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THE EFFECT OF TARGET POSITION AND TACTUAL RECOGNITION FIELD SIZE ON TOUCH BIAS AND ACCURACY

by

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A Thesis Submitted to the
Department of Human Factors & Systems
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Human Factors & Systems

Embry-Riddle Aeronautical University
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Elizabeth L. Brix

This thesis was prepared under the direction of the candidate's thesis committee chair, Shawn Doherty, Ph.D., Department of Human Factors & Systems, and has been approved by the members of the thesis committee. It was submitted to the Department of Human Factors & Systems and has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Human Factors & Systems.

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ABSTRACT

Past studies have shown that touchscreen display angles other than those that perpendicularly bisect the operator's line of sight cause the operator to touch slightly below the target. The amount of touch bias created from this misjudgment fluctuates according to the target's position on the screen. Additionally, the percentage of touches that activate a specific target varies according to the size of the tactual recognition field. Out of three square tactual recognition field sizes, this study sought to match these fields with the amount of touch bias occurring in each location (i.e., small amount of touch bias requires only a small field). The results showed that although bias differed according to location, the tactual recognition fields did not vary enough in size, nor were they large enough to find a significant difference between them in the number of touches captured according to the location of the target.

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INTRODUCTION

Although they have only recently been introduced into mainstream society, touchscreen devices have been in existence since the 1970's. They are now abundant in banks, casinos, restaurants, hotels and airports (Fritz, 2000). Inside of kiosks, they supply information to the busy shoppers at malls and the fun seekers at amusement parks. They are also widely used in many different industries for manufacturing, merchandizing and training (Hall et al., 1988). The application of touchscreen computers range from personal digital assistants, to displays used in the United States air-traffic control system and hospital intensive care units (Weisner, 1988).

The touchscreen's single interface is one of its strongest advantages; the location of the input is also the location of the output. The interface is natural and convenient, allowing users to simply touch the item they are interested in (Sears & Shneiderman, 1991). This feature allows users to keep their eyes on the screen, eliminating the constant up-and-down head scanning motion associated with ensuring accuracy (Whitford, 1999). Additional advantages can be found in a study completed by Lorning in 1995. Lorning designed a touchscreen interface for a microwave oven to be used by older consumers. She performed this study with the purpose of improving the usability of the conventional microwave oven by providing a touchscreen interface, and found the interface to be an ideal way to accommodate all of the microwave's requirements. For instance, it displays the steps a user must take in order to complete a task by walking them through an interface for each sequence of steps. It also presents the user with only the appropriate targets for the task, unlike a touchable interface, which is fixed. This reduces memory requirements and allows for large and widely spaced buttons. Touchscreens also eliminate the need for the user to twist, turn, or pull any type of knobs or handles. Finally, they allow for adjustable fonts, font sizes, and icons (Lorning, 1995).

1.1 Statement of the Problem

Although the advantages are numerous, touchscreen computers possess inherent characteristics that negatively affect the performance of their operators. In fact, as the numbers of touchscreen applications grow, the problems associated with these devices will also increase. These problems lie in the presentation of the hardware and the design of the software. Issues relating to the angle between the operator and the device become prevalent because the physical nature of a touchscreen device varies drastically from small handheld devices to large embedded displays. Past studies have shown that angles other than those that perpendicularly bisect the operator's line of sight cause the operator to misjudge the location of the target and thus affect his or her accuracy (e.g., Beringer et al., 1983, 1985 & 1989; Hall et al., 1988; Sears et al., 1991, 1992, & 1993). The amount of touch bias created from this misjudgment fluctuates according to the target's position on the screen (e.g., upper left quadrant versus the center middle quadrant). Additionally, the percentage of touches that activate a specific target varies according to the size of the tactual recognition field (the amount of touchable region behind the target). Out of three tactual recognition field sizes (1mm, 2mm, and 3mm border around the target), this study sought to match these fields with the amount of touch bias occurring in each location (i.e., small amount of touch bias requires only a small field). This test was performed using a screen angle that has shown to produce a high amount of bias error.

1.2 Review of the Literature

In 1981, Pfault and Priest pointed out the need to improve the interaction between the human and the touchscreen computer. The human is usually the most stringent limitation imposed on a system because of the variability between users and within each user. Finding the optimum tactual recognition field size and position will strengthen the interface between the human and the device, thus increasing productivity. This study first discusses touchscreen computers; the section includes the relevant input devices, providing the advantages, disadvantages and applications of each in comparison to touchscreen devices. Following this discussion are three sections on variables that affect the error rates associated with touchscreen devices: viewing angle, tactual recognition field size and target position. Within each of these three sections is an explanation of the relevant theories and the studies that are related. Conclusions are then drawn from the past literature and hypotheses are provided for the current study.

1.2.1 Touchscreen Devices: A touchscreen computer is an input device, which is used to relay information from the operator to the computing tool. Input devices are defined as the link between the operator, with real objects and forces, and the computer, with graphics and symbolic representation of information. Input devices mediate the human-computer interaction. Casswell (1988) defines seven functions of the input device. They are as follows: (a) select, as in menu items or command lists; (b) position the cursor (i.e., the pointer that indicates where the user's inputs will be located on the screen); (c) orient an object on the screen; (d) describe a path or a sequence of positions; (e) quantify variables, as in dials or scales; (f) associate the groups of display data; (g) input text or information. There are three possible input device interfaces to study: user / device, user / application (software), and device / application (Casswell, 1988). This section and subsequent study focuses on the user / device interface.

Input devices range from keyboards to joysticks, whose main function resides in communicating information from the operator to the computer (Pfauth & Priest, 1981). The different input devices accomplish the same goal through vastly different means; because of this, each device is better suited to perform different functions. Whitefield (1986) classified the touchscreen as a pointing device; therefore, this section will focus on the devices in this category. Pointing devices such as the touchscreen and the mouse are one of the most widely used input devices; they operate by positioning a pointer, such as a cursor, over the item the user would like to select (Whitefield, 1986). Pointing devices are either direct or indirect. A device is considered direct when the physical movement is toward the actual location of the target in space. An indirect device uses a mapping technique because the physical movement takes place towards an area that is physically different from the actual location of the target. The user then selects targets through visual feedback. Mice, trackballs, joysticks and graphics tablets are all indirect devices because they exert control in a plane of space different from that of the device's surface. Any touch-entry system is considered direct because they exert control in the same plane as the surface of the display (Hall et al., 1988). Since different input devices are better suited for different tasks, an explanation of the different devices is provided for mice, trackballs, joysticks, light pens, and touchscreen devices.

1.2.1.1 Input Device Description: A mouse is an indirect hand held device that fits under the palm and fingertips of the user. It attaches to the computer through a wire and operates on any flat surface. It operates by generating cursor movements, and is able to select and/or change menus, draw lines, and confirm inputs. A mouse is used to navigate through the computer, generally in conjunction with a keyboard. The advantages of a mouse are: (a) a mouse can be picked up, moved and operated in small places; (b) its control-display gain can be modified (i.e., the amount of area covered by the cursor in relation to the amount of movement by the mouse); (c) a mouse is relatively inexpensive compared to other input devices; (d) a mouse can be operated while still looking at the screen; and (e) it has a low error rate per number of attempts. The mouse also has a few disadvantages: (a) it needs space in addition to the keyboard; (b) it can only be operated in relative mode, which limits drawing tasks (i.e., the mouse is moved on one plane of space, while the product of those movements are displayed on another plane); and (c) due to the different planes, it is not as natural as a direct pointing device (Arnaut & Greenstein, 1988). The next device, the trackball, both operates and looks similar to a mouse.

The trackball resembles an upside-down mouse, containing a fixed housing with a ball that can be manipulated in any direction by the user's fingertips. Like the mouse, a trackball is an indirect pointing device that moves a display cursor to navigate through the computer and is used as an ancillary device to the keyboard. The advantages of a trackball are, (a) it's good for extended use because the user's forearm is rested and his or her hand is kept in one place; (b) it provides direct tactile feedback and high resolution of movement (i.e., when the ball is moved slowly, the cursor moves slowly, and conversely when the ball is moved quickly, the cursor moves quickly); (c) it is small, and fits in a fixed amount of space; (d) it provides rapid cursor movement; (e) its control-display gain (i.e., the corresponding movement between the ball and the cursor) can be modified; and (f) it is very accurate. The next input device, the joystick, is a trackball with a lever to control movement.

A joystick consists of a lever ranging from small (2.5cm) to large (10cm), which is mounted vertically in a fixed base. Using indirect control, joysticks fall into three categories, displacement, force, and digital. Like the mouse, all three types are best suited to tracking/pointing tasks. The overall advantages of joysticks are as follows: (a) all three types occupy a small, fixed amount of space; (b) most joysticks also include a palm rest, keeping hand fatigue down to a minimum; and (c) many models can be modified to fit the user's needs. The disadvantages to the joystick are as follows: (a) they contain low accuracy; (b) joysticks also have low resolution; and (c) they are unable to digitize drawings or input characters (Arnaut & Greenstein, 1988). Besides touchscreen devices, the last input device covered in this section is the only other direct pointing device, the light pen.

A light pen is an input device that generates information when pointed at a screen. It operates by an electron beam in a screen passing over and refreshing the phosphor at the spot where the light pen is pointing. This causes an electrical signal to be sent to the computer and then its coordinates are calculated. Most light pens contain a finger-operated switch that hinders inadvertent activation. The light pen is most suitable for menu selection tasks, as well as tasks such as placing and moving symbols on a display. There are two modes in which the light pen operates, pointing mode and tracking mode. In the pointing mode, the operator points to a spot on the display and activates the pen. While in the tracking mode, the pen is used to position a cross hair (or cursor) on the display, and when the pen is moved, a line is traced from the cross hair to the pen's new position. The light pen's advantages are (a) its inherent direct eye-hand coordination, and (b) it needs no extra space around the display. Arm fatigue and user position relative to the display (i.e., the user must be close to the display, and the arm and/or pen may obscure the display) comprise this device's disadvantages (Arnaut & Greenstein, 1988). Touchscreen computers, the final input device covered, is the focus of the current study.

Any touchscreen device can be defined as an apparatus that allows an area on the display to be selected by touching the screen (Davies, Mathews, & Smith, 1988). In other words, it is a technology that permits the operator to make a selection by simply touching. It permits the user "to designate a selection among options available on an output device by touching an area of the screen with a finger or other pointing devices" (Phauth & Priest, 1981, p. 500).

1.2.1.2 Touchscreen Characteristics: Before discussing how the various touchscreens operate, three measures of quality inherent to all touchscreens are explained first in order to compare the different types of touchscreen computers later. The three measures are durability, optical clarity, and resolution. Durability is the characteristic that helps define a system's lifespan. The device must be resistant to scratches, dirt and dust because touchscreen devices are often used continually in public areas such as hotels, banks and museums. These factors may reduce the life of the device, or make the device difficult to read. Optical clarity is related to durability; if the screen is damaged or dirty, less light is allowed to pass through the surface to the user. This quality reduction can lead to eyestrain and eye fatigue. Additionally, some of the touchscreen devices have inherent optical clarity problems due to an overlay reducing the amount of light reaching the user. Finally, resolution refers to the amount of discrete touch points on the screen. The higher the resolution, the easier it is for the software to map them to the targets on the screen. Although low resolution can cause a multitude of pixel locations to be returned for a touch in a single location resulting in an inability to provide precise information about the user's selection, with contemporary devices the resolution is usually high enough to avoid these problems. Next is a description of the general operation of touchscreen devices, with the characteristics of each type of device and the various selection strategies. This is followed by a section that includes the touchscreen devices' intrinsic advantages and disadvantages.

1.2.1.3 Touchscreen Operation: Touchscreens operate through an input signal that is created in response to input (i.e., a touch or movement on the surface). This signal produces the location of the touch specified by the coordinate X (i.e., horizontal position) and Y (i.e., vertical position); this data travels to the Central Processing Unit (CPU), which then compares it to the current information displayed. The CPU then calculates the operator's request, and performs the action before returning to a ready state (Pfauth & Priest, 1981).

There are two primary types of touchscreens, which use different methods of operation. The first method consists of an overlay placed on the screen that senses the touch or the pressure changes from the touch, thus creating a signal. In other words, the user's finger applies force onto the screen, and its position is determined by resistance measurements in two orthogonal axes and then converts them into screen coordinates. The devices that use this overlay method (also called pressure sensitive method) characteristically have low durability because the overlay is easy to scratch, although the overlays are designed for easy replacement. The overlays also reduce the amount of light that reaches the user causing low optical clarity. The devices that use this method also characteristically have high resolution (1,000 x 1,000). The second method senses touch through an interruption of beams that are projected across the screen. Since the light beams are placed in front of the screen, a finger or stylus will interrupt the beam without actually touching the screen. The detectors will sense the interruption and calculate the corresponding location on the display. The devices that use the signal interruption have high durability because the user does not actually have to touch the surface in order to activate it. They also have high optical clarity because nothing filters the light before it reaches the user. Finally, the devices that use this method vary in resolution depending on the manufacturer (Arnaut & Greenstein, 1988; Davies, Mathews & Smith, 1988).

