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POSITION CONCORDANT - HAPTIC MOUSE

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Abstract

POSITION CONCORDANT- HAPTIC MOUSE

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Haptic mice, computer mice modified to have a tactile display, have been developed to enable access to computer graphics by individuals who are blind or visually impaired. Although these haptic mice are potentially very helpful and have been frequently used by the research community, there are some fundamental problems with the mouse, limiting its acceptance. In this paper we have identified the problems and have suggested solutions using one haptic mouse, the VT Player. We found that our modified VT Player showed significant improvement both in terms of the odds of obtaining a correct responses and the time to perform the tasks.

1 INTRODUCTION

The complex design of the human body has various senses, which we rely on these senses for our daily activities. One such sense that is often taken for granted is haptics: the combination of the sense of touch and the sense of kinesthesia (the sense of the position of the joints and forces of the muscles). Some common activities where we rely heavily on the sense of touch are feeling the fabric of clothes, the temperature of running water from a tap, as well as the structure of objects in the dark. Exploring through haptics helps us perceive nearby objects and their spatial layout, when viewing is not feasible, and tells us about object properties most salient through touch (i.e., size, shape, texture, hardness and temperature) and events (which are signaled by vibrations) inaccessible by other senses.

The sense of touch is particularly important for those who have lost their sense of sight. Although a variety of techniques and devices have been developed for individuals who are visually impaired, there is still a great need for devices that can make them more independent. One such area for which there is a need for better devices and representations for individuals who are visually impaired is in an alternative to graphical visualization. For sighted people, graphical visualization has been found to be the best way for conveying unfamiliar information about objects, figures or other pieces of information. As a result, an increasing amount of the information content in work, school and everyday living has been presented in visual diagrams. This has resulted in increasingly limited access by people who are visually impaired to the information provided, as graphical information is not easily converted for use by other senses. This is likely one of the contributing factor for the high unemployment of people with disabilities. In 2002, only 55% of adults who were blind or visually impaired were employed with an annual salary of $15,884 (US Census Bureau, 2002).

One alternative to visual graphics is to present the graphic information in text or auditory form. However, the ability to *make* discoveries about spatial patterns or relationships is often lost when replacing a graphical representation with words. For example, describing graphical time dependent data, such as trends in the stock market, in a summary "word description" is often the most valuable contribution of an analysis. This is true in many fields, including the sciences, geography and engineering. In addition, concepts that involve mathematical waveforms (e.g., the description of phase for sinusoidal waveforms) can be very difficult to understand when relying on text or sound.

The other alternative is to provide this kind of graphical information to people who are blind and visually impaired through tactile graphics (Loomis and Lederman, 1986). The most common type of tactile graphic is the use of raised line drawings, where an outline drawing of a diagram or illustration is raised above the background surface. This method has been used to provide representations of many different types of graphics, from maps to graphs, universal symbols, health information and common objects. Unfortunately the production of raised line drawings requires a special type of paper (e.g., swelltouch paper by American Thermoform Corp.), which is expensive, and involves a time consuming process (the outline must first be drawn or printed on the paper, after which the paper is “puffed up” by use of, for example, a Tactile Image Enhancer). The thickness of raised line graphics also means that they can be cumbersome to carry, particularly if more than a few are being used. Also there is a limitation to the amount of information that can be displayed on the tactile graphic (eg, geographical, contour maps etc).

The use of raised line drawings is particularly problematic in dynamic environments, where a user may want to look at several different graphs or pictures in rapid succession, such as when using a computer to analyze data from various viewpoints or navigating the web. For this reason, other types of tactile computer interfaces have been developed to convey graphical information to individuals who are visually impaired. One commonly proposed method is to use some sort of distributed tactile display with a position sensing system. This type of systems works with outline drawings displayed on the screen or virtually represented in the computer. The position sensing system senses where the user on the graphic (by the user moving the device) and displays the appropriate local graphical information on the distributed tactile display. The only display of this device which has been commercially available, and which we use here, is the VT Player (VirTouch, Israel).

The VT Player consists of an optical mouse with two adjacent four by four matrices of pins. The two matrices are aligned to sit under the index and middle finger with a normal grasp of the mouse by either hand (figure 1c). The pins can raise and lower to give a sense of the local geometric information on a graphical representation. The VT Player works by sensing the x-y position through its mouse sensor, as usual. It then converts the corresponding grey scale / color image information to binary image formation, black for raised pins and white for lowered pin, at the corresponding location on the computer screen on the tactile display. Figure 1a) shows the top view of the VTPlayer (Virtual tactile player), having the two tactile pads consisting of sixteen tactile pins (white) which can rise and lower. Figure 1b) shows the side view of the VTPlayer. There are four buttons, two on each side left and right (figure 1a). The buttons on the left side work similar to right click and left click of a normal computer mouse. The buttons on the right side can be programmed as required.

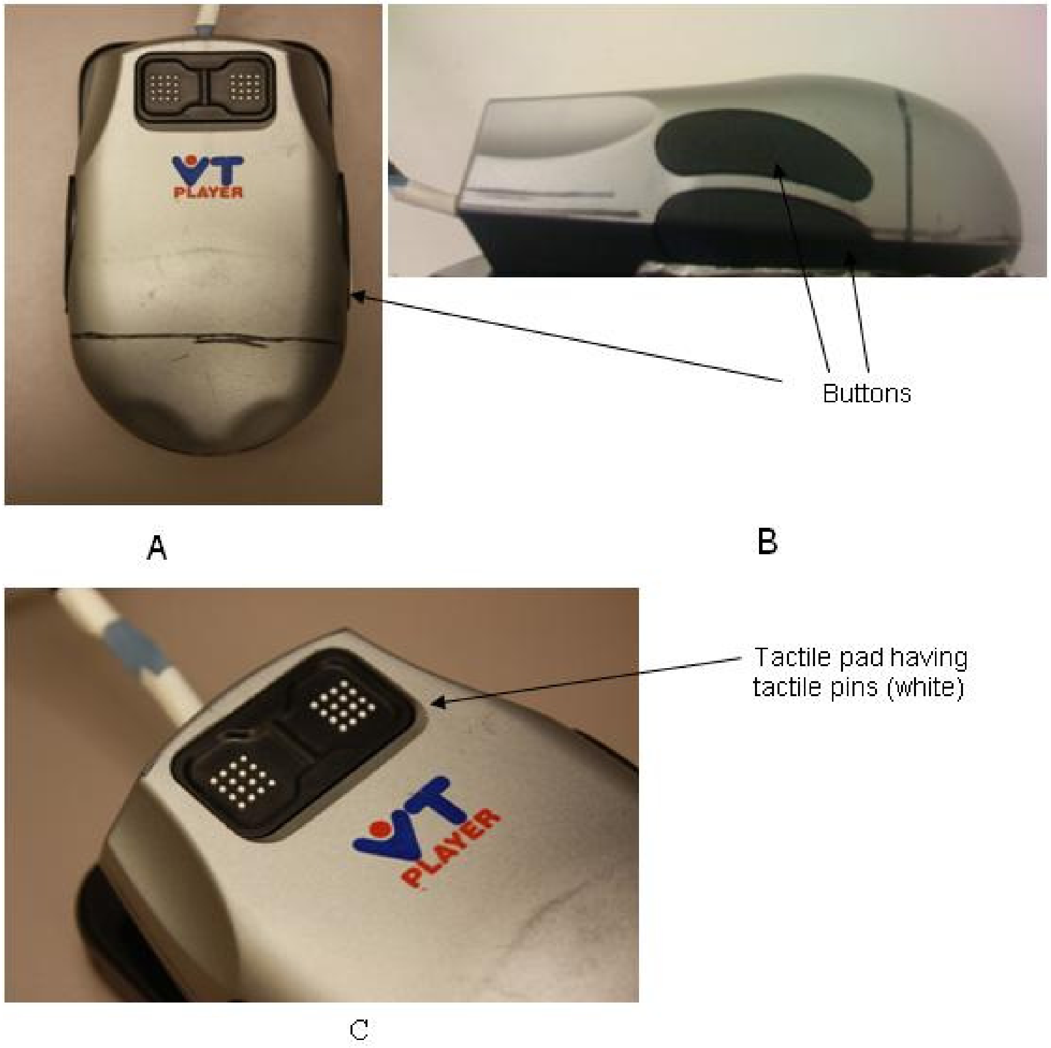


Figure 1: VTPlayer (Virtouch inc, Israel)

