound vibration into electrical and chemical energy that can be transmitted to the brain via the auditory nerve.

Conversion of sound waves to sensations. Two main theories attempt to explain how sound vibrations are differentiated: the place and temporal theories (Goldstein, 1996; Matlin & Foley, 1992). The place theory states that the fibers on the basilar membrane are differentially sensitive to frequencies because they are of different lengths, much as a harp. The temporal theory states that pitch is determined by the interval of nerve impulses emitted by the fibers. Lower frequencies are indicated by slower firing rates and higher frequencies are indicated by faster firing rates. Neither the place nor the temporal theories adequately explain all auditory phenomena. Future research will likely show that the two theories are compatible.

Masking. Masking is a condition in which the presence of one auditory signal reduces the sensitivity of the ear to another auditory signal by raising the absolute threshold of the second auditory signal (Goldstein, 1996; Matlin & Foley, 1992). The amount that the absolute threshold is raised is referred to as the masked threshold. Masked thresholds are measured in the same manner as absolute thresholds, except that the measurement is taken in the presence of background noise. The effects of masking depend on the frequency and intensity of the masking noise. If the masking signal is less than about 40 dB(SPL), the effect of the masking signal is confined to the frequencies surrounding the masking signal. However, if the masking signal is greater than about 40 dB(SPL), the effects of the masking signal spread to frequencies greater than the masking signal. Therefore, lower frequency broadband noise (such as a shower) can easily mask higher frequency signals (such as the ringing of a telephone).

Auditory Displays

In certain circumstances, auditory signals can be used to the advantage of visual signals. Sanders and McCormick (1993, p. 169) offer the following guidelines for deciding when to use an auditory signal instead of a visual signal:

- When the origin of the signal is itself a sound.
- When the message is simple and short.
- When the message will not be referred to later.
- When the message deals with events in time.
- When warnings are sent or when the message calls for immediate action.
- When continuously changing information of some type is presented, such as aircraft, radio range, or flight path information.
- When the visual system is overburdened.
- When speech channels are fully employed (in which case auditory signals such as tones should be clearly detectable from the speech).
- When illumination limits use of vision.

- When the receiver moves from one place to another.
- When a verbal response is required.

Detection of signals.

The use of auditory signals necessitates proper design of these signals so that they are readily detectable within the environment in which they are to be used (Sanders & McCormick, 1993). In quiet environments, auditory signals are easily detected if the intensity of the signal is 40 to 50 dB(SPL) above absolute threshold. However, many situations are not quiet and, therefore, changes to the signal must be introduced to increase their detectability. To overcome masking effects, Deatherage (1972) recommends increasing the amplitude of the signal to the midpoint between the masked threshold of the signal and 110 dB(SPL). For example, the intensity of a signal with a masked threshold of 70 dB(SPL) should be increased to 90 dB(SPL). Additionally, the duration of auditory signals can be increased. Sounds require a certain amount of time to build up and a certain amount of time to decay. These times vary with the nature of the sound, but are more pronounced with pure tones as opposed to complex sounds. Therefore, signals should be at least 500 ms in duration to afford reliable detection. It is also possible to filter some of the masking noise in order to increase signal detectability.

Relative discrimination of auditory signals. Certain auditory displays may require the listener to respond differently to auditory signals that vary along one or more dimensions. When designing for these environments, it is important to consider the human ability to detect differences in the properties of auditory signals.

Differences in the intensity of signals are most easily detected if the signals are at least 60 dB(SPL) above absolute threshold and for frequencies between 1000 and 4000 Hz (Stevens, 1951; Stevens & Davis, 1938). For signals below about 60 dB(SPL) or outside the range of 1000 to 4000 Hz, intensity differences must be greater in order for differences in signals to be reliably detected.

Differences in the frequency of signals are most easily detected if the signals are 1000 Hz or less and the intensity is at least 20 dB(SPL) above absolute threshold (Stevens, 1951; Stevens & Davis, 1938). Frequency differences are much more difficult to detect above 1000 Hz and at lower intensities.

Differences in the duration of signals are most easily detected with shorter duration signals (Stevens, 1951; Stevens & Davis, 1938). For example, people can detect a difference of about 4 ms with 10 ms sounds but the difference must be increased to about 60 ms with a 1000 ms sound.