There are also three different touchscreen selection strategies that can be programmed into any touchscreen device: land-on, first-contact, and take-off. With the land-on strategy, the location of the initial touch is used for the selection. The initial touch must correspond to a selectable region, or no selection is made. After the initial contact with the screen is made, all further movement is ignored. This strategy does not provide continuous touch data; therefore dragging the finger will not produce a selection. The first-contact strategy chooses the fist selectable region the user comes into contact with. This strategy is similar to the land-on strategy, but it uses the continuous stream of touch data to allow the users to drag their fingers to the desired target. In other words, in using the land-on strategy, if the users' touch lands in an unselctable region, they must lift up their fingers and try again; in the first-contact strategy, if the users' fingers land in an unselectable region, they simply drag their fingers to the desired target. All selections made outside of selectable regions are ignored. Finally, the take-off strategy, when the user touches the screen, a cursor is placed slightly above either his or her fingers. The cursor indicates the exact location of the user's contact with the screen. The cursor is then dragged to the desired region and selected when the user removes his or her contact with the screen. Again, if there is not a selectable region under the cursor, the action is ignored (Potter et al, 1988; Sears & Shneiderman, 1991). Sears and Shneiderman (1991) performed a study comparing the three selection strategies. The study indicates that the first-contact strategy is the fastest selection strategy, but the results pertaining to error rates did not consistently favor one strategy. In 1993, Sears et al. performed another study finding that with the lift-off strategy, it is possible to yield accurate results for targets approximately 0.2cm per side. Additionally, Plaisant (1999) asserts that the lift-off strategy is the most accurate out of all the strategies; stating that with it, it is even possible to select a single character. Potter et al. (1988) also performed a study comparing these three touch strategies, using speed, accuracy and user satisfaction to measure the performance of each. The overall mean time for the first-contact strategy was significantly higher (took longer) then either land-on or take-off. There were significantly fewer errors with the take-off strategy than with either of the other strategies, and it also received a significantly higher rating than the land-on strategy, but not the first-contact strategy.

1.2.1.4 Touchscreen Advantages and Disadvantages: With all of the different characteristics available in the family of touchscreen computers, there are advantages and disadvantages shared by all. For example, the very nature of touchscreen devices lies in its hands-on design. People naturally point to objects as means of communicating position. Pointing is almost instinctive in nature, as shown by the example of a young child pointing at a cookie he or she would like to have (Pfault & Priest, 1981). Fritz (2000) comments on the intrinsic nature of pointing, "Even before a newborn infant's vision has completely cleared, it is already exploring its new world by reaching out and touching. The desire to touch is innate, primal. Therefore, what could be more intuitive and natural than interactive computer applications that can be controlled by touch?" (Fritz, 2000, p. 28). The pointing action is a natural method of identifying objects that satisfy the user's natural mode of expression. Consequently, the user becomes more productive in performing tasks (Davies, Mathews, & Smith, 1988; Pfault & Priest, 1981). Due to this quality, touchscreens have been accepted in areas where either unskilled or untrained operators use systems. It has been shown that touchscreens are well suited for naïve users. For example, Usher (as cited in Whitefield, 1986) compared unskilled operators using a touchscreen device and a keypad. He found a performance difference favoring the touchscreen. It is reasonable to expect that devices that most resemble everyday pointing activities will produce the least cognitive load for unskilled operators, since the user simply touches the item they are interested in (Whitefield, 1986). In the last decade, specifically in the last five years, the number of naïve or occasional computer users has risen. Couple that with the fact that the number of touchscreen devices has also risen, and the need to improve the interface between the operator and the computer becomes apparent. This next section describes the advantages and disadvantages of using a touchscreen computer, leading into an explanation of three variables that affect operator performance, along with the factors and theories affiliated with each of the variables.

There have been a variety of advantages associated with the use of touch screen computers. One of its most important advantages lies in its directness, "what you touch is what you get" (Fritz, 2000, p. 28). Additionally, the direct hand-eye coordination allows the user to input information without memorizing commands. Related to the reduced memory requirements inherent to touchscreen devices is the idea that the software design leads the operator through the steps to completing a task by changing the possible inputs. Additionally, the devices are easy to learn, requiring little training, but yielding high acceptance rates (i.e., shortens the learning curve). Many touchscreens are mobile, requiring little to no additional workspace. Touchscreens have no moving parts; this produces a lower maintenance downtime rate. Additionally, attached input devices such as the keyboard and mouse are easy to steal and more susceptible to vandalism in public places, while touchscreens are embedded either into a larger system, or securely bolted to a surface. Touchscreens also allow application-specific layouts and customized interfaces to complement both the user and the task (i.e., different types of keyboards). Touchscreens possess favorable operator reaction times, which reduces the overall operating time on a task. Finally, touchscreen computers have the same medium for display output as for display input, which allows the user to remain focused on the screen at all times (Arnaut & Greenstein, 1988; Fritz, 2000; Pfault & Priest, 1981; Sears & Shneiderman, 1991; Sears et al., 1993; Whitefield, 1986; Whitford, 1999; & Wright et al., 2000).

In addition to the advantages, touchscreen computers also have a number of disadvantages. For example, the gross motor movements inherent in these devices make physical discomfort and fatigue inevitable without additional arrangements (i.e., a rest pad). The user also must be within arms reach of the display. In addition, the arm and hand may obscure the screen. Moreover, depending on the room's light source, glare can impede the device's readability. Touchscreens have also been shown to be slow for unstructured data entry due to the pointing motion. Currently, they are not suited for applications requiring high accuracy, because unfortunately, even with the newest touchscreen technology a high error rate still exists. (Arnaut & Greenstein, 1988; Fritz, 2000; Pfault & Priest, 1981; Sears & Shneiderman, 1991; Sears et al., 1993; Whitefield, 1986; Whitford, 1999; & Wright et al., 2000).

It is important to understand both the advantages and disadvantages innate to touchscreen devices in order to ensure that form follows function. In other words, that the right input device is used for the task at hand. For example, a touchscreen is best suited for selecting tasks and operations that require the user's attention to remain on the screen (i.g., air-traffic control).

1.2.1.5 Input Device Comparison: Many studies have been performed comparing these input devices in terms of human performance (e.g., Albert, 1982; Schulze and Snyder, 1983; & Whitefield, 1986). Albert (1982) compared the performance of several devices on a target acquisition task. Using a touchscreen, light pen, trackball, displacement joystick, force-operated joystick and keyboard, the subjects positioned the cursor within a 2.54-cm square target and then confirmed their position. The devices with the most accurate performance turned out to be the trackball, graphic tablet, and force joystick, while the devices that were least accurate were the touchscreen and the light pen. On the other hand, the touchscreen and light pen held the fastest positioning speed, while the keyboard and the joysticks were the slowest. Albert attributed this speed to the direct eye-hand coordination inherent in the touchscreen and the light pen. Additionally, subjects preferred the touchscreen and the light pen to the other devices (Albert, 1982).

Whitefield (1986) illustrated the differences between the light pen, mouse, graphics tablet, and touchscreen and demonstrated the optimal uses for these pointing devices by comparing them on accuracy and time. His deductions were similar to Albert's results: the most accurate devices were the mouse and the graphics tablet, while the touchscreen and light pen were the fastest. Whitefield believes this is due to the fact that the optimum position for viewing the touchscreen display differs from the optimum position for interacting with the device. Pointing devices tend to rely on visual feedback, which can be problematic for touchscreens for a number of reasons. For example, the arm and hand movement can partially obscure the target; so inputting more than one response may require the user to move his or her hand away from the screen to get a clear view in order to locate the new target (Whitefield, 1986). Mauatore (as cited in Sears & Shneiderman, 1991) reviewed 14 studies that compared various input devices. She found that touchscreen devices were the fastest, but least accurate. Ahlstrom and Lenman (as cited in Sears & Shneiderman, 1991) compared a touchscreen and a mouse, finding once again that the touchscreen was faster, but compiled significantly more errors than the mouse.

The results of the studies comparing touchscreens with other input devices indicate that it is best used for rapidly selecting relatively large targets, but the error rates for these studies were significantly lower for the other devices. Of course, there are times when a touchscreen is the best device for the task, but performance errors still hinder operation (e.g., air-traffic control). In the case of air-traffic control and similar operations, it is important to achieve the optimal performance from the device. This is accomplished through avoiding or correcting the disadvantages and using or strengthening the advantages. For example, Stammers and Bird (1980) evaluated a touch-input system for airport air-traffic control (ATC) operators. Data was collected on a transferring data and displaying data task through questionnaires and video/sound recordings. They found both advantages that are unique to touchscreens and disadvantages that need to be reduced or eliminated. For the touchscreen devices themselves, they found a high acceptability rate among the controllers. Additionally, they found a high level of compatibility between the display and the control. In other words, the screen acted as both the input device and the output device. They also found that only after a couple minutes of practice the controller understood and performed the tasks adequately (i.e., a steep learning curve).

Unfortunately, a majority of the controllers reported encountering parallax problems. When found in literature, parallax has slightly different meanings, but always the same result. Parallax causes a touch to be inaccurate. Carrol Touch (2001) defines parallax as occurring when a touch is detected while the stylus is still a small distance from the surface of the display, indicating that parallax can only occur in devices that use signal interruption. Conversely, Arnaut & Greenstein (1988) state that parallax "occurs when the touch surface or detectors are separated from the targets." Pfauth & Priest (1981) concur, saying it is caused by the distance between the screen and the LED beams, thus affecting the varying ambient light conditions on the LEDs. In other words, the touch surface of all touchscreen devices is placed slightly above the targets due to the glass cover. This surface creates a gap between the phosphor target and the operator's finger or stylus (Arnaut & Greenstein, 1988). If the device has an overlay, the distance is even greater, causing the overlay to bend the light from the target slightly, thus causing a small misalignment between the target and intended touch points. The literature agrees that the curved surface of CRTs (the face of the computer) accentuates parallax because the curved glass bends the light more than a flat display. Therefore, the more flat the display face, the lower the amount of parallax present. All of the studies examined in this review used touchscreen computers with curved surfaces and overlays (using the pressure sensitive method, not the signal interruption method). Therefore, for the remainder of this study, parallax will refer to the gap between the surface and the receptor.

The controllers in Stammers and Birds's study also indicated they had to touch an icon more than once to activate it (again, possibly due to parallax). Additional complaints were recorded about the screen angle and the distance between the controller and the screen. Stammers and Bird emphasized that in order to improve the interface between the operator and the device, there is a need to minimize the number of errors, and to provide adjustment controls for factors such as distance, angle, brightness, and contrast. Plaisant (1999) stated that choosing the wrong target or having to touch a target more than once is frustrating to the operator. Pfault and Priest (1981) also accentuated the need to minimize the number of operator errors associated with the human's limitations with respect to reliably, accurately and quickly making selections of targets requiring high accuracy. The next section expands upon this topic, covering three relevant performance variables, and their associated theories: viewing angle, tactual recognition field size, and target location.

1.2.2 Viewing angle: As stated earlier, touchscreen devices have been shown to be the least accurate of all the input devices (Whitefield, 1986; & Sears & Shneiderman, 1991). This leads to the question, how accurately can a user touch targets manually on the face of a display? The answer to this question is related to issues such as the device's display angle, and the design of the software in terms of tactual recognition field size and target location. This section provides a review of the past studies that have manipulated the angle between the face of the device and the operator.

In 1966, Orr and Hopkin (as cited in Beringer, 1983) suspected that the optimum display angle for a touchscreen device is not necessarily the appropriate or optimum input angle. In 1977, Bird (as cited in Pfault & Priest, 1981) tested a touchscreen computer with a tilt angle of 30° (the standard typewriter slope in Great Britain) and found that this angle allows for arm support, but produced accuracy and glare problems. Since then, there have been more studies performed that provide additional insight into the psychological principles that underlie the touchscreen's human-computer interface. For instance, Beringer et al. (1983, 1985, & 1989) performed a series of experiments examining the accuracy of a touch in relation to the device's display angle, and the position of the target on the screen. When he began studying touchscreen devices in the early 1980s there was not an abundance of behavioral and performance data to aid in the design process. Designers were not able to take full advantage of the unique interface technique provided by the touchscreen due to this lack of information. Additionally, a study by Coskutuna (1983, in Beringer & Peterson, 1983) examined operator preference of computers mounted at 20°, 30°, and 45° from the vertical. There were no performance ratings indicated, but the majority of standing operators preferred the screen with a 45° tilt.