The VT Player, and similar devices, has several advantages over physical raised line diagrams: it is more interactive, cheaper and more portable, and does not wear as easily. Inspite of this and the fact that the VT Player has been frequently used by the research community (e.g. Jannson, Juhasz and Cammilton (2006), Wall and Brewster (2006), Thomas, Isabella and Benoît (2006)), it has yet to really be adapted by the community of people who are blind or visually impaired (in contrast to the more inconvenient static methods). This suggests that there may be a fundamental problem with the VT Player, and tactile mice in general, that limits its acceptance. We suggest that this is due to the lack of accuracy in the position information obtained by the mouse for the device's location on the graphical representation. This is due to three main reasons:

(1) The mouse is a relative position measuring device, based on velocity, rather than an absolute positioning device. This can result in the position measured being plain wrong. For example, moving the mouse from a position and then back to the same position can result in the cursor on the screen, representing the location of the VT Player in the graphic, being significantly off. Another example, likely due to the algorithm used, is when the mouse is moved vertically while oriented at an angle. In this case, the cursor on the screen moves at an angle even though the mouse in the real world is moving straight upwards;

(2) When the mouse is moved past the border of the screen, the cursor remains at the edge, thereby resulting in a mismatch between the position of the mouse and the location within the graphical representation. To make matters worse, when the mouse is moved back in the direction of the screen, it does not remain at the edge of the screen

until it reaches the same position as where it left the screen, but rather, changes position immediately;

(3) There is a mismatch between the optical sensor location and the position of the matrix of the tactile pins. This result in angular movements of the mouse about the optical sensor location not being accounted for: the same tactile information is displayed independent of the angular movement, as the optical sensor location is the same.

In addition, for those with partial vision, the mismatch between the visual and haptic velocity scaling of the normal mouse settings can be confusing. These problems with the VT Player have been noticed, to some degree, by other researchers. Jansson and his colleagues (2006) observed that the motion of the cursor does not completely mirror the movements of the mouse. However, they only identified the problem that the rotation of the mouse produced position errors, but they did not identify the fundamental cause or suggest its solution. They also observed that lifting the mouse and placing it down again can result in position errors as well; however, this is easily fixed by reminding the user not to lift up the mouse.

Wall and Brewster (2006a) found that they needed to reset the mouse between stimuli to the center of the bitmap. Although they did not identify any reason, this was possibly due to the subjects experiencing the inaccuracies in the position measurement. This may explain the limited accuracy they obtained with the VT Player in perceiving slopes (Wall and Brewster, 2006a). In (Wall and Brewster, 2006b-c), they propose using a graphics tablet with a stylus in the dominant hand and the VT Player (with the mouse pointer disabled) in the non-dominant hand. This was, in part, to address the issue of absolute versus relative position sensing, although it introduces a new problem with the lack of position concordance between the kinesthetic information and tactile information (i.e., the kinesthetic and tactile information are not obtained with the same hand, let alone the same location on the hand).

It should be noted that others (Chang J.S, Maucher T, Schemmel J, Kilroy D, Newell and Meier (2007)) have developed position concordant displays, where the kinesthetic information and tactile information are matched in location but they still use an optical sensor to detect the position making the device relative. The contribution of this thesis is to document whether solving for the limitations outlined above, without introducing additional problems, will address the poor performance of the VT Player noted by ourselves and Jansson and his colleagues (2006). This will be done by developing a modified version of the VT Player that solves the above problems of relative positioning, the mismatch between the optical and tactile pin positioning, and the edge effects. We will then validate our hypothesis by comparing the modified VT Player to the VT Player in perceiving basic components of raised line drawings. In addition, the modified VT Player will be compared to raised-line drawings, the ultimate in accuracy.

2 BACKGROUND

2.1 PHYSIOLOGY OF TOUCH

Haptic perception is a combination of two different senses: the cutaneous sense and the kinesthetic sense (Loomis and Leaderman 1986). Most of our daily tactual perception falls in this category. Haptic processing is used to successfully identify objects and to extract valuable information like shape, size, weight, texture, compliance, orientation and thermal properties. Both senses are also needed for processing raised-line drawings.

2.1.1 THE CUTANEOUS SENSE: provides information about the mechanical stimulation of the skin by means of four major touch receptors found under the skin: the corresponding endings are the Meissner corpuscles, the Merkel cell neurite complexes, the Ruffini corpuscles and the Pacinian corpuscles (Figure 2). Other types of receptors present in skin are: thermoreceptors (temperature sensations) and nociceptors (pain sensation).

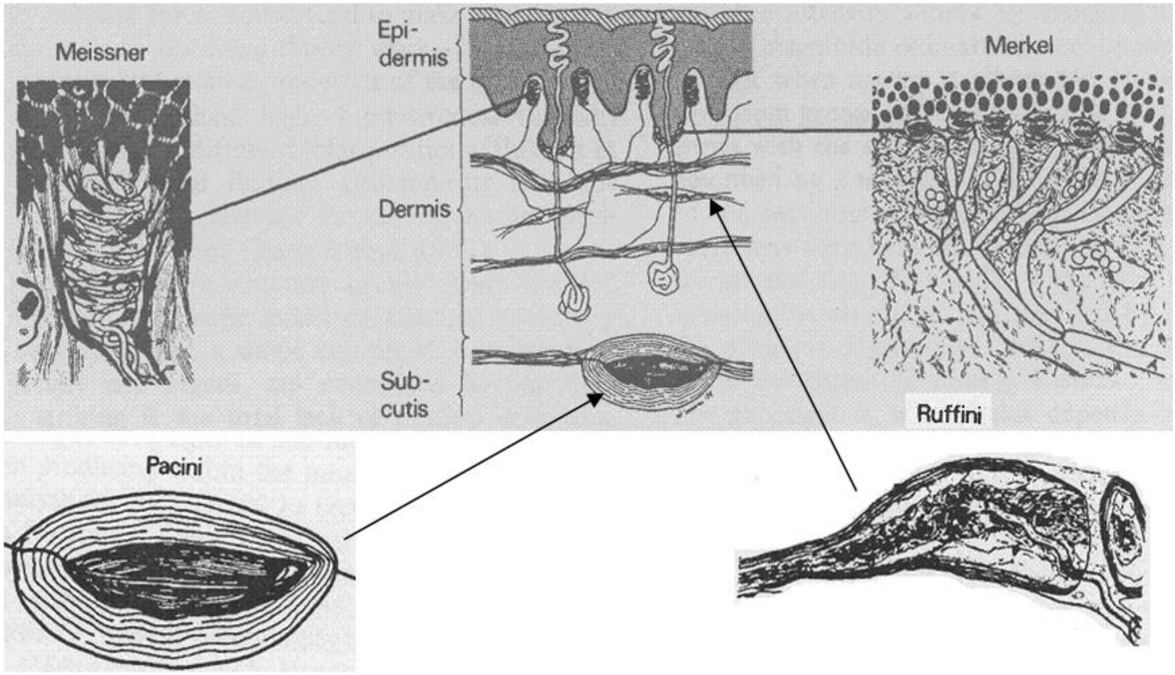


Figure 2: Different Layers of Skin (Vallbo & Johansson,1984)*

The figure shows the different layers of skin: epidermis, dermis and subcutaneous tissue. *Merkel cells* are found in clusters near the tip of the deep epidermal folds that project into the dermis. These are the end organs which correspond to the slowly adapting Type I mechanoreceptors. *Meissners corpuscles* are found at the epidermis-dermis junction and are ovular in shape. They are the end organs of the fast adapting Type I mechanoreceptors. *Ruffini corpuscles* are found at the deep dermal layers and are spindle shaped. They are the end organ of the slowly adapting Type II mechanoreceptors. *Pacinian corpuscles* are located within the subcutaneous tissue and are structured like an onion. These are the end organs of the fast adapting Type II mechanoreceptors.