Sound localization. The human ability for localization of the origin of signals can be capitalized on in the design of systems (Goldstein, 1996; Matlin & Foley, 1992). The ability to localize the direction from which sound waves are emanating, or stereophony, is a function of interaural time and intensity cues. Interaural time cues are available when the sound is directed at the side of the head. Sound requires a certain amount of time to travel a given distance. So, a sound directed at the side of the head will reach one ear approximately 0.6 to 0.8 ms sooner than the other ear. The interaural time difference is effective for sounds below about 1500 Hz. Above this frequency, the speed with which the sound travels is too great to generate an usable interaural time difference. Additionally, a person is unable to tell if the sound is emanating from a point in front of or in back of the head without moving the head. The interaural time difference is also susceptible to a phenomenon known as the cone of confusion. The cone of confusion is a cone shaped area with the point of the cone at the ear. A sound emanating from any given point on the cone can be confused with a sound emanating from any other point on the cone. Thus, a listener must move his/her head to adequately localize the sound. Interaural intensity differences are also available when a sound is directed toward the side of the head. When a sound is directed toward the side of the head, the sound will be of greater intensity at the near ear. The head effectively shadows the far ear and the intensity is less. This cue is available for sounds above about 3000 Hz. Frequencies below about 3000 Hz envelop the head and any intensity differences are minute. Given the nature of interaural time and intensity differences, frequencies between about 1500 and 3000 Hz are difficult to localize. Thus, people must move their heads to aid in the localization of sounds.

Principles of auditory displays. Given the nature of hearing and the importance of auditory displays, Sanders and McCormick (1993, pp. 176-177) present a number of auditory signal design principles:

1. General principles
   - A. Compatibility: Where feasible, the selection of signal dimensions and their encoding should exploit learned or natural relationships of the users, such as high frequencies associated with up or high and wailing signals with emergency.
   - B. Approximation: Two-stage signals should be considered when complex information is to be presented. The signal stages would consist of:
     - (1). Attention-demanding signal: to attract attention and identify a general category of information.
     - (2). Designation signal: to follow the attention-demanding signal and designate the precise information within the general class indicated by the first signal.
   - C. Dissociability: Auditory signals should be easily discernable from any ongoing audio input (be it meaningful input or noise). For example, if a person is to listen concurrently to two or more channels, the frequencies of the channels should be different if it is possible to make them so.
   - D. Parsimony: Input signals should designate the same information at all times.
   - E. Invariance: The same signal should designate the same information at all times.
2. Principles of presentation
   - A. Avoid extremes of auditory dimensions: High-intensity signals, for example, can cause a startle response and actually disrupt performance.

B. Establish intensity relative to ambient noise level: The intensity level should be set so that it is not masked by the ambient noise level.

C. Use interrupted or variable signals: Where feasible, avoid steady-state signals and, rather, use interrupted or variable signals. This will tend to minimize perceptual adaptation.

D. Do no overload the auditory channel: Only a few signals should be used in any given situation. Too many signals can be confusing and will overload the operator.

3. Principles of installation of auditory displays

A. Test signals to be used: Such tests should be made with a representative sample of the potential user population to be sure the signals can be detected and discriminated by them.

B. Avoid conflict with previously used signals: Any newly installed signals should not be contradictory in meaning to any somewhat similar signals used in existing or earlier systems.

C. Facilitate changeover from previous displays: Where auditory signals replace some other mode of presentation (e.g., visual), preferably continue both modes for a while to help people become accustomed to the new auditory signals.

Pre-dissertation Research

During an internship with NCR and the subsequent work completed under a grant from NCR, I have conducted a variety of empirical studies investigating touch screen performance. This section briefly presents a few of these studies.

Touch Selection Strategy

The method by which a touch screen registers a user's touch is an important factor to consider when designing an interface for a touch screen. Three common methods of registering a touch include the land-on, lift-off, and land-on—lift-off touch selection strategies. The land-on touch selection strategy registers a touch as soon as the user's finger contacts a target on the touch screen. The lift-off touch selection strategy registers a touch when the user's finger is removed from a target on the touch screen. The land-on—lift-off touch selection strategy is a combination of the land-on and lift-off strategies. The user's finger must contact and release from the same target on the touch screen before a touch is registered.

Bender (1998c) conducted a pilot study that compared the land-on, lift-off, and land-on—lift-off touch selection strategies using two button sizes (14 or 25 mm). Seven participants completed 30 menu selection and ten-key entry trials under each of the six conditions. The menu selection and ten-key entry tasks were chosen because they are typical of retail POS tasks. Additionally, participants stood during the task to better approximate a retail environment. Results indicate that the land-on touch selection strategy is superior to either the lift-off or land-on—lift-off touch selection strategies with regard to speed. No significant difference in accuracy were observed.