Schultz, Batten, and Sluchak (1998) comment that a number of studies have been performed on workstation design analyzing the design and placement of monitors and keyboards. These have resulted in guidelines for the designers of workspace areas to use. Unfortunately, there are few such guidelines related to touchscreen displays in common working and commercial areas. Schultz, Batten, and Sluchak (1998) performed a study to determine the optimum viewing angle or range of angles through an anthropometrics/workstation analysis and a usability study. They looked at user preference by allowing the operator to adjust the display to a comfortable angle. Neither the time on task nor error rates were collected. In the workstation analysis, Schultz, Batten, and Sluchak used Humanscale® to define the "normal standing sight line" (10° below the horizontal eye level) and the "ease of eye movement" (30° below the horizontal eye level) (Schultz, Batten, & Sluchak, 1998, p. 345). They then used this information to establish the best viewing angle of the display. They hypothesized that adjustment of the touchscreen would be necessary to provide optimal viewing angles (in terms of subjective data) for the full range of possible users. They also expected to find an optimal range of viewing angles as opposed to a single suitable viewing angle. Using the 2.5^{th} percentile Japanese female and the 97.5^{th} percentile United States male they obtained the theoretical extreme boundaries of the viewing angle or display tilt. For the female, given the display height, a head tilt of 15° (which is within the 30° range of easy head motion), and a display angle of 55° from the horizontal, "created the desired perpendicular angle between the bisecting vector of the preferred viewing cone and the middle of the screen" (Schultz, Batten, & Sluchak, 1998, p. 345). In other words, the angle of the screen and the tilt of the head were perpendicular to one another (i.e., the operator was looking directly at the device). The male required a head tilt of 40° (which is not within the range of easy head motion, but with in the 60° maximum head motion) and a display angle of 30° from the horizontal to create the same perpendicular angle. Therefore, because of the workstation analysis, they expected their usability study to find the subjects adjusting the angle of the display 30° to 55° in order for the screen to perpendicularly bisect their line of sight. In actuality, the angles ranged from 19° to 54.5° off the horizontal, with 92% of the subjects adjusting the display between 30° and 55°, and 46% between 44° and 49°. This data suggest that there is no optimal viewing angle for touchscreen displays, especially given the natural dynamic set of user heights and static workstations and kiosks. There is however a range of angles that will satisfy the majority of the population, so designers should ensure that their display is adjustable to these angles. Schultz, Batten, & Sluchak state that, "Unless people become the same size and display technology enables viewing from any location, there will probably never be a single, optimal viewing angle. However, there may always be an optimal range that is dependent on the user set, the environment and the tasks" (Schultz, Batten, & Sluchak, 1998, p. 349).

In 1983, Beringer looked at the accuracy of a user's touch in terms of its x- and y-axis position as well as the user's response time. These were measured as a function of both the display angle, and the location of the target on the screen (the later will be covered in section 1.2.3). He had four display angles: 90°, 75°, 60°, and 45° from the horizontal, and he measured performance by recording the distance of the user's actual touch to the center of the target in both the x-and y-directions (called x-error and y-error respectively), and by timing the subject's response to the stimulus (i.e., the target). Beringer held constant the angle between the subject and the device, by using an ophthalmology chair. This chair was vertically adjustable to bring the subject up to the height of the device. Each subject was seated at the standard eye position, which is achieved when the display center is 15° below visual horizon and the display plane is orthogonal to the line of sight. Although screen angle did not significantly affect response time, there was a significant effect found between the 90° angle (-0.49 touch units or -1.56mm) and the 45° angle (-0.94 touch units or -2.99mm) in terms of accuracy. Essentially, Beringer found that subjects touched slightly below the targets, and this bias increased when the display was at an angle other than perpendicular to their line of sight. He also found that the error was exaggerated toward the top of the display, and dissipated as the target appeared closer to the center of the display. He speculated that the low accuracy rates were due to parallax (i.e., the difference between the touch surface and the targets). Beringer commented, "It is not surprising that individuals have a tendency to touch somewhat lower than intended on near-vertical surfaces or in situations with parallax problems. This has been documented previously. What is of interest here is the amount by which this occurs and how that amount can be influenced by variations in the control-display surface" (Beringer, 1983, p. 14). He then recommended designing the software to compensate for this known touch bias (i.e., changing the tactual recognition field size), which will be covered in section 1.2.4. Beringer also recommended training the user in selection strategies through feedback.

A study by Beringer and Peterson (1985) replicated the previous experiment but took the research one step farther by investigating feedback. This study also sought to find how accurately the operator could manually designate targets on the display with varying screen angles. A significant difference in y-error was again found as the angle of the display rotated from 90° to 45°. This study also accounted for errors Beringer and Peterson termed as "blunder errors." Occasionally, a subject would accidentally touch the screen with his hand or clothing. This data could potentially confound the results of the study, and therefore they named, defined, and categorized these errors. An input that appears more than six touch-units away from the target was labeled a blunder error, and a response time less than 200ms was called a zero-time blunder. They recorded over twenty blunder errors and did include them in their results. These errors generally occurred while the subject was "on the way" to the target. These errors were also associated with the subject's hand resting position. The most blunder errors occurred during toward the end of the experiment, correlating with subjective reports of fatigue and a 45° screen angle.

The second experiment performed in this study (1985) examined Beringer's idea of training through feedback. He felt that providing the user with feedback in terms of both cursor location and the correctness of their actions would affect performance by making the user aware of the results of his or her inputs. When the user interacts with the touchscreen device, any kind of response from the system is feedback. For instance, if the user touches the file menu and a list of the available file options appear, the user knows that the correct target was selected; but if the edit menu appeared, the user would know that the incorrect menu was selected. If it takes a bit of time for the computer to open or run a certain application, a timing device of some sort appears to let the user know that his or her request is being processed. If this feedback is not apparent, the user might try to reactivate the same target, slowing down the process or even freezing the computer. Feedback increases accuracy and therefore ease of use (Arnaut & Greenstein, 1988). The second experiment required the subjects to touch a square target (3.175mm each side) on a blank field. In the feedback condition, a series of squares appeared around the target when it was touched correctly, while in the no feedback condition, the target disappeared when the subject touched the screen and a new one appeared after 500 ms. The target positions were selected from a grid of 108 positions (18 across x 6 down), and the screen angle remained fixed at 90° to the subject's line of sight. In the no feedback condition, the subject, on average, touched lower than the target on the screen, and the higher the target appeared, the greater the error became. The fact that they still found a touch bias at 90°, although small, indicates that something besides screen angle influences touch bias. Beringer suggests this small bias is due to parallax because of the curved nature of the screen. An x-error was found near the extreme corners of the screen, but is attributed to the curved surface of the device. There was also a significant difference between the left-handed subjects and the right-handed subjects in relation to the x-error; right-handed subjects touched slightly to the right of targets, and left-handed subjects touched slightly to the left. In addition, an interesting behavior was uncovered when calculating response time; Beringer and Peterson found that subjects responded to the targets in rhythmic patterns. In fact, "One subject had an average response time of exactly one second for each of the four blocks" (Beringer and Peterson, 1985, p. 454). Therefore, response times were not calculated due to the heterogeneity of variance present. In other words the variance within the scores of one participant differed significantly from the variance within the scores of another participant. Feedback reduced y-error from –0.375 units (-1.191mm) without feedback to –0.063 units (-0.20mm) with feedback. Feedback also reduced blunder errors. These studies by Beringer et al. (1983 & 1985) show that a small amount of error on the vertical axis is likely to be present when no extrinsic feedback is present, and it is exaggerated as the surface is tilted away from the operator.

Up to this point, throughout all of experiments performed, Beringer et al. (1983 & 1985) have suggested that the touch bias is due to the parallax inherent in most touchscreen devices. When using a CRT touchscreen (i.e., a screen containing a convex curve), Pfauth and Priest (1981) suggest avoiding placing targets on the edge of the screen because the screen is most curved at the extreme sides of the screen, bending the light rays and increasing the effects of parallax. The parallax theory is partially supported through the bias errors found by Beringer and Peterson's (1985). They found a small touch bias on the vertical axis when the screen was positioned perpendicularly to the operator's line of sight, indicating that parallax influences touch bias. In 1989, Beringer and Bowman studied the effects of screen angle and target location while using a high-resolution touchscreen device to minimize parallax. As stated earlier, Beringer (1983) and Beringer & Peterson (1985) suspect that it is parallax's influence that is reduced (but not eliminated) when the operator's line of sight perpendicularly bisects the device's surface. Beringer & Bowman's (1989) study reproduced the second experiment in Beringer and Peterson's study, but with using a much higher resolution device to minimize the touch bias caused by parallax.

In this experiment, Beringer and Bowman (1989) used only two levels of the independent variable, screen angle. One angle was 90° to the subject's line of sight, and the other was 17° below orthogonal to the subject's line of sight. Assuming standard table height, nonadjustable monitors are usually set up with a screen angle that is 15° to 20° below orthogonal, which explains why they chose a 17° angle to test. Although parallax was not directly manipulated they expected to find less touch bias because the device they employed reduced parallax. They anticipated finding targets located at the extremes of the surface increasing touch bias, and an exaggerated y-error as the surface declines away from the subject. There was in fact a significant difference in y-error between the normal or standard screen position of 17° below orthogonal, and the orthogonal screen. Even though parallax was reduced through the new touchscreen, a touch bias was still found. The results are inconclusive because parallax was not manipulated, and therefore, it is not known how much bias is due to parallax and how much is due to other factors. Consequently, it can be said that parallax is a factor in touch bias, but it collaborates with another contributor: slant underestimation.

Perrone (1980) proposes a slant underestimation model based on the users' miscalculating the location of the device's perpendicular angle relative to their view point. When this device is tilted away from the operator, the direction of the line from the eye to the bottom edge of the device is mistaken for the perpendicular line that bisects the user's line of sight. This is due to the lack of information concerning the true direction of the perpendicular, and causes information in the optical array to produce a visual slant underestimation on the basis of the perpendicular lying in this new direction. Essentially, slant underestimation is due to a common perceptual illusion where surfaces appear to lie closer to the fronto-parallel plane (Perrone, 1991). In other words, the top part of the slanted surface appears to be slightly closer to the observer (i.e., the slant is underestimated). Gibson (1950) states that users have a 'frontal tendency', where the judged slant is displayed in the direction of a frontal surface.

In real-world applications, touchscreens are often used in environments where the reference axis is obscured. It occurs when reference lines, such as the horizon, are hidden. This is especially the case as touchscreen technologies become wide spread in transportation vehicles, such as in moving cars, aircraft and even training simulators. Therefore, more often than not, slant misinterpretation will occur where the perceived straight-ahead direction does not coincide with the actual straight-ahead direction. This occurs in these types of conditions because the operator uses the strategies that correspond to the tactics used in optimal conditions, and therefore perceives straight-ahead to be the direction from the eye to the nearest part of the surface. In both optimal and sub-optimal conditions, the device's angle of convergence and the distance of the line from the center of the device to the user are used to determine the device's slant. If either if these factors is misinterpreted, the device's derived slant will be incorrect. Essentially, this means that in less than optimal conditions, the operator's perceived straight-ahead direction will not correspond with straight-ahead. This is due to the operator thinking that straight-ahead is in the direction of the nearest part of the device (Figure 1).

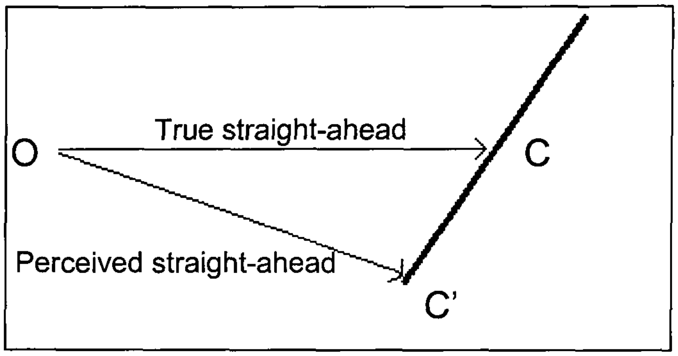

Figure 1: Straight-ahead interpretation: The shortest distance to the display's surface lies in the direction OC', which causes the operator to misinterpret it as straight-ahead.

For example, for a device that is perpendicular to the operator's line of sight (i.e., a wall mounted touchscreen), the straight-ahead direction passes through the central pivot of the surface or the shortest distance to the surface. As the device is slanted back away from the operator about its central axis, the shortest distance to the screen is no longer the distance from the eye to the device's central axis, but rather from the eye to the bottom edge of the device. This misjudgment does not occur in optimal conditions because the operator can use cues from the environment to estimate the device's slant angle. However, touchscreens that are mounted in kiosks or vehicles may lack the necessary cues for the operator to accurately judge their slant. The operator is left to rely on the cues inherent in the device itself, namely, its angle of convergence and the distance of the line from the center of the device to the operator's eyes. The angle of convergence is created when a device is no longer perpendicular to the observer's line of sight. When the device is perpendicular, the left and right side are parallel to each other, but when it is tilted away, the sides look as if they are converging. The greater the tilt, the closer the lines are to converging near the top. Perrone (1982) explains how this misinterpretation occurs:

> Consider a line passing through the center of the eye and running perpendicular to the frontoparallel plane. Call the length of this line, from the eye to where it meets a surface, *d*. Now consider what happens to the value of *d* as the head is orientated at various angles in relation to the surface. Only when we are oriented 'straight-on' to the surface will *d* be at a minimum. In other words, we are orientated 'straight-on' to a plane surface whenever the length of the perpendicular is at a minimum. Under this condition the perpendicular to the frontoparallel plane of the observer is parallel to the perpendicular to the plane of the surface (Perrone, 1982, p. 645).

In other words, the observer's perceived straight-ahead direction does not coincide with the true straight-ahead direction when the external reference of the environment is obscured. Again, the operator resorts to the common relationships normally experienced when the device is positioned 90° to the line of sight; this corresponds to the shortest distance from the operator to the surface (i.e., the bottom edge of the device). When the operator uses this incorrect straight-ahead position, an incorrect distance is registered and therefore an incorrect angle. This incorrect angle is usually underestimated because the operator uses both the angle of convergence produced by the edges of the touchscreen, and the total visible length of the surface. This total length is used as opposed to the top half of the surface that would be used if the device were perpendicularly bisecting his or her line of sight (Figure 2).