In the description of the receptors, the type (either I or II) refers to the size of the receptive field: type I being small receptive fields and type II being much larger receptive fields. The cutaneous receptors can also be divided as to how they adapt to external stimuli: fast adapting units do not respond to the static portion of indentations, whereas slowly adapting unit's response to both dynamic and static portions of indentations (Vallbo & Johansson, 1984).

2.1.2 THE KINESTHETIC SENSE: provides feedback about body postures (position of the hand, limb, torso, head, etc.), as well as force on the basis of the afferent information originating from within the muscles, body and skin.

2.2 IMPORTANCE OF HAPTICS IN OBJECT IDENTIFICATION

Haptic identification tasks of any object involve both the cutaneous and kinesthetic senses. It has been found that people can accurately and quickly identify 3D objects using haptics (Klatzky and colleagues, 1993). During the identification of 3D unknown objects in unstrained conditions, people use both the senses together combined with different exploration strategies (Lederman and Klatzky, 1987). There is no evidence to show which sense precedes the other, while exploring unknown objects, but constraining either sense, during these tasks, reduces a person’s ability to identify the objects (Lederman and Klatzky, 2004). In terms of 2-D raised line drawings, Magee and Kennedy (1979) found that kinesthetic information was the most important for identifying an object’s shape. However, the cutaneous information was critical in free exploration to determine if the subject was on a line or not.

It has also been found that identification tasks of 3D objects involving multiple figures are more accurate as compared to using a single finger. This is due to the limited field of view of single fingertips (Klatzky and colleagues, 1993; Wijntjes and colleagues (2008)). However, when exploring raised line drawings, Klatzky and Lederman (1991) showed that there is no significant difference between using two fingers as compared to using a single finger of the same hand during. This is because 2-D geometric information, in contrast to material properties and coarse 3-D shape information, is processed serially.

2.3 VISUAL IMPAIRMENT

There are many reasons that contribute to the variability between subjects. One main reason when using subjects from the community of people who are visually impaired is that the population is heterogeneous. People vary in their degree of blindness, haptic ability and to use visual imagery. All play a part in interpreting raised line drawings.

Visual impairment is defined as a set of conditions that cover the spectrum of degrees of lacking sight. According to the American Optometric Association, people having vision worse than 20/200 that cannot be corrected by lenses are considered legally blind. Normal eyesight is said to be 20/20, which means that a normal person can identify a row of 9mm letters placed 20 feet away. But a person who is legally visually impaired [20/200] has to be 2 feet away from the same row of letters to identify it. A person can be visually impaired but not necessarily be legally blind. People who are legally blind can be subdivided into following categories based on the age of onset of their impairment: individuals who are blind from birth are said to be *early or congenitally blind*. People who lose vision at a very early age are also called as *early blind*. This terminology is very vague and sometimes is used interchangeably. People who lose there vision at a later age are referred to as *adventitious blind or late blind*. There can be varying degrees of vision for people who are legally blind but not completely blind: people who can perceive day and night are said to have *light perception,* whereas people lacking total vision are referred to as *totally blind* (Review by Vincent Levesque).

People who have visual impairments rely on different techniques to communicate with the world based on their abilities (text, voice, sign language, etc.) and experience. For haptics, the ability to use one's hands to perceive information is important. People who can read Braille can be subdivided into three categories: Grade I Braille and Grade II Braille. People reading grade II have an advantage of reading text faster as compared to grade I, due to the short hand nature of grade II Braille. It is likely that the increasing ability to read Braille is reflective of a person's ability to use haptics to perceive information. People who are visually impaired due to diabetes typically have a disadvantage, in contrast to others, in that they typically have limited, if any, sensitivity on their fingers.

Similarly, previous visual exposure makes people who are adventitiously blind significantly better in the perception of pictures and patterns as compared to people who are congenitally blind (Heller, 1989).

2.4 HAPTIC DISPLAYS

This section explains the various techniques used to provide graphical information (like, shapes, maps, etc.) to people who are blind or visually impaired. Haptic displays can be divided into two main categories: static displays and dynamic displays. *Static Displays* use the more conventional form of raised line drawings to provide graphical tactile information to the users. In contrast, *dynamic tactile displays* use tactile devices to provide virtual graphical information to the users (for more information see reviews by Wall, S.A and Brewster, S. (2006); Levesque, V. (2005); Jones, L. and Lederman, S.J. (2006); Dargahi, J. and Najarian, S. (2004)).

2.4.1 DYNAMIC TACTILE DISPLAYS:

These kinds of haptic displays provide dynamic control over a virtual tactile graphic displayed on the computer screen. The graphic is typically displayed on computer screen and the user has active control of the cursor, which can be controlled in the real world by using some sort of pointing device. These dynamic haptic displays can be further subdivided into two types: point contact displays or distributed contact displays.

2.4.1.1 POINT CONTACT TACTILE DISPLAY

Point contact displays are displays that provide information about a single point of contact. Information at the cursor can be transmitted to the user by means of force feedback (e.g., the PHANTOM, Sensable Technology Inc.; the Wingman forced feedback mouse, Logitech; Falcon, Novint Technologies, Inc.) or vibratory feedback. The nature of the point interaction results in the limited application of these devices, as it does not provide the spatially varying cues of a distributed display. As a result, the perception of shape information is very slow and imposes a high demand on a user’s memory.

2.4.1.2 DISTRIBUTED CONTACT TACTILE DISPLAYS

Distributed tactile displays on the other hand provide information about various points of the virtual graphic on the same finger tip. Two examples of distributed contact display devices are: the Optacon (TELESENSORY SYSTEMS, INC.), the VT Player (Virtouch Inc.). The OPTACON was designed to be used for visual to text (Braille) conversion, although it could be used to interpret visual graphics as well. Similarly, the VT Player was designed to provide tactile information about a visual graphic. Both devices determine the position information of a hand and then output a tactile signal to a matrix of tactile pins. The two main differences between these devices are that the Optacon vibrates at 230 Hz, whereas the VT Player can display static displacements, and the Optacon is used with two hands, whereas the VT Player is used in a single hand. The use of a 230Hz vibrating frequency and the provision of cutaneous and kinesthetic feedback to two separate hands, made the task of reading tactile graphics very difficult with the Optacon.

2.4.1.3 POINT CONTACT V/S DISTRIBUTED CONTACT TACTILE DISPLAYS

Although Riedel and Burton (2001) showed that there was no significant difference in performance, as measured by the discrimination of the slope of a line, between using raised line drawings and a force feedback device, many other researchers have noted the difficulty of using only a single point of contact. In contrast, distributed contact is expected to provide more detailed information to the finger, producing better results (Lederman, S.J. and Klatzky, R.L. (1987)).