Practice Effects

Previous studies comparing touch screen to mechanical key performance have failed to control for the amount of practice participants have with these two devices (Barrett & Krueger, 1994; Wilson et al., 1995). With practice, the advantage evident in mechanical keys may diminish and touch screen performance may approach that which is commonly achieved with mechanically keyed devices. Bender (1998a) conducted a study comparing three devices: a touch screen with small buttons, a touch screen with large buttons, and a NCR DynaKey. Thirty participants performed 75 menu selection and ten-key entry task trials on one of the three devices each day for 10 days. Results indicated that the NCR DynaKey was superior to the touch screen with small buttons and the touch screen with large buttons in terms of speed. The touch screen with large buttons was also superior to the touch screen with small buttons in terms of speed. No significant difference in accuracy were observed.

Auditory Feedback Duration

In a pilot study, Bender (1998b) manipulated the duration of auditory feedback in a reciprocal movement task on a touch screen. Results indicate that both movement time and contact time are influenced by the duration of the auditory feedback signal. Specifically, movement time and contact time increase as the duration of auditory feedback increases.

APPENDIX B

Sound Blaster AWE64 Gold Specifications

Signal to Noise	90 dB
THD	Better than 0.005% (A Weighted)
Frequency Response	15 Hz-50 kHz (+0/-1 dB)
S/PDIF Output	20 Bit, 120 dB Dynamic Range
Environment Temperature	(non-operating) -40C to 70C, (operating) 10C to 50C
Relative Humidity	(non-operating) 30% to 95%, (operating) 30% to 80%
MTBF	>60,000 hours
Drop Test	30 cm above concrete ground on all 6 sides
Vibration	Sine wave for X, Y and Z axis (non-operating)
	5 Hz to 15 Hz : 0.76 mm (P-P)
	5 Hz to 25 Hz : 1.5G
	25 Hz to 50 Hz : 0.15 mm (P-P)
	50 Hz to 100 Hz : 3G

APPENDIX C

Altec Lansing GCS 100 Specifications

Satellites	Two 5-watt
Driver	One 3-inch full range
Frequency Response	90 Hz – 20 kHz
Sensitivity	100 mV (1 kHz/1M) for 88 dB(SPL)
Audio Power	4 Watts per channel RMS
Treble	(+/-) 7 dB at 7 kHz
Input Impedance	>10k Ohms
Headphone Impedance	32 Ohms
Headphone Jack	1/8" (3.5 mm) stereo
Power Requirements	+15 VDC @ 800 mA

APPENDIX D

AIWA CA-DW530 Specifications

Cassette deck track format	4 tracks, 2 channels
Cassette deck frequency range	normal tape: 50 – 12,000 Hz (EIAJ)
Speaker type	100 mm cone type, 27 mm ceramic type
Speaker dimensions	(W) 179 mm x (H) 235 mm x (D) 243 mm
Speaker weight	1.25 kg

APPENDIX E

Participant Instructions for Experiments 1 and 2

In this session, you will see a ten key pad centered on the screen and a 4 digit number in the upper left corner of the screen. Your task is to enter the 4 digit number using the ten key pad. After you enter the 4 digit number press the equal (=) button. After you press the equal (=) button, another 4 digit number will replace the previous 4 digit number. Continue to enter the 4 digit numbers.

Be sure to only use your right index finger to touch the screen.

Please complete this task as quickly and accurately as possible.

APPENDIX F

Participant Instructions for Experiment 3

In this session, you will see a ten key pad centered on the screen and a 4 digit number printed on the face of a video tape. Your task is to pick up a video tape, hold it in your left hand, and enter the 4 digit number using the ten key pad. After you enter the 4 digit number press the equal (=) button. After you enter the 4 digit number, set the video tape aside and pick up another video tape. Continue to enter the 4 digit numbers.

Be sure to only use your right index finger to touch the screen.

Please complete this task as quickly and accurately as possible.

APPENDIX G

Transformation Formulas

Square Root Transformation

$$Y' = \sqrt{Y + 0.5}$$

Logarithmic Transformation

$$Y' = \log_{10}(Y + 1)$$

Reciprocal Transformation

$$Y' = \frac{1}{Y + 1}$$

Inverse Sine Transformation

$$Y' = 2 \arcsin \sqrt{Y}$$