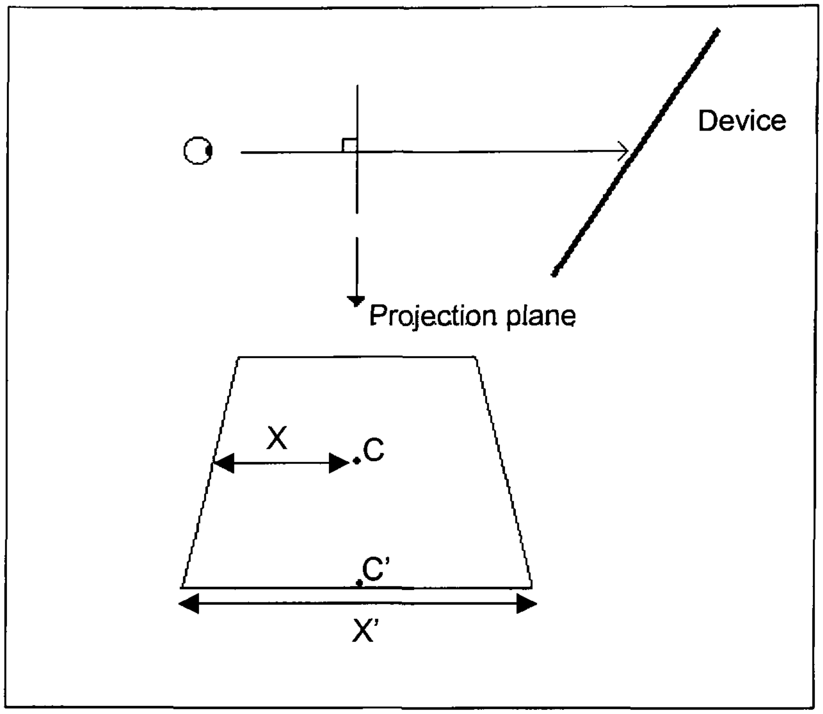

Figure 2: Slant underestimation: When the device is projected on to a projection plane (such as the retina), C' is interpreted as the straight-ahead, while C is actually the true straight-ahead. This causes X' to be used in estimating the slant angle in place of X.

Two-dimensional slant information can be derived from the angle of convergence and the distance of a particular line from the center of the projection plane (such as a retina) to the edge of the device. In other words, both the length and the width of the surface must be taken into account (i.e., the surface of a touchscreen device). Perrone (1991) theorizes that the base of the device (X') is used to estimate the slant as opposed to the length from the true straight-ahead direction over to the side of the device (X). Essentially, the operator erroneously uses the total width of the base rather than the correct half-width at the axis of rotation. By using the convergence angle of perspective lines and the correct X (half the width), a correct slant angle can be determined, however, if X is over estimated, the slant angle will be underestimated. Essentially, in the mind's eye, the touchscreen device is rotated slightly closer to the operator at the base of the device.

In 1984, Perrone applied this theory to the illusions experienced by pilots making night landings. In this case, the pilot's visual system (similar to that of the touchscreen operator) uses the wrong variables to calculate the appropriate approach path to the runway. Without cues from the environment, the pilot rotates the runway closer to the fronto-parallel pane. Under normal viewing conditions, (i.e., day light) the pilot compares the vertical distance from the aimpoint to the top edge of the runway to an equal horizontal distance from the aimpoint, then to a point beyond the side edge of the runway. This information is sufficient for the pilot to maintain the appropriate approach angle. However, during a landing at night, most perspective information about the correct horizontal distance from the aimpoint is missing. The pilots then use the only perspective information available, the edge-lights of the runway. This horizontal length is much smaller than the correct length (similar to the X' of the touchscreen device). This causes the pilot to misinterpret the dimensions of the runway, thus affecting his or her approach angle and distance from the runway. More precisely, the runway looks smaller to the pilot, which makes him or her perceive his or her approach path to be about twice what it should be to land near the aimpoint. In order to make the approach look "normal," the pilot will descend and decrease the approach angle. With a smaller approach angle, the approach path will shorten, causing the pilot to land short of his or her aimpoint. This effect is more prevalent for long, narrow runways.

Now that there is an understanding of how and why users underestimates an angle that is tilted away from them, the question remains, why would underestimating a slant cause the user to touch slightly below the target. Put simply, the target appears to be located slightly lower on the screen. The operator's touch where the target would be located if the device were positioned at an angle rotated slightly closer to them. In other words, the actual touch lands slightly below the target because the user perceives it to be lower due to the distance between the true straight-ahead and the perceived straight-ahead and therefore the perceived target location is lower than the actual target location. Additionally, the higher the target is located on the screen, the greater the error (Perrone, 1991). Hall et al. (1988) provided more evidence to support Perrone's slant misperception theory.

Hall et al. (1988) investigated the effect of tactual recognition field size (covered in section 1.2.4) and screen angle on user performance. They performed two experiments, reporting system accuracy rates as a function of the angle between the user and the device, target size, parallax, and gender. Beringer et al. (1983 & 1985) had looked extensively at the angle between the operator and the device, but parallax was not actually manipulated, it was just referred to as a potential source of error. Additionally, the tactual recognition field size was never changed in any of the previous experiments, so they were interested in the effects this would have on accuracy. They combined these variables because they wanted to know how these factors, together and separate, would bring about changes in bias error to achieve desired levels of accuracy. The performance of the subjects were measured through x- and y-error, in millimeters, between the center of each target and the location of the actual touch, and accuracy. They defined and measured accuracy as, "when a subject touched a target on the screen, the display system calculated an estimate of the location of the subject's touch. If the location of the touch was within a prescribed software boundary (a tactual recognition field, defined on the x- and y-axes), the display system would accept the touch for the intended target; if, however, the location of the touch was outside of the boundary, the system would reject the touch" (Hall et al., 1988, p. 713). They excluded data that created errors similar to Beringer and Peterson's (1985) blunder errors; these were defined as any touch that produced an x- or y-error greater than 999.99mm or a response-to-stimulus time of less then a millisecond (i.e., a nanosecond). In the first experiment, the subject was seated at a workstation. The vertical angle of regard was held constant with the device perpendicular to the line of sight; however, the horizontal angle of regard was manipulated. In other words, they measured the subject from the left, right, and center of the display. Three different sized solid boxes were presented as targets for the subjects: 10.8mm x 12.2mm, 12.6 x 16.01mm, and 12.6mm x 12.20mm. This experiment was a mixed design with gender as a between subjects variable and all other variables within subjects. The screen was equally divided into nine sectors, having four targets in each, therefore the targets appeared in 36 different locations on the screen. The targets were presented to the user one at a time, in a random order. Each subject participated in five trials, two of which consisted of the pretest and the posttest with the subject located directly in front of the display. The other three trials were randomly presented to the subjects, in terms of horizontal angle of regard (i.e., participant to the left, right, and center of display).

Hall et al. found a significant effect for horizontal angle of regard. In other words, there was a significant difference between standing to the left and to the right, as opposed to the middle. Additionally, comparisons of the pretest and posttest showed a significant difference between the y-error. Hall et al. presented two explanations. The first explanation was that data were not reliably recorded for all subjects during the pretest and the posttest, and therefore this data may not be generalized to the rest of the sample. The second explanation for the difference is muscular fatigue. Muscular fatigue is due to overstressed muscles, in this case, the muscles located in the shoulders and arm. It occurs while operating a touchscreen for a long period of time because the arm must be held in a static position. When a muscle is held in a static position (i.e., a prolonged muscle contraction) the blood flow is restricted, waste products accumulate and produce the acute pain associated with muscle fatigue. Due to this pain, static muscular effort cannot be held for a long period of time, and the operator is compelled to relax (Kroemer & Grandjean, 1997). Fortunately, muscular fatigue can be avoided through breaks between the trials, or by providing a pad for the subjects to rest their arms.

The second experiment executed by Hall et al., manipulated parallax by fitting a thin, translucent overlay to the top of one device. The visual targets were etched onto the surface of the overlay over the actual phosphor targets, canceling the effects of parallax, and thus resulting in parallax that was negligible in the system. The subjects remained standing for all five trials, and the target size remained constant. Besides the afore mentioned variables, experiment two used the same method as experiment one. They found that x-error was larger for targets with inherent parallax (2.79mm) than for subjects with parallax reduced by the overlay (2.40mm). Y-error was also significantly higher for subjects touching the screen with inherent parallax present (3.76mm) than for subjects touching targets with parallax reduced (2.02mm). Additionally, more touch responses were accepted as valid by the system for subjects using the device with reduced parallax

(96.6%) than for subjects using the device with inherent parallax (93.5%). They did not, however, comment on the percent of the error for which parallax was actually responsible. There is a high probability that slant misperception also played a role because touch bias was still apparent in the no parallax condition.

In 1991, Sears published a three-phase study to evaluate touchscreen keyboards using high precision touch strategies. Phase one looked at the screen angle relative to the operator by collecting fatigue and preference ratings. Phase two studied the touch bias created by a 30° screen angle and different target sizes. Phase three compared a touchscreen keyboard (i.e., a touch display that had the appearance of a standard keyboard) with a mouse-activated keyboard and standard keyboard. This section focuses on the methods and results of the first phase. The section on target location (section 1.2.3) covers the second phase. In this study, Sears defined biases as consistent differences between the location users want to touch and where they actually touch. He hypothesized that biases exist in both the x- and y-axis will vary with the angle between the user and the device. Sears wanted to maximize the design of touchscreen keyboards because they are optimal for workspaces with little or no extra space (i.e., a restaurant), for tasks requiring a flexible interaction with the computer, or simply for tasks requiring infrequent data entry.

During the first phase of the experiment, Sears collected user preferences and fatigue rankings for subjects using a touchscreen mounted inside a desk at 30°, 45°, and 75° from the horizontal. It was a within subject design, with the angles presented randomly to the subjects. He also built in delay trials to prevent sequence effects or negative performance due to fatigue and not a manipulated variable. Although the touchscreen was mounted at different angles, the visual angle of the subjects was not held constant. In other words, the user was free to adjust his or her head to find the optimum viewing angle; therefore, the viewing angles varied even within the treatments. From the first phase, Sears discovered that the 30° and 45° mounting angles did not differ significantly from one another in fatigue and preference ratings; however, when mounted at 75°, the touchscreen received significantly lower ratings than the other two angles. Later in 1991, Sears again studied the effects of screen angle and target location on user performance.

Almost identical to Sears's (1991) previous study, Plaisant and Sears (1992) performed a three-phase study looking at screen angle and target location to find an optimum target size. The first phase looked at fatigue and preference ratings resulting from different screen angles (30°, 45°, and 75° from the horizontal). Again, subjects preferred using the touchscreen mounted at 30° or 45° from the horizontal. Also, information was collected on touch biases with the monitor mounted 30° from the horizontal. Plaisant and Sears found that the subjects consistently touched below and to the left of the targets, which they again attributed to parallax.

Depending upon the light source and the physical setup of the hardware, there will be times when the operator will not be able to adjust the touchscreen to perpendicularly bisect his or her line of sight. For instance, even a small lamp, if positioned correctly, can create enough light that reflects off the surface of the screen into the operator's eyes. Additionally, most kiosks such as automatic teller machines (ATM) are not adjustable. So the question is, how can touchscreen computers be designed to optimize the user's performance no matter the angle between the display face and the user? Beringer et al.

(1983, 1985 & 1989), Hall et al. (1988), and Sears et al. (1991, 1992, & 1993) included variables in their studies that also include either tactual recognition field size or target location to answer this question.

1.2.3 Target location: The location of the target on the screen has an impact on the amount of touch bias produced by the operator. Many of the studies reported in the previous section also manipulated target location to examine the interaction between target location and the device's angle. For example, Beringer's first experiment in 1983 looked at the accuracy of a user's touch in terms of its x- and y-axis position as well as the user's response time. These were measured as a function of both the display angle, and the location of the target on the screen. As a reminder, he had four display angles, as well as 18 x-axis positions and 6 y-axis positions. He measured performance by recording the distance of the user's actual touch to the center of the target in both the x- and y-directions (called x-error and y-error respectively), and by timing the subject's response to the stimulus (i.e., the target). In terms of target location, he found that reaction time formed a U-shaped curve, meaning that the targets near the extreme sides of the device brought about a longer reaction time than those centrally located. He also found that the relative y-position had a significant effect on accuracy. Error was greatest near the top of the display and progressively decreased from –2.86mm near the top to +0.64mm near the bottom (one touch unit is equal to 1/8 of an inch). This was not due to a "frame effect" (i.e., the area around the edge of the device shifting the user's touches slightly toward the center of the screen in order to avoid the boundaries) because subsequent examination using a cardboard overlay produced similar results.

Additionally, an interaction between screen angle and target location in terms of the horizontal axis (i.e., the x-error) was found, but Beringer suspects that the effect was not due to his manipulations but due to the hardware used in the study. The curved surface of the device created a bias in the corners of the screen, leading him to believe that the error found was due to the bias, and not to his manipulations (i.e., a type one error).