2.5 VT PLAYER

The ability of providing both tactile and kinesthetic feedback with the help of a portable and affordable distributed tactile display gives an advantage to the VTPlayer over many other devices. However, its two fingered display is likely not an advantage over a one fingered display given what is known about geometric information processing, and the fact that it is too slow to make an effective texture set. In fact, Jansson and colleagues (2003) found that, at least for reading virtual maps, there was no significant difference between using one or two fingers during an exploration task.

Access to individually control the tactile pins of the tactile display allows the users to use the VT Player to provide either cutaneous information keeping the device stationary or by providing both kinesthetic and cutaneous feedback by active exploration of the tactile graphic. As mentioned previously, Wall and Brewster (2007c) used the VT Player for providing cutaneous information on the left hand, while controller the cursor on the screen using a stylus in the right hand. Although this solved the relative positioning problem, by using two hands, it introduced the problem of the lack of position concordance between the cutaneous and kinesthetic information.

Martin and his colleagues (2006a) suggested using the VT Player to provide icon like information to aid in movement related tasks. They came up with static and dynamic icons that represented directional information that can be presented on the tactile pads of the VT Player. In addition, keeping the VT Player stationary, they (2006b) used it to determine absolute angles using dedicated icons representing We suggest that using icons for providing angle information or for guidance tasks in a maze or puzzle just helps in learning how to navigate the mouse and has a very limited scope.

In comparing the VT Player to other methods: Wall and Brewster (2007) compared the VT Player with raised line drawings and previous results from a force feedback mouse (WingMan). They found a significant difference between the thresholds of the VT Player as compared to other two devices. Also Jansson and his colleagues (2006) in a virtual map reading task found that the use of the tactile feedback portion of the VT Player did not help over the use of auditory feedback. We suggest that these limitations of the VT Player have to do with the problems inherent in its design, which this thesis proposes to fix.

3 CORRECTING ROTATIONAL MISMATCH

Initially the main problem of the poor performance of the VT Player was thought to be due to the mismatch between the position of the optical sensor and that of the tactile display. This result in angular movements of the mouse about the optical sensor location not being accounted for: the same tactile information is displayed independent of the angular movement, as the optical sensor location is the same (see Figure 3). This chapter explores solutions to this problem.

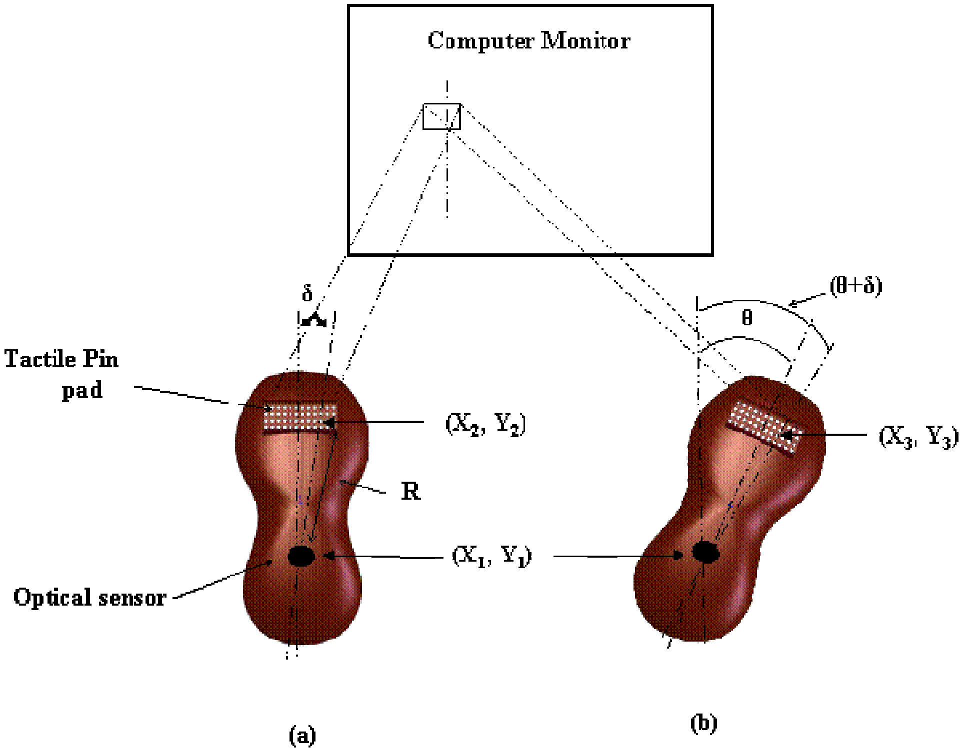


Figure 3: Mismatch between the Optical Sensor and Tactile Pins

Figure 3.1a) shows the VT Player placed straight such that the position of the optical sensor is at (X1, Y1) and that of a tactile pin is at (X2, Y2). Keeping the position of the optical sensor at (X1, Y1) constant, if the mouse is rotated at any angle(•), the position of the tactile pin changes to (X3, Y3); however, the information displayed on the tactile pin still remains the same as the position of the optical sensor remains unchanged. This problem can clearly create confusion as to the actual form of the tactile graphic.

Two potential solutions to the problem were considered. The first was to move the position of the optical sensor underneath the center of the tactile pins to decrease the position mismatch. However, this solution was initial thought to be unsatisfactory as it only decreases the error to a certain point for all pins rather than completely. The second solution was to measure the angular rotation of the mouse in real world coordinates (Figure 4) and use a mathematical transform (Equation 1) to accurately predict the location of the matrices on the computer screen (Figure 4).

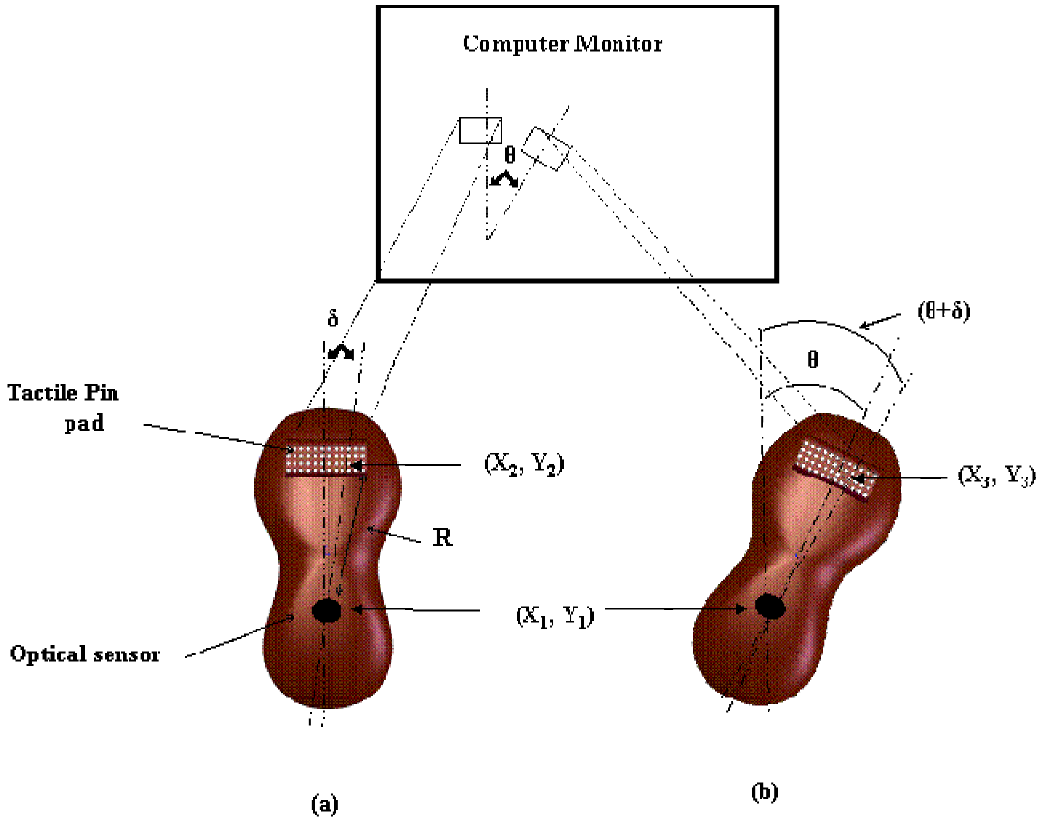


Figure 4: Modified Haptic Mouse

The figure shows how the rotational angle of a haptic mouse can be taken into account with its relation to a computer screen. When the mouse is rotated by an angle •, about the optical sensor point as shown in the figure, the pin position changes to (X_3,Y_3). This angular displacement • is measured by the angle sensor and the new pin position (X_3,Y_3) can then be determined by Equation 1. The information on the screen corresponding to the new pin position is then displayed on the tactile display.

$$\left(X_3, Y_3\right) = \left(X_1 + R\sin(\partial + \theta), Y_1 + R\cos(\partial + \theta)\right)$$

Equation 1: Determination of coordinate position of the pin

This equation gives us the new *(*X_3, Y_3*)* coordinate position of the tactile pin given the rotational angle of the mouse (Figure 3.2 b). Here, *(*X_3, Y_3*)* is the new coordinate position of the pin, *R* is the radial distance between the pin's position and the optical sensor, • is the angular position of the pin from the midline, and • is the angular displacement of the midline with respect to the calibrated starting position.

For the mathematical transformation to be used, the angular rotation of the mouse about its central axis needs to be measured. At least two different methods can be used to determine the angular rotation: *(1)* directly measure the angle, using an analog compass sensor; or *(2)* measure a second coordinate (x,y) location (e.g., using another mouse position sensor, or a light sensor in combination with a contrast gradient), to determine the angle of the mouse through mathematical transformations.

3.1 FIRST APPROACH

As the direct measurement of the angle of rotation is a more straightforward approach than inferring the angle from two positions on the VT Player, it was examined first. Different sensors were considered; however, we restricted ourselves to the use of only cost effective sensors due to the need to keep costs down for individuals who are blind and visually impaired. We chose to use an *analog compass sensor* {Dinsmore R1655, $20} to determine the angle of rotation, from which we can calculate the (x,y) position of the pins. This sensor has a two channel output with a 90 degree phase difference between channels, both of which are used to determine the angular rotation of the sensor within their (approximately) linear regions. The sensor can be mounted on the front part of the mouse to determine the angular displacement of the midline (Figure 5).

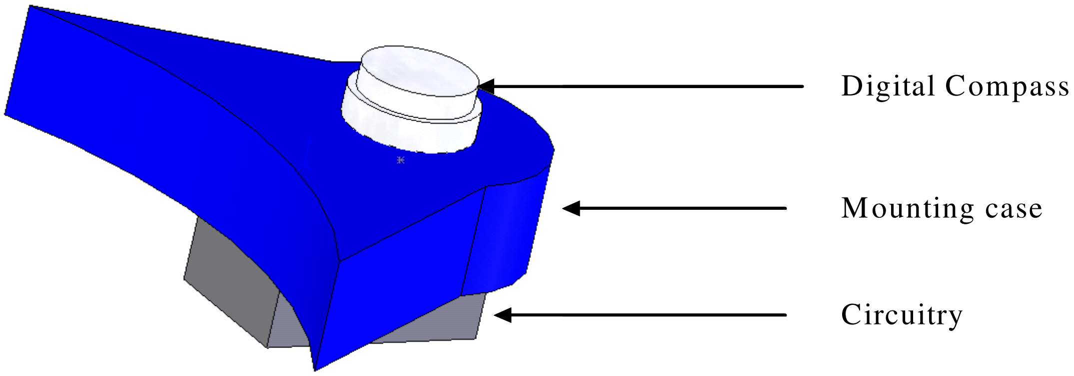
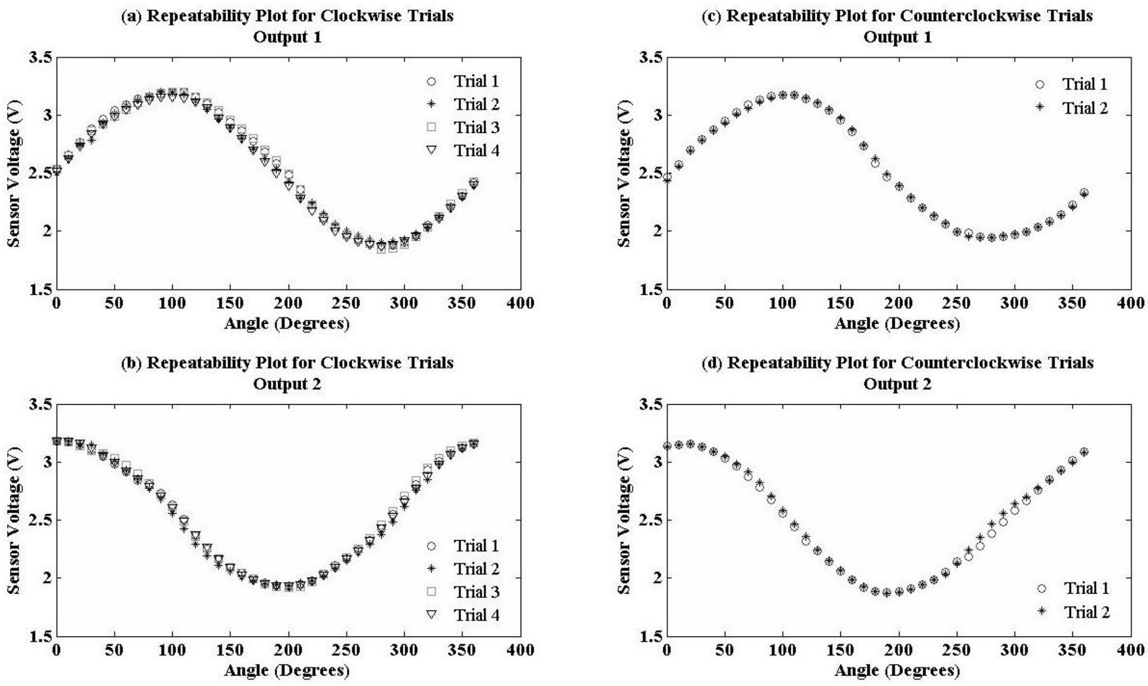


Figure 5: Compass Sensor Mount

This figure shows the compass sensor mount. The case has a cylindrical hole where the sensor is mounted to withstand any vigorous movements of the mouse. A circuitry box is protruding beneath the mount which houses the electronic circuit required for the sensor. This mount is fixed in front of the haptic mouse to obtain the angular displacement information of the mouse.