Beringer and Peterson's study in 1985 replicates the previous experiment but took the research one step farther by investigating feedback. The first experiment was almost identical to Beringer's 1983 experiment. It also sought to find how accurately the operator could manually designate targets on the display with varying screen angles and target location. Again response time was longer for targets located on the sides of the display. Target location again affected the accuracy of the subject's touch; the higher the target on the screen, the lower the subject touched.

In the experiment by Beringer and Bowman (1989), only two levels of the independent variable, screen angle (90° and 17°), and target location were manipulated. Just as expected, the display 17° from the orthogonal created an interaction between the location of the target, and the amount of touch bias; again, the higher the target appeared on the screen, the greater the touch bias.

In 1991, Sears published a three-phase study to evaluate touchscreen keyboards using high precision touch strategies. Phase one looked at the screen angle relative to the operator (covered in section 1.2.2), and phase two studied the touch bias created by a 30°-screen angle and different target locations (covered in this section). Phase three compared a touchscreen keyboard with a mouse-activated keyboard and standard keyboard and is not necessary to the current study. Sears sought to design an effective interface by determining the most optimal target position(s), given the preferred viewing angle that resulted in the lowest error rates. For phase two of the study, Sears chose to mount the touchscreen 30° from the horizontal due to the distribution of rankings for preference and fatigue. Touch bias was collected using the screen at this angle, and by varying the target's position. The goal was to find range data to allow him to "determine the distribution of where users actually touched as compared to where they were trying to touch" (Sears, 1991, p. 259). The subjects were presented with two blocks of 70 small targets (1.65mm) in a 10 by 7 matrix. Sears estimated although a target of this size is difficult to touch, it will allow for more precise calculations of the distance between where users mean to touch, and where their touches actually landed. With large targets, it becomes difficult to calculate where the subjects were trying to touch (the edge of the target or the middle), and where the actually touched. The device automatically recorded the distance from the user's first touch to the center of the target. Sears then compared the subject's touch bias to where the targets were positioned on the screen. Not surprisingly, he found that users consistently touched below and to the left of the desired target. Additionally, users touched to the left of the target no matter which side of the screen the target was located, although the bias became smaller as the target appeared closer to the center of the screen. Staying consistent with Beringer at al. (1983, 1985 & 1989), the y-bias increased as the target location appeared closer to the top of the screen. This y-axis bias contributed to parallax. Sears went on to explain, "When the monitor is mounted at 30° from horizontal, the user's line of sight was approximately 38° from the orthogonal with the monitor surface. The extra hardware mounted on the touchscreen used in this study is approximately 0.64cm^2 thick, accounting for bias of approximately

+0.49cm² (below the target). This is very close to the vertical biases measured in this phase which varied from +0.41 to +0.54cm²" (Sears, 1991, p. 261). Although this explanation seems logical, it is suspect because the user's line of sight was not held constant.

Throughout all of these studies, the users consistently touched below the target. This touch bias increased as the target appeared higher on the screen. This bias can arguably be due to both parallax and slant misinterpretation. In Perrone's theory of slant misperception, the taller the device, the greater the misinterpretation of the angle and consequently the lower the touch. For example, in the runway approach situation, the longer the runway, the greater the chance the pilot will over shoot the aimpoint. Often, system designs are operated under conditions or by methods that are not ideal. Touchscreen devices are no different; users often contend with off-axis viewing and non-optimal positioning. These situations increase the possibility of vertical and horizontal bias error. In fact, in real-world applications, off-orthogonal viewing seems to be the rule rather than the exception. For example, touch-activated directories in shopping malls are rarely (if ever) adjustable. Even more prevalent are the center-panel displays in both land and air vehicles (Beringer & Bowman, 1989). So the question remains, how can a touch screen device be designed to compensate for bias error, no matter the angle of regard, or the location of the target on the screen. The answer to this question lies in the size of the tactual recognition field.

1.2.4 Tactual recognition field size: The tactual recognition field size is the amount of area around the target that will indicate to the computer that the target has been activated.

When Beringer discusses his study in 1983, he recommends designing the software to compensate for this known touch bias. He suggests enlarging the touch area around the target to capture the touches that fall slightly below the target (i.e., create tactual recognition fields). This can be achieved in two ways: through population modeling, where the size of the touch area is determined through sampling the population and finding the size that will accommodate most of the users; or through individual modeling, where the size is determined through sampling the bias of a single user and accommodating for his or her particular bias. With population modeling, the software uses the mean y-error of the population to compensate for the touch-bias. Beringer speculates that due to the large variance of touch bias within the population, this type of modeling might not produce a significant reduction in bias error. Beringer and Peterson tested the subjects' variance with Scheffe's test of variance homogeneity; it showed homogeneity (small amount of variance) within each subject, but heterogeneity (large amount of variance) across subjects. Individual modeling, where the software "learns" the bias error of the particular user, can be the next logical step in finding a solution to the touch bias problem. This method works particularly well for privately owned touchscreen devices, but is not a reliable method for devices used by the general public. Beringer estimated that the vast majority of errors were within one touch unit of the target; therefore he concluded that a tactual recognition field consisting of 3 x 3 (+/- 32mm) touch units might eliminate most errors.

Beringer and Bowman (1989) again reinforce the idea of individual software compensation to alleviate the touch bias. Unfortunately, this solution will not be adequate if the device must be used by more than one person (which is the case for military and common area devices). They also suggest training as a way to compensate for this natural bias. Of course, this will not prove effective for equipment located in public places; for example, it would prove very difficult (and not cost effective) to train all of a bank's costumers to use the Automatic Teller Machine's touchscreen computer.

Hall et al. (1988) also investigated the effect of tactual recognition field size and screen angle on user performance (covered in section 1.2.2). They performed two experiments, reporting system accuracy rates as a function of the angle between the user and the device, target size, tactual recognition field size, parallax, and gender. The performance of the subjects were measured through x- and y-error, in millimeters, between the center of each target and the location of the actual touch, and accuracy. They defined and measured accuracy using the tactual recognition field, when the touch was located within the boundaries of this field, the touch was considered accurate, otherwise, it was considered inaccurate. Again, the screen was equally divided into nine sectors, having four targets in each, therefore the targets appeared in 36 different locations on the screen. The targets were presented to the user one at a time, in a random order. As far as target size, tactual recognition field size and error, the mean x-error for the small-sized target was 1.34mm, 1.32mm for the medium-sized target, and 1.35mm for the large-sized target. These x-errors did not differ significantly from one another. The y-errors also did not differ significantly from one another: -1.61mm, -1.71mm, and –1.50. Although the x- and y-errors did not differ significantly for target size, the mean number of touch responses (or accuracy) accepted by the system did significantly differ. Of the small-sized tactual recognition fields, 94.3% of the responses were accepted, 98.2% of the responses for the medium-sized tactual recognition fields were accepted, and 99.6% of the responses for the large-sized tactual recognition fields were accepted.

Overall, Hall et al. found that there is considerable variability in error among users, but calculated that performance would be best when the size of the touch field exceeded 30mm x 30mm. The size and design of a tactual recognition field is a function of the level of accuracy desired for a target. Increasing the tactual recognition field around the visual target increases the accuracy of the system, but reduces the number of targets the screen is able to hold. In other words, increasing this field around the target accommodates the variability in performance among users and minimizes the effects of optical parallax, screen angles, the location of the target on the screen, and the size of the target itself. In her guidelines for designing touchscreens, Pleasant (1999) suggests "making the selectable area larger than the visible target itself (e.g., the button) will really help – it's true for all devices but makes a big difference with the touchscreen" (Plaisant, 1999). Hall et al. did not, however, investigate the effect of target size in relation to target location and angle. Target size and the resulting tactual recognition field size was also studied by Sears and Sheiderman in 1991.

In 1991 Sears and Sheiderman completed two studies comparing speed of performance, error rates, and user preference for the selection of small rectangular targets using a touchscreen, with and without stabilization. The targets were each 1, 4, 16, and 32 pixels per side (0.4 x 0.6mm, 1.7 x 2.2mm, 6.9 x 9.0mm and 13.8 x 17.9mm). The first experiment compared a stabilized touchscreen to a non-stabilized touchscreen. Stabilization permits a user to select a single pixel by allowing a single touch to result in the selection of a single pixel. This will reduce the errors caused by the software/hardware limitation, but it cannot account for the inherent liveware limitation (the size of the finger makes it nearly impossible to designate one pixel). While all of other studies employed the land-on strategy, this study used the take-off selection strategy throughout the study, which provides the user with continuous feedback about cursor location. The non-stabilized touchscreen produced more errors than the stabilized touchscreen for a 4 x 4 pixel target. The results of the first experiment indicate that touchscreens are able to select targets as small as 1.7 x 2.2mm (when using the take-off strategy). The second experiment again measured the differences between the stabilized touchscreen to the non-stabilized touchscreen, but the subjects were also given a brief training session on selecting small targets. They found that the stabilized touchscreen was faster in selecting the single pixel target. The stabilized touchscreen also produced fewer errors when selecting the single pixel target, and again, it was also preferred over the non-stabilized device. This study shows that target size effects error rates.

Using the range of the touches (i.e., the extreme misses on either side of the target) in the various positions, Sears (1991) calculated a target size / tactual recognition field size that should capture all touches: 26.1mm^2. These results are similar to Hall et al. (1988), who found that touch recognition fields must be 26mm^2 to produce 99% accuracy, and Beringer (1983) who estimated that a tactual recognition field of 32mm would catch most of the touches. Sears's study in 1991 did not actually measure the effect of this target size on the subjects' performance but provides evidence consistent with prior results.

1.3 Summary

The literature review has shown that touchscreen devices are the fastest but least accurate of the input devices. It is important to optimize the human interface by reducing the amount of errors because of their ever-growing presence in society. The errors have been linked to the users' inherent bias to touch slightly below the target. The biases increase when the device is slanted away from the angle that perpendicularly bisects their line of sight. All of these studies have shown that a touch bias exists in situations where the touchscreen device is mounted at an angle other than perpendicular to the user's line of sight, but besides parallax, there is little consistent explanation for this occurrence. It has also been shown that parallax is not the sole contributor to touch bias. For example, Beringer and Bowman (1989) showed that the bias still existed even with a parallax-reducing high-resolution device. And Hall et al. (1988) found a touch bias in both the devices containing inherent parallax and reduced parallax, with the touch bias being significantly lower when using the device with the reduced parallax. Perrone's theory also offers an explanation to account for the remaining touch bias by examining the operator's perception of slant angles. He specifies that the operator underestimates the angle of the device, perceiving the target lower and therefore contacts lower than the true target location on the screen (Perrone, 1980).

Although never manipulated in the same study, the net effects of these findings taken together shows that tactual recognition field size and target location affect user performance in terms of touch bias and accuracy. Beringer et al. (1983, 1985, & 1989) consistently found that the touch bias on the y-axis increased as the target appeared higher on the screen. There was no significant x-error found consistently throughout all of the studies; and when a significant effect was found as in Sears et al. (1991 & 1992) and Hall et al. (1988), it was blamed on a combination of parallax and the effect of the screen's edges. In the case of tactual recognition field size, Beringer et al. (1983, 1985, & 1989), Hall et al. (1988), and Sears et al. (1991 & 1992) speculated that a tactual recognition field size of around 30mm can accurately register 99% of all touches.

Out of three square tactual recognition field sizes, this study sought to match these fields with the amount of touch bias occurring when the target is positioned equally in twenty-five different locations on the screen while using an angle that has been found to produce a great amount of bias. The display angle chosen to represent an environment conducive to producing high bias errors was 45°, which is the angle that created the greatest bias error in the past experiments (Beringer et al, 1983, 1985, & 1989). Combining the methods of experiments conducted by Hall et al. (1985) and Beringer et al. (1983, 1985, & 1989), this study manipulated target location by designing the target to appear randomly on a 5 x 5 grid with 3 different target recognition field sizes. Performance was measured through the amount of x-error and y-error present, along with accuracy of response.

1.4 Statement of the Hypothesis

The participants were expected to touch below the target in all locations, and the magnitude of the touches was expected to grow as the target moved up the screen. The percent of accurate touches was expected to be highest near the bottom of the screen, but increasing at all locations as the tactual recognition field increases. The resulting size and shape of the participants' touches was expected to form oblong circles around the targets, expanding towards the right of the targets.

METHOD

2.1 Participants

There were 20 participants used in this study ranging between the ages of 18 and 42, with an average age of 24. The individuals had normal or corrected to normal vision (20/20, tested by using an eye chart) and were right-handed. Additionally, the participants had less than 30 minutes of experience using a touchscreen within a 2-month period (Hall et al., 1988). In order to control for the individual differences in hand stability, the participants also had to pass a steadiness test with at an average score of 15 touches or less. The participants were volunteers from Embry-Riddle Aeronautical University.

2.2 Apparatus

The study used a Fujitsu PenCentra 130 touchscreen computer. It is a pressure sensitive touchscreen that contains a resolution of 640 x 480 points. The Fujitsu PenCentra 130 uses the land-on selection strategy.

2.3 Design

The study was a 5x5x3 full factorial within subjects design.