3.1.1 EVALUATION OF THE SENSOR

Before using the Dinsmore sensor to determine the angle for our mathematical transformation, we performed initial testing to check the sufficiency of the sensor by evaluating three sensors for hysteresis and repeatability over time. Each sensor was tested for repeatability and hysteresis by performing four sets of voltage readings in the clockwise direction, followed by two sets of readings in the counterclockwise direction. During these trials we took readings from the sensor at ten degree intervals starting from zero degrees and going to three hundred and sixty degrees for the clockwise trials, and starting at three hundred and sixty degrees and going to zero degrees for the counter clockwise direction. Readings for two of the four clockwise trials were taken at time intervals of 5 minutes to check repeatability over realistic time usage duration. The data points of the other sets were taken at intervals of approximately 30 seconds each. We found that the sensor characteristics were repeatable in both the clockwise direction and counterclockwise direction (Figure 6).


(a) Repeatability Plot for Clockwise Trials Output 1

(c) Repeatability Plot for Counterclockwise Trials Output 1

(b) Repeatability Plot for Clockwise Trials Output 2

(d) Repeatability Plot for Counterclockwise Trials Output 2

Figure 6: Repeatability testing plot (clockwise and counterclockwise)

This graph shows the result of the repeatability testing that was done on one of the sensors. Figures on the left, show the repeatability testing in the clockwise direction of the 2 channels of the sensor. Four trials were performed: trial 1 and 2 at thirty second intervals between measurements, trial 3 and 4 at 5 five minute intervals. Figure 3c and Figure 3d show the repeatability testing plot in the counterclockwise direction for the 2 channels of the sensor. Two trials were performed with thirty second intervals between measurements. On the figures, the different trials are plotted with different symbols. There is a close agreement between all of the trials for a given sub graph.

Hysteresis did exist for all sensors (Figure 7), however, each curve (clockwise or counterclockwise) was fortunately repeatable independent of how many rotations were done before reversing direction and where the reversal took place.

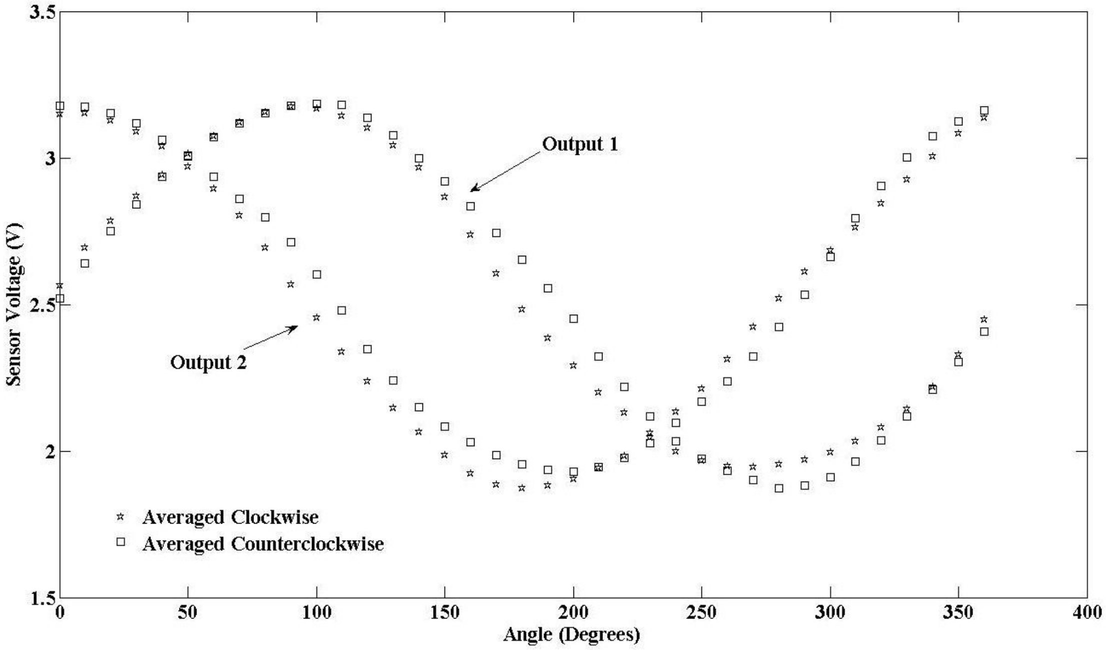


Figure 7: Hysteresis testing plot

This graph shows the result of the hysteresis testing on the sensor. In this plot the averaged reading of the four clockwise trials and the averaged reading of the two counterclockwise trials are plotted. Both output channels of the sensor are represented by different symbols. There is a nonlinear shift in the data between the clockwise and counterclockwise direction.

Because of the consistency of the two curves in the clockwise and counterclockwise direction, in spite of the differences in outputs for the two different directions, the two outputs of the sensor could be used to predict the angular displacement of the sensor. Third degree polynomial equations were fitted to the approximately linear portion of the curves for each output: one for the clockwise direction and one for the counterclockwise direction. An algorithm was then used to choose which sensor output and which curve (i.e., clockwise or counterclockwise) should be used to calculate the angle of rotation. Our testing of the algorithm accurately predicted any angular displacement of the mouse to within two degrees, with an average error of 0.9123 degree.

3.1.2 IMPLICATIONS

The average angle accuracy that was obtained was approximately 1 degree. To determine whether this is sufficiently accurate, we need to compare the resulting position error to the tactile acuity of the fingertip. Knowing that the radial distance, R, of the pins from the optical sensor is approximately 8-9cm, and considering the rotation of the hand within the range of 0 to 30 degrees, the Cartesian accuracy of the location of the pins is: 1.2-

1.6mm in the x direction and 0-0.7mm in the y direction. This is reasonably acceptable in consideration of the pin spacing of the VT Player (i.e., 2mm), except at larger errors of 2 degrees (producing an error of 3.1mm around 0 degrees in the x direction). However, spatial acuity can be achieved with the VT Player with movement of the mouse as well as spacing of the pins. It is therefore more appropriate to compare the accuracy of this sensor to the spatial resolution of the human tactile system, which is 1mm (Johnson and Phillips, 1981), and the ability to tactually localize a point in space, which is 0.1mm (Loomis, 1979). Note that to display a tactile resolution of 1mm, assuming the Nyquist frequency, would require a position accuracy of the pins of 0.5mm.

Another confounding problem is that the settling time of the sensor is around 500 msec. This delay must be added to the 200 msec delay of the VT Player to produce a pin movement. This is considerably slower than natural hand movements. Although with slow hand movements, the use of the Dinsmore sensor shows that the method proposed can correct, to a degree, the mismatch between the optical sensor and the pin location, we feel it is still not accurate enough for normal usage by individuals who are blind and visually impaired. Unfortunately other angle sensors that we have investigated are much higher in cost without any increase in angular accuracy (although some have a faster settling time).

3.2 SECOND APPROACH

The alternate solution was to use a sensor that is fast, accurate, cheap and easily available to measure a second (x,y) location on the VT Player. With two positions on the mouse known in real world coordinates, the angle of the mouse can be determined accurately, using a mathematical transformation. Then the individual position of the pins can be determined through Equation 3.1.

3.2.1 SENSING TWO POSITIONS

Two alternate technologies were considered to determine the two real world positions needed: mice position sensors (either mechanical or optical) and EMR technology (such as used in tablets). Both are expected to provide more than sufficient position accuracy. However, initially, due to the additional cost factor involved with the EMR technology, we decided to use an optical mouse positional sensor. A small, compact USB optical mouse was disassembled and mounted onto the front of the VT Player.