2.3.1 Independent Measures: The target (2.5mm²) whose size remained constant, had one of three tactual recognition field sizes (4.5mm², 6.5mm², and 8.5mm²). Each recognition field size appeared randomly in one of twenty-five locations on the screen

2.3.2 Dependent Measures: For each target, x-error, y-error, and accuracy of touch was collected. The x-error (collected in mm, two places after the decimal) is the horizontal distance from the location of the participant's touch to the center of the target: [x-x']. The x is the horizontal position (x coordinate) of the center of the actual target; the x' is the horizontal position (x coordinate) of the touch. The y-error: (collected in mm, two places after the decimal) is the vertical distance from the location of the participant's touch to the center of the target: [y-y']. The y is the horizontal position (y coordinate) of the center of the actual target; the y' is the horizontal position (y coordinate) of the touch. Finally, the accuracy signifies whether the touch is within the tactual recognition field.

2.4 Procedure

The experimenter greeted participants and had them read and sign a consent form that included a brief summary of the study and the sequence of events that they should expect (Appendix A). The participants then completed an eye test and a steadiness test to ensure they are able to participate in the study. The experimenter then had them fill out an information sheet (Appendix B). Next, the experimenter sat participants directly in front of apparatus, and provided them with written instructions (Appendix C). The touchscreen was then mounted on a stand with an adjustable angle. The experimenter then used a meter stick that was attached to the stand, extended it to the side of the participants right eyes and measured the resulting angle with a "Johnson Magnetic Angle

Locator." The participants' chair heights and touchscreen angles were then adjusted to produce an angle that was 15° below their line of sight, after which, an angle that bisects their line of sights at 45° was produced. To control for glare, the workstation was covered with sheets to prevent the light from reflecting off the surface of the screen. The experimenter then instructed the participants to start the practice trial when they were ready.

When the practice trial was complete, in order to combat the arm fatigue found in the study performed by Hall et al. (1985), the computer then instructed the participants to rest their arms and provided a countdown from 30seconds ("Rest your arms, the next trial will begin in 30 seconds."). The first target appeared for the next block of trials after the participants touched a target indicating they were ready to begin the next trial ("Begin"). After each trial, the experimenter measured the angle between the touchscreen and the participants and made the appropriate adjustments. This cycle continued until the last block of trials was complete. Each size tactual recognition field appeared randomly in the center of each location or quadrant making a total of 75 targets appearing per trial. There were 6 blocks of trials, the first block was used as a practice session and data was not used in the analysis. Participants were then instructed to touch each target as quickly and accurately as possible. The other 5 block yielded the data for hypothesis testing. There were a total of 450 targets presented, 375 targets used in the analysis, 125 targets with each size of the tactual recognition field, and 15 targets in each location.

Finally, the experimenter thanked the participants and provided them with a certificate of completion, which included a way to obtain the results of the study (Appendix D).

RESULTS

3.1 Data Analysis

The dependent measures for all of the trials were x-error, y-error, and accuracy (the mean number of touches that would have activated the target because of the tactual recognition field). Perrone's slant misperception theory and past research has indicated that the participants should touch below the target in all locations, and that the magnitude of the touches should grow as the target moves up the screen. Past research also specified that right-handed operators have touched slightly to the right of the target, and left-handed operators have touched slightly to the left of the target; but a significant difference was never found between the amount of x-error and the location of the target on the screen. An increase in accuracy was also found as the size of the tactual recognition field was increased around the target in past research, but was never analyzed by location on the screen.

This investigation found that the participants consistently touched below the target at all locations on the screen, but unlike the previous research, the magnitude of the y-error grew as the target moved away from the straight-ahead position and was greatest near the bottom of the screen. Additionally, participants (who were right handed) touched to the right of the target, but the magnitude of the x-error grew as the target moved from the top of the screen to the bottom (Figure 3). The increase in the tactual

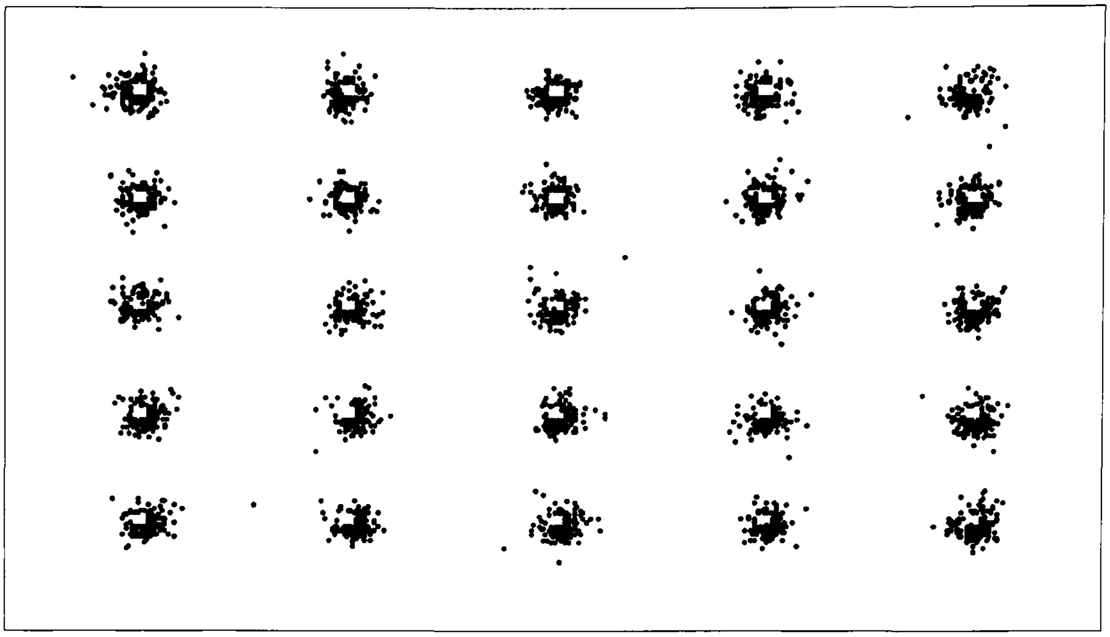

Figure 3: Plot of missed touches: This graph shows the size and shape of the x- and y-error, which can be used to design the tactual recognition fields.

recognition field sizes, produced an increase in the amount of touches that would have activated the target, but they were not significantly different by location.

The 5 x 5 x 3 (x-position x y-position x target recognition field) repeated measure design was broken down over location (5 x-positions and 5 y-positions), and the accuracy was computed as the mean percentage of responses accepted for each location. About 2.5 percent of the total data fit the description of what Beringer and Peterson (1985) called blunder errors. For this study, a blunder error was an input that was too far away from the target on the x- or y-axis (determined by the outlying 0.5% of the data in both the positive and negative direction). It was also defined as an input that took either too long or too short to register (again determined by the outlying 0.5% of the data). These errors occurred if the participant accidentally touched the screen while on the way to activate a target, or if the participant repeatedly touched the same target that did not immediately disappear. After these data points were removed, a repeated measures ANOVA was performed for each dependent variable.

3.1.1 x-error: A significant effect was found for both x-position, [F(4, 76) = 4.40, p<.05], and y-position, [F(4,76) = 70.06, p<.05], although no interaction between the two was found. Looking at the x-position ANOVA, a significant difference was only found between the far right position and all the other positions. Participants tended to touch to the right of the target (as found in other studies), but as seen in figure 4, the tendency in this study decreased when the target appeared in the right side of the screen (0.81mm compared to 1.0 to 1.15). This outcome is most likely due to a frame effect.

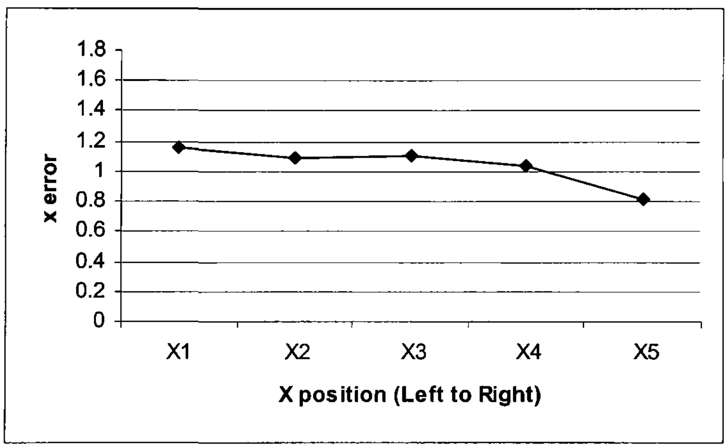

Figure 4: X-error in the X-position: Only the very right side of the screen contains a significantly smaller amount of x error than the other portions of the screen.

Examining the y-position, a significant difference was found between the average x-errors over all of the y-positions (Figure 5). Participants tended to touch to the right of the target, as it appeared closer to the bottom of the screen (from 0.45mm at the top to 1.69mm at the bottom). This is most likely due to hand-eye positioning. Additionally, there was no effect of the tactual recognition field size on x-error [F(2,38) = 0.19, p>.05], nor any three-way interaction between x-position, y-position and the tactual recognition fields [F(32,608) = 0.77, p>.05].

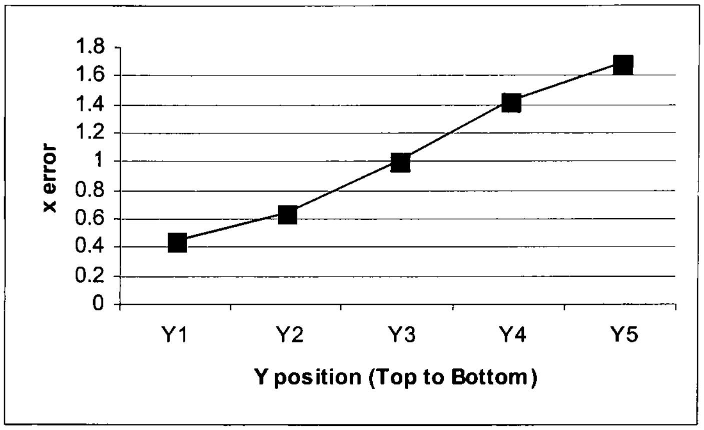

Figure 5: X-error in the Y-position: Participants touched farther to the right of the target as it appeared lower on the screen.

3.1.2 y-error: In terms of the y-error, a significant effect was also found for x-position, [F(4, 76) = 10.82, p<.05], and y-position, [F(4,76) = 22.34, p<.05]. An interaction between the x-position and the y-position was also discovered, [F(16, 304) = 2.62, p<.05]. Looking at the x-position means for y-error in figure 6, a significant difference was found between the far left side of the device, the far right side of the device and the

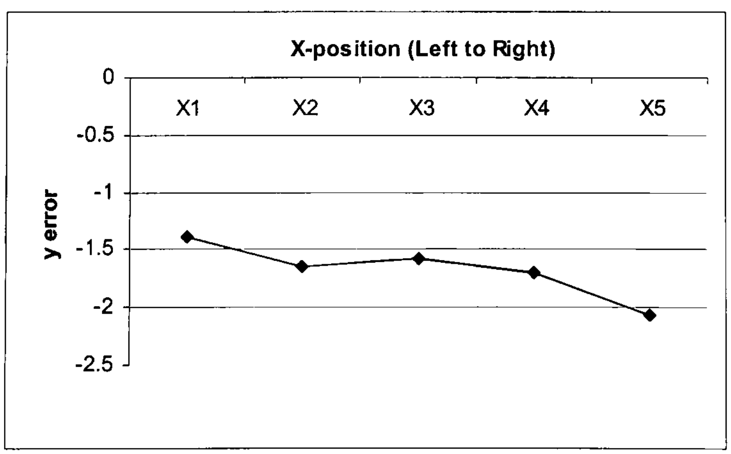

Figure 6: Y-error in the X-position: There is significantly less y-error in the far-left position, and significantly more y-error in the far-right position.

other positions. Participants touched further below the target towards the right side of the screen (2.07mm) than towards the left (1.38mm), although the ANOVA did not show a significant difference between the three central x-positions. In all likelihood, this is again due to the relative hand-eye positioning.

The participants touched below the target (creating a negative y-error) at all points on the screen, but the y-position averages are not as straight-forward as the x-position averages. As seen in figure 7, the position with the least amount of y-error is Y2 (directly above the center of the touchscreen computer). Positions Y1 and Y3 (top and center) are not significantly different from one another, but are larger than Y2. Finally, Y4 and Y5 are also not significantly different from one another, but are larger than Y1, Y2, and Y3. This effect is most likely due to a combination of slant underestimation and the stylus attack angle.

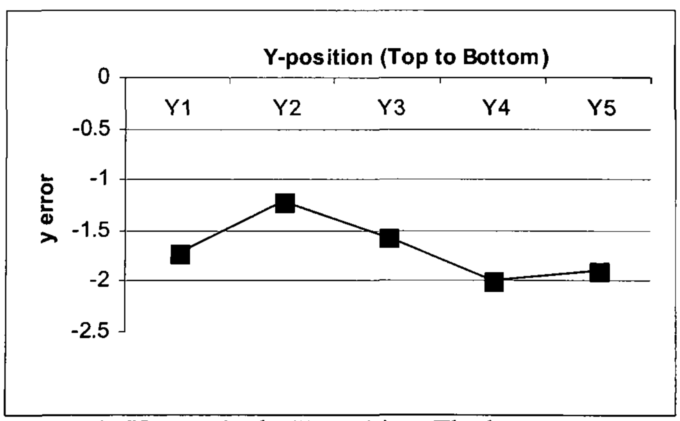

Figure 7: Y-error in the Y-position: The least amount of y-error occurred in Y2, and increased as the target moved away from it.

The interaction effect combines the effects of both positions. It shows that the touches increase in y-error when the target appears toward the bottom of the screen compared with the far-right position (as seen in Figure 8). The interaction effect is due to a combination of the physical motor movement on the way to touching the target (hand-eye movements), slant misperception and the stylus attack angle.

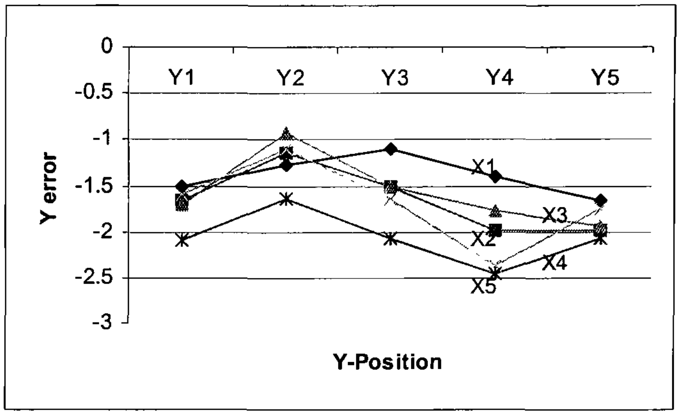

Figure 8: X- & Y-position interaction: Y-error increases when the target appears toward the bottom of the screen compared with the far right position.

As in x-error, there was no effect of the tactual recognition field size on y-error in either the x- or y-position, nor a three-way interaction between the x-position, y-position and the tactual recognition fields [$F(32,608) = 0.82$, $p>.05$].

3.1.3 Accuracy: A significant effect was found for x-position [$F(4, 76) = 3.37$, $p<.05$], and y-position [$F(4,76) = 14.33$, $p<.05$]. An interaction was found between the x-position and y-position for accuracy, [$F(16, 304) = 1.67$, $p<.05$]. Looking at accuracy according to the x-position, the only significant difference found was between the far right position and the rest of the screen (there were fewer accurate touches on the right side of the screen). Accuracy is the inverse of the x- and y- errors, the larger the error, the smaller the percent accurate. Accuracy according to the y-position was significantly highest at Y2, the position directly above the center (41% of all the touches would have activated the targets). The y-positions that accepted the next highest percent of touches were the top, Y1, and the center of the screen, Y3 (35%). The y-position directly below the center of the screen, Y4, accepted 29% of the touches, and the bottom of the screen, Y5, accepted 26% of the touches (as seen in figure 9). These results correspond with the

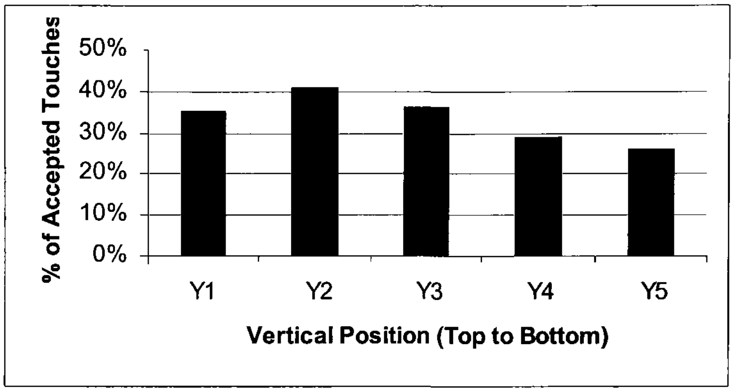

Figure 9: Accepted touches on the vertical axis: Position Y2 contained the highest amount of accepted touches.

number of direct hits according to location, with the largest number of direct hits occurring in Y2. The tactual recognition field sizes did not differ significantly from each other in terms of percent of touches that would have activated the targets and target location because the sizes did not vary enough to find a difference. Reanalyzing the data by inspecting whether each data point would have been activated according to each of the tactual recognition field sizes showed a significant difference between the three field sizes. Tactual recognition field size one ($4.5mm^2$ - 1mm on each side of the target) would have yielded a 41% accuracy rate, size two ($6.5mm^2$ - 2mm on each side of the target) would have yielded a 64% accuracy rate, and size three ($8.5mm^2$ - 3mm on each side of the target) would have activated yielded an 86% accuracy rate (Figure 10). These rates did not differ significantly according to the x- or y-position.

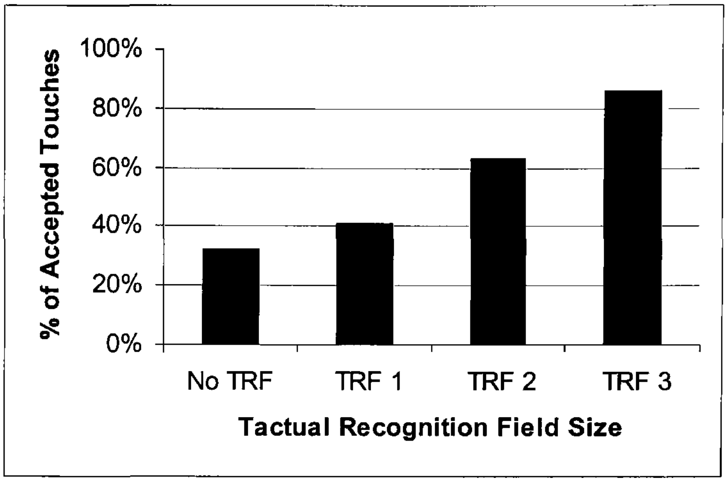

Figure 10: Tactual Recognition Field Size and Accuracy: As the tactual recognition field size increased, the percent of accepted touches also increased.

DISCUSSION

Previous research has shown that operators tend to underestimate the slant angle of a mounted device, and therefore touch below the target. It has also shown that this bias varies according to where the target is located on the screen. Hall et al. (1989) suggested the use of tactual recognition fields around the visual target to produce an increase in the system accuracy. This study sought to combine the tactual recognition fields and the target location by placing a smaller tactual recognition field around the targets located in areas that produced less touch bias, and a larger tactual recognition field around the targets with more touch bias. The results from this study were similar to the past results, with a few exceptions.

4.1 x-error

4.1.1 x-position: The significant difference found between the far right position and the other positions, was not found in the pervious research. Participants tended to touch to the right of the target (as found in other studies), but the tendency decreased as the target appeared in the far right position on the screen in this study (Figure 4). This finding is mostly likely due to a frame effect. A frame effect occurs when the physical boundaries of the screen cause the participants to touch slightly closer to the center of the screen to avoid the boundaries (Beringer and Peterson, 1985). the participants tended to touch to the right of the target because they were right handed; therefore, it would make sense that the only boundary that influenced their touches was the right side of the screen.

4.1.2 y-position: When examining the y-position, a significant difference was found between the average x-errors over all of the y-positions. Participants touched more to the right of the target as it moved from the top to the bottom of the screen (Figure 5). This effect was not found in the similar studies performed by Beringer et al. (1983 & 1985), but since the errors are so small (0.45mm to 1.69mm), the reason this study found a difference is most likely due to the difference between the discriminating ability of the stylus versus the finger. In other words, this study used a pen stylus that was more precise than the human touch, which was used in the other studies. This type of tool made the measurements in the x- and y-errors more sensitive and able to pick up the subtle differences between the left side and the right side of the screen. The question is why did the x deviations grow as the target moves from the top to the bottom of the screen? This could be due to the position of the participant's hand relative to their sight (i.e., hand-eye positioning). When a target appears below and to the right of a previous target, the participant's hand (and possibly arm) is covering it; therefore, the participant must physically pass over the target and keep his or her hand out of the way in order to preserve the eye contact between himself or herself and the target. This causes the touches to pull more to the right of the targets that appear below and to the right of a previous target.

4.1.3 Accuracy: Since the participants never actually saw the tactual recognition field, it did not (as expected) have an effect on x-error.

4.2 y-error

4.2.1 x-position: In terms of the y-error, a similar trend was found in the y-position means, a significant difference between the far-left side of the device, the far-right side of the device and the other positions. Participants touched further below the target towards the right side of the screen (2.07mm) than towards the left (1.38mm), although there was not a significant difference between the left side and the center of the screen (Figure 6). Again, this follows a similar pattern as seen in the x-error, and the same explanation holds. The participant's touches become more variable in the direction of the error's trend (below the target) as their touches move from the far left column to the far right column because of the hand / eye position. Again, the hand covering the target causes the left to right movements to be more difficult than the right to left movements, therefore the participant's touches are less accurate and more variable, in terms of y-error, below the target in the far right position.

4.2.2 y-position: The y-position averages showed a significant difference between the y-error in all of the positions except between the very top of the screen and the center (although a difference was found between the second highest position and the center), and between the bottom two most positions (Figure 7). The slant misperception theory indicated that participants would touch below the target at all location on the screen because of the shift in the perceived straight-ahead from the center of the screen to the

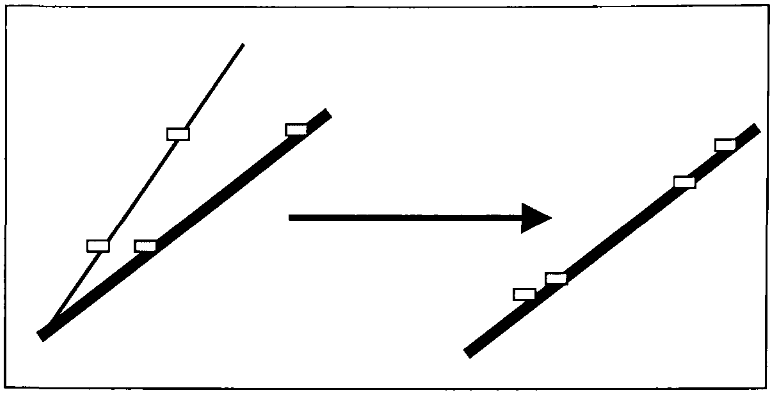

Figure 11: Slant misperception: The axis of rotation was at the bottom of the device, therefore participants touched below the target at all locations on the screen. The magnitude of the y-error should decrease as the target appears lower on the screen.

bottom of the screen (Figure 11). What this theory did not predict was the increase in the magnitude of the y-error as the target appeared further from the true straight-ahead. The explanation for this result was not clear until the apparatus set up was examined. The analysis showed that because the touchscreen was placed 15° below the horizon, the true straight-head was Y2, or the row above the center (Figure 12).

Contrary to Perrone's theory , the magnitude of the y-errors grew as the target

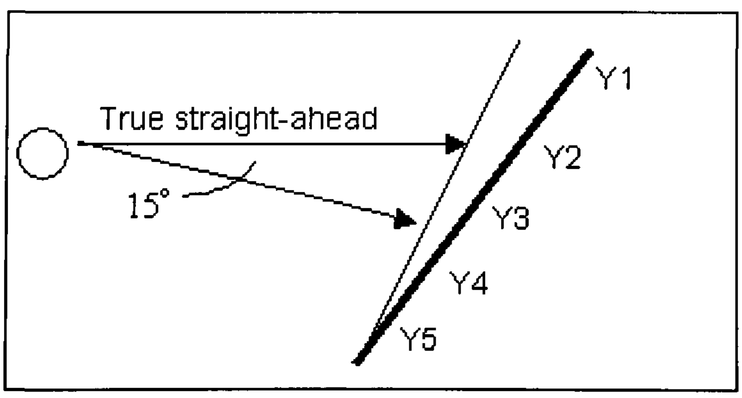

Figure 12: Apparatus set-up: Because the touchscreen was placed 15° below the participant's line of sight, the true straight-ahead became Y2 instead of Y3.

moved away from the true straight-ahead position. According to the theory, the magnitude of y-error should decrease as the target appears lower on the screen (Figure 11). This study found that the magnitude of the y-error did not differ significantly between the top (Y1) and the center (Y3) of the screen, while increasing significantly as it moved down the screen to Y4 and Y5 (Figure 13). Positions Y4 and Y5 do not differ significantly from each other due to the frame effect influencing Y5. It seems logical to conclude that the y-error increased as a function of the distance of the target from the true straight-ahead direction.

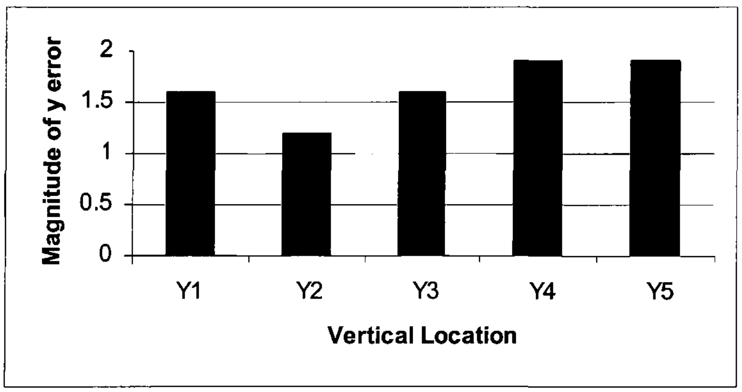

Figure 13: Amount of y-error and location: Y-error is least at Y2 (location of the true straight-ahead), and increases as a function of the distance between the target and the true straight-ahead direction.