3.2.2 IMPLEMENTATION DIFFICULTIES

While testing the new optical mouse sensor, we came across some unexpected problems. We were successfully able to get the position of this secondary optical sensor but were not able to get the position information from the VT Player optical sensor. It was later found that the optical sensor of the VT Player was outdated (production was stopped) and that it required a special driver to get the positional information. As a result, the mouse optical sensor was replaced with a new one compatible with the current operating systems (Figure 3.6). We then attempted to use the Microsoft Development Network APIs to get the position of the two optical sensors. However, we then came across another problem, as Microsoft does not allow two pointing devices to be attached to a single computer. After some research, we found that it would require major software modifications to get the positional information from two pointing devices to work around Microsoft's limitations.

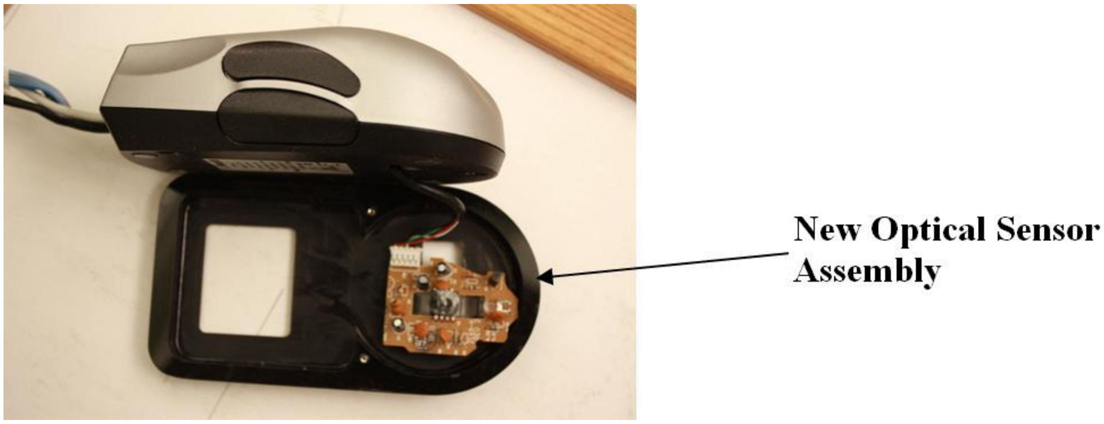


Figure 8: New Optical Sensor for VT Player.

3.2.3 IMPLICATIONS

As the use of an angle sensor or two mice sensors does not solve all the problems with the VT Player (and, in particular, the problem of the position being measured relatively with a velocity based sensor with the VT Player, rather than through one that senses absolute position) this avenue of pursuit was halted. Absolute position devices, such as a graphics tablet, were considered instead.

4 THE MODIFIED VT PLAYER

This chapter discusses the various modifications that were finally used to solve the problems of the haptic mouse. In particular it changes the VT Player from having a relative position measuring device based on velocity to an absolute position device, considers minimizing the error introduced by rotation of the device and defines physical borders to prevent problems due to the cursor reaching the edge of the screen.

4.1 USE OF AN ABSOLUTE POSITION DEVICE

In (Wall and Brewster, 2006b,c,d), they proposed using a graphics tablet (Wacom, Inc.) with a stylus in the dominant hand and the VT Player (with the mouse pointer disabled) in the non-dominant hand. The VT Player was kept stationary and only used to receive tactile information, whereas the graphics tablet was used as a pointing device to get kinesthetic information. This configuration was, in part, to address the issue of absolute versus relative position sensing, although it introduces a new problem with the lack of position concordance between the kinesthetic information and tactile information (i.e., the kinesthetic and tactile information are not obtained with the same hand, let alone the same location on the hand). We suggest that users will get better haptic feedback if both the tactile and kinesthetic information are provided to the same hand.

In order to make our device absolute we also used a graphics tablet from *Wacom Inc.* However, the outer casing of the stylus was removed and the circuitry of the RF transmitter was cut away from the rest of the circuitry. A special hollow case was designed such that the transmitter circuitry could be positioned in the desired tracking location with the VT Player resting on top of the case. The position of the RF transmitter was tracked by the digital tablet and, accordingly, the position of the pointer on the computer screen changed. The use of this technology also allowed the position of the pointer to be insensitive to the lifting of the mouse, one of the problems that Jansson and his colleagues (2006) observed.

One concern with this design is that it resulted in an increase of the height of the mouse, which could potentially increase the difficulty of manipulating the mouse. Informal testing of the modified mouse for comfort was performed on 10 subjects. All participants were instructed to always start the exploration from the lower left corner of the mouse pad. This position was considered the default position of the haptic mouse. Only one subject felt uncomfortable while moving the mouse back and forth during the testing. This subject was allowed to use the upper left corner as default position. The entire testing task was repeated for the same subject with the new default position. This position was kept constant through out the trials. With the new default position, the subject felt comfortable with the mouse.

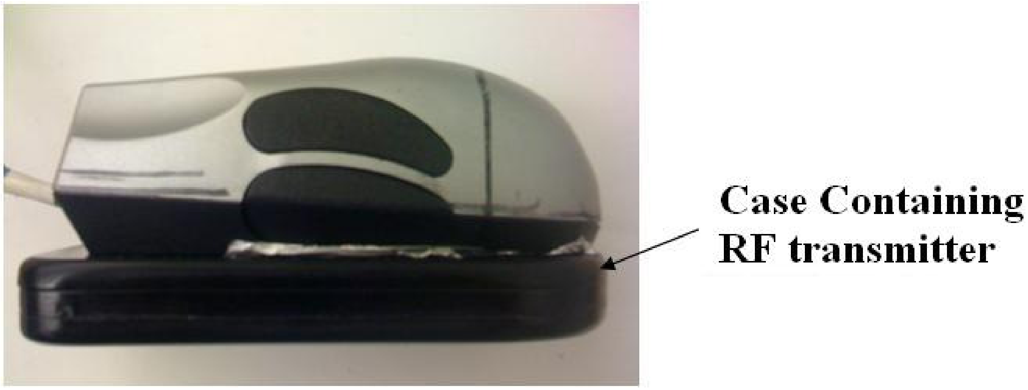


Figure 9: VT Player with the Bottom Casing.

This figure shows the special casing that was made to house the RF transmitter circuit of the digital pen of the tablet, which acted as a pointing device.

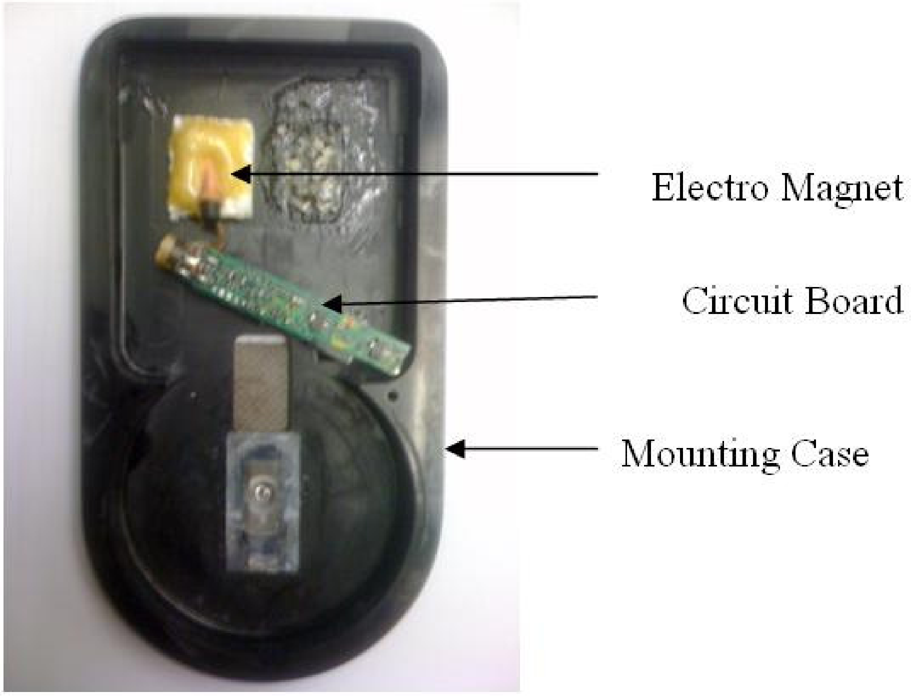


Figure 10: Showing the RF Transmitter of the stylus placed inside the mount.

Another concern with the design was that during the pilot testing of the absolute positioning haptic mouse, we found that the proximity of the high voltage regulator present in the driver circuit of the VT Player created interference with the RF transmitter. This resulted in the jittering of the cursor on the computer screen and corresponding jittering of the tactile pins when moved along a straight line. This was corrected by shielding the voltage regulator and moving it away from the RF transmitter close to the male USB port of the computer.

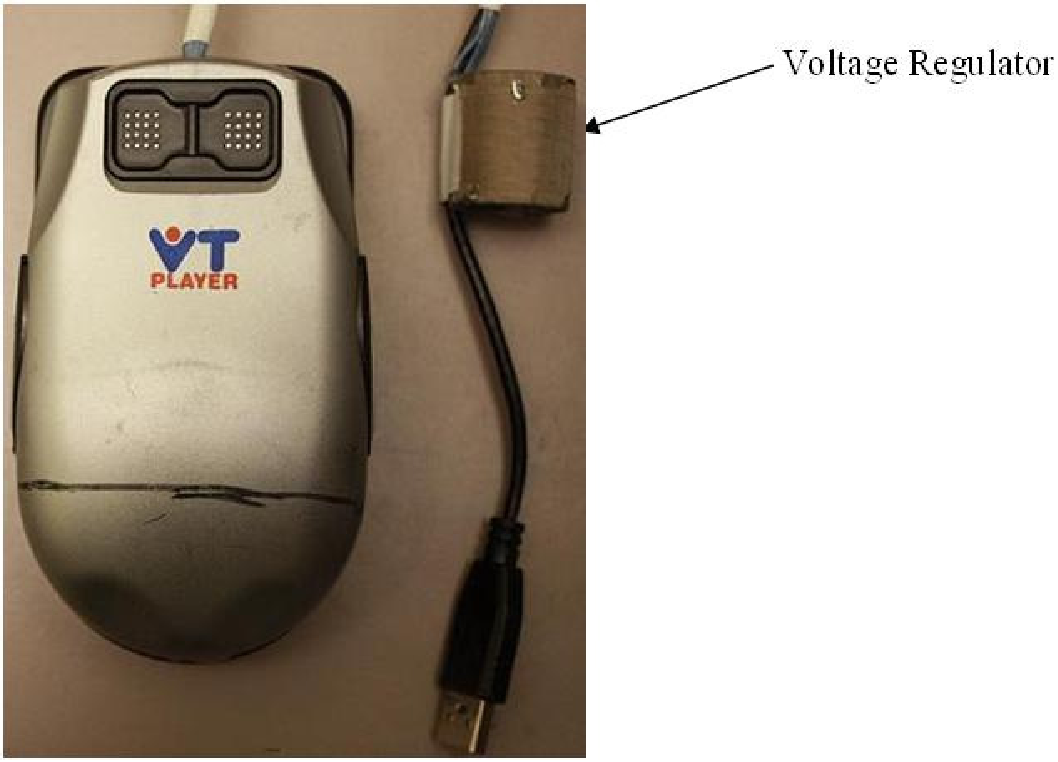


Figure 11: Voltage Regulator Cage

The above figure shows the voltage cage (in grey), next to the haptic mouse (VT Player), that encases the high voltage regulator (5V to 200V) used to drive the piezoelectric actuators of the Braille cells. The voltage regulator was placed near the male USB port so as to place it farthest from the tablet and RF transmitter.

4.2 Minimizing Error Due to Rotation

Due to complications involved in making software changes, instead of using two position sensors to determine position and angle we decided to use only one position sensor, which would only be able to measure one position (and not rotation). However, the RF transmitter can be placed underneath the tactile display in a position to minimize the error introduced by rotation. Two possible positions are: (1) in the center between the two tactile pads, and (2) if only one pad is used, in the center of that pad. We chose to use only one pad, the pad of the index finger, because this allows an improvement in accuracy (see below) and Loomis, Klatzky & Lederman (1991) found very little difference between using two fingers compared to a single finger of the same hand while using conventional static method of raised line for reading tactile graphic.

Positional errors were calculated for the tactile pins at three different positions of the optical sensor for +/- 30 degrees rotation. The best position was to place the position sensor in the center of one pad (Table 1). In the table, the '*+30* rotational position' represents rotation in the clockwise direction and the '*-30* rotation position' represent rotation in the counter clockwise direction about the center line passing through the position of the optical.

Table 1: Positional Error in terms of pixel values

Serial No.	Position of the Optical Sensor	Rotational position (Degrees)	Errors (mm)	
			X-axis	Y-axis
1	Original position	+30	40.5	10.8
		-30	40.5	10.8
2	Center of the tactile pads	+30	3.24	6.37
		-30	9.10	10.76
3	Center of the tactile pins	+30	1.9	1.1
		-30	1.9	1.1

This table shows the absolute error that will be introduced when the mouse is rotated +/- 30 degrees about its midline.

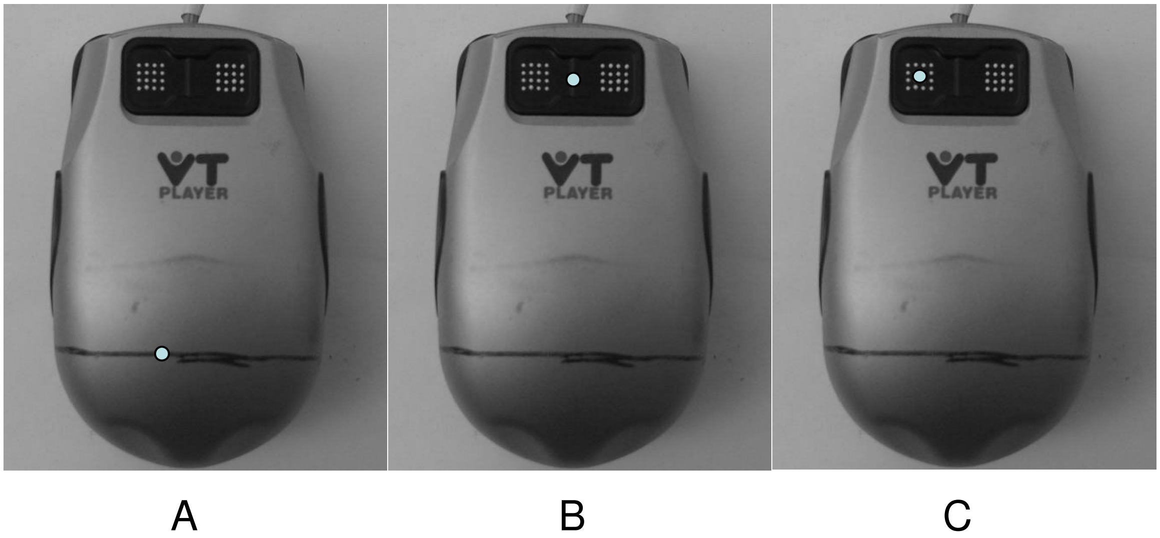