Again, the question is what caused the y-error to increase as a function of the distance of the target from the true straight-ahead direction? The answer to this question lies in a combination both the true straight-ahead direction, the angle at which the stylus hit the screen (i.e., stylus attack angle), and slant underestimation. The stylus hits the target at a perpendicular angle to the screen because Y2 lies in the direction of true straight-ahead. As the target appears further away from this position, the angle of the stylus becomes increasingly steep (Figure 14). The increased angle of the stylus (especially in Y 4 and Y5) caused the participant to touch below where they perceive the target to be located, which is already below the actual target due to slant underestimation. In other words, the participant's touches were pulled below the targets in Y3 through Y5 and slightly above the target in Y1 (countering the effects of slant underestimation). Remember that Peronne's slant underestimation theory states that Y1 should have the greatest magnitude of y-error, with it decreasing as the target moves down the screen. In this case, slant underestimation is still occurring, but the touch is also influenced by the stylus's angle of attack.

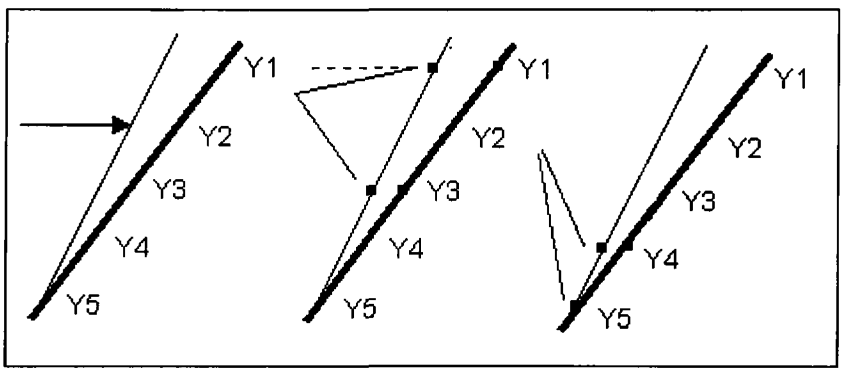

Figure 14: Stylus angle of attack: As the angle between the stylus and the screen moved from the perpendicular, the participants' touches were pulled in the direction of the angle. In order to reach Y1, most participants had to lift their arm off the table, thus creating a perpendicular angle between the stylus and the screen.

Additionally, some subjects had to lift their arm from the table to reach the target in Y1. This would create a more perpendicular angle of attack and add to the explanation of why Y1 did not have the greatest amount of y-error. From this argument, Y5 should have the greatest amount of y-error because the angle of the stylus is steepest at this point. It is not significantly different from Y4 again because of the frame effect mentioned in earlier (section 4.1.1); in order for the participants to avoid the boundary at the bottom of the screen, their touches in Y5 were shifted slightly toward the center of the screen.

The interaction between the x- and y-position (Figure 8) combine the effects of both positions by showing that the touches increase in y-error when the target appears in the bottom two rows (including the frame effect) and the far right position. To reiterate, this is due to a combination of the factors that effect how accurately a target may be selected, which are, slant misperception, hand-eye movement, and stylus attack angle.

4.2.3 Accuracy: Again, because the participants never actually saw the tactual recognition field, it did not (as expected) have an effect on y-error.

4.3 Accuracy

The accuracy rate was expected to follow the pattern set by the x- and y-errors, but no differences were found in the other locations because although the touches followed certain patterns in the x-direction and other patterns in the y-direction, there was little interaction between the x-error and y-error, and the y-position and x-position. Looking at the data from the touches and a graph of those touches, it becomes apparent that the original tactual recognition fields were not large enough or shaped correctly to find a difference between each size and target location (Figure 3).

Perhaps redesigning the shape of the tactual recognition field will yield differences in the x- and y-positions (i.e., different sizes and shapes required for different locations on the screen). Looking back at the trends in the data and at figure 3, it is apparent that a square tactual recognition field is wasting valuable space above the target, while missing touches below and to the right of the target. For the bottom two rows (Y4 and Y5), an oblong circle, or a pear shaped recognition field (including the estimated

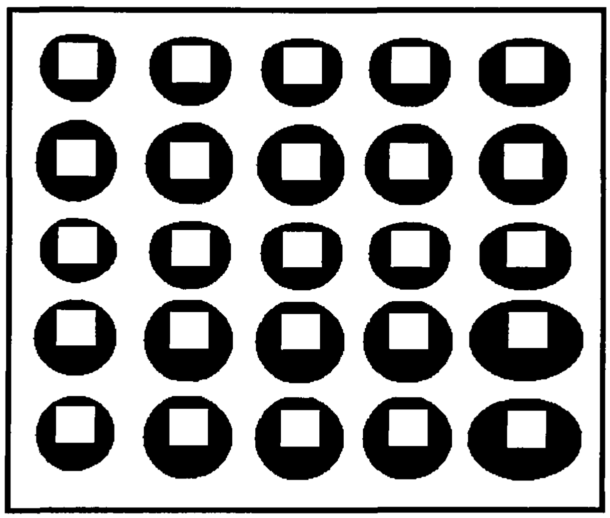

Figure 15: Approximate Tactual Recognition Fields: According to the x- and y-errors, the size and shape of the tactual recognition field varies according to location.

touches of left-handed operators toward the left) would accept the same percentage of touches as a more circular design toward the top of the screen (Figure 15). Additionally, the vertical location of the straight-ahead will require a smaller recognition field to yield the same accuracy percentage as a larger field in the other areas of the screen (in this case, Y2). If the touchscreen is set up using all the same variables that were used in this study, these tactual recognition fields should have an overall accuracy rate of about 99%.

CONCLUSIONS

The real question lies in the meaning of all the information gathered from this study. How can the people who design the interface for touchscreen computers use these findings? When compared with past literature, it is clear that there are many variables that effect touch bias and consequently the tactual recognition fields. Viewing angle (both horizontal and vertical), distance from apparatus, parallax (in the different touch screen technologies), target location, size and shape of target, type of stylus, selection strategy (i.e., land-on, first contact, or take-off), and handedness (left versus right) represent many of the variables that affect touch bias.

As mentioned earlier, this study used a stylus, while the other studies used the participant's finger. This difference seemed to cause the results of this study to differ from the previous research. Additionally, this study's straight-ahead position differed from the other studies' position, causing the location of the greatest amount of direct hits and the least amount of deviation to shift. A change in operator height can also cause this shift in the true straight ahead.

Looking the effect of these different variables, it is clear that a standard tactual recognition field fluctuating according to screen location may not lead to the desired system accuracy. Perhaps the interface designers can create a screen to the approximate standards according to the expected users, environment (apparatus set-up), type and size of targets, and tools (i.e., stylus versus finger). Then the computer can perform what Beringer and Peterson (1985) termed individual modeling. This is where the computer learns the bias errors of each individual operator and creates the tactual recognition fields in accordance to their individual biases. Of course, there are problems with this approach when there are multiple users in a system (i.e., an Automatic Teller Machine). More research is needed in looking at the variables that effect touch bias like viewing angle, distance from apparatus, parallax, target location, size and shape of target, type of stylus, selection strategy, and handedness. More research is also needed in individual modeling to design touchscreen computers that will activate the intended target and produce that amount of accuracy needed in a particular system.

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APPENDEX A

INFORMED CONCENT

The experiment in which you are about to participate is designed to investigate the relationship between the tactual recognition size and location of the target on a touchscreen computer. It is being conducted by Elizabeth Brix in conjunction with the Human Factors and Systems Department to fulfill the requirements of the Master of Human Factors and Systems from Embry-Riddle Aeronautical University. Essentially, this experiment seeks to supply designers with information as to the optimal tactual recognition size in relation to where the target is located on the screen.

In this experiment you will be presented with 6 sets of blocks, the first block will be used as a practice session and the data will not be used in the analysis. Before you begin the practice trial, the experimenter will set the angle between you and the device. To combat arm fatigue, in between each block the computer will display the message, "Rest your arms, the next trial will begin in 30 seconds." A countdown will then be provided a while you rest your arms. During this rest period, the angle between you and the device will be measured again. The first target will appear for the next trial when you indicate you are ready by touching "OK". After you have finished the final trial, the computer will signify the end of the experiment. This experiment should take a total of about 15-20 minutes.

Please be assured that any information that you provide will be held in strict confidence by the researchers. At no time will your name be reported along with your responses. All data will be reported in group form only. At the conclusion of the study, a report of the study will be available in Embry-Riddle Aeronautical University's library.

Please understand that your participation in this study is voluntary and you are able to withdraw from the study at any time without penalty. You may also have your data removed from this research at any time.

I acknowledge that I have been informed of, and understand, the nature and purpose of this study, and I freely consent to participate. I am also at least 18 years of age.

Signed____

Date____

APPENDEX B

Touchscreen Study Information Sheet

Name______________________________ Date________________

Age_________________ Gender______________

Personal Information

Do you have either corrected or uncorrected vision of at least 20/20?

Yes No

Are you right or left handed?

Right Left

Score on Steadiness test: _________________

Touchscreen Information

Have you ever used a touchscreen computer? Yes No

If yes:

About how much time have you spent using a touchscreen computer within the last 2 months:

A) None
B) Less than 30 minutes
C) 30 minutes
D) More than 30 minutes

APPENDIX C

Instructions

1. After the angle between you and the device is measured, please try not to move your head until the block is completed. The angle will be measured in between each block.
2. During the rest period, please rest (lay) your arm on the table until the computer indicates it is ready to begin the next block.
3. Rest your elbow on the table while you are performing the experiment, unless you need to lift it momentarily to touch a high target.
4. During the experiment, a target will appear randomly on the screen. Just simply touch the center of the target with the tip of the stylus as **quickly** and **accurately** as possible. A light tap is all that is necessary to activate the target.
5. Do not touch the screen with anything but the stylus.

APPENDIX D

Certificate of Participation

Thank you for lending your time to participate in this touchscreen computer study. The results of this study will be available in the library of Embry-Riddle Aeronautical University under either the author's name: Elizabeth L. Brix, or the study's title: THE EFFECT OF TARGET POSITION AND TACTUAL RECOGNITION FIELD SIZE ON TOUCH BIAS AND ACCURACY

APPENDIX E

Source Table

Dependent Variable	Source	df	SS	MS	F	Significant
x-error	x-position	4	22.16	5.54	4.4	0.003
	Error (x-pos)	76	95.75	1.26		
	y-position	4	318.84	79.71	70.06	0.000
	Error (y-pos)	76	86.47	1.14		
	Target Recognition Field	2	0.63	0.32	0.19	0.825
	Error (TRF)	38	62.03	1.63		
	x-position * y-position	16	11.42	0.71	0.69	0.803
	Error (x-pos * y-pos)	304	314.25	1.03		
	TRF * x-pos	8	8.76	1.1	1.43	0.516
	Error (TRF * x-pos)	152	145.61	0.96		
	TRF * y-pos	8	4.3	0.54	0.61	0.77
	Error (TRF * y-pos)	152	133.48	0.88		
	x-position * y-position * TRF	32	22.2	0.69	0.77	0.820
	Error (x-position * y-position * TRF)	608	549.59	0.9		

Dependent Variable	Source	df	SS	MS	F	Significant
y-error	x-position	4	73.45	18.36	10.82	0.00
	Error (x-pos)	76	128.96	1.70		
	y-position	4	111.85	27.96	22.34	0.00
	Error (y-pos)	76	95.13	1.25		
	Target Recognition Field	2	2.94	1.47	1.57	0.22
	Error (TRF)	38	35.53	0.94		
	x-position * y-position	16	36.34	2.27	2.62	0.00
	Error (x-pos * y-pos)	304	263.56	0.87		
	TRF * x-pos	8	5.09	0.64	0.67	0.72
	Error (TRF * x-pos)	152	144.73	0.95		
	TRF * y-pos	8	9.36	1.17	1.62	0.12
	Error (TRF * y-pos)	152	109.84	0.72		
	x-position * y-position * TRF	32	24.07	0.75	0.82	0.75
	Error (x-position * y-position * TRF)	608	555.65	0.91		

Dependent Variable	Source	df	SS	MS	F	Significant
Accuracy	x-position	4	0.83	0.21	3.37	0.01
	Error (x-pos)	76	4.69	6.17E-02		
	y-position	4	3.92	0.98	14.33	0.00
	Error (y-pos)	76	5.2	6.84E-02		
	Target Recognition Field	2	7.27E-02	3.64E-02	0.80	0.46
	Error (TRF)	38	1.73	4.55E-02		
	x-position * y-position	16	1.11	6.91E-02	1.69	0.05
	Error (x-pos * y-pos)	304	12.47	4.10E-02		
	TRF * x-pos	8	0.30	3.79E-02	0.85	0.57
	Error (TRF * x-pos)	152	6.82	4.49E-02		
	TRF * y-pos	8	0.57	7.14E-02	1.78	0.08
	Error (TRF * y-pos)	152	6.09	4.01E-02		
	x-position * y-position * TRF	32	1.03	3.12E-02	0.76	0.83
	Error (x-position * y-position * TRF)	608	25.68	4.22E-02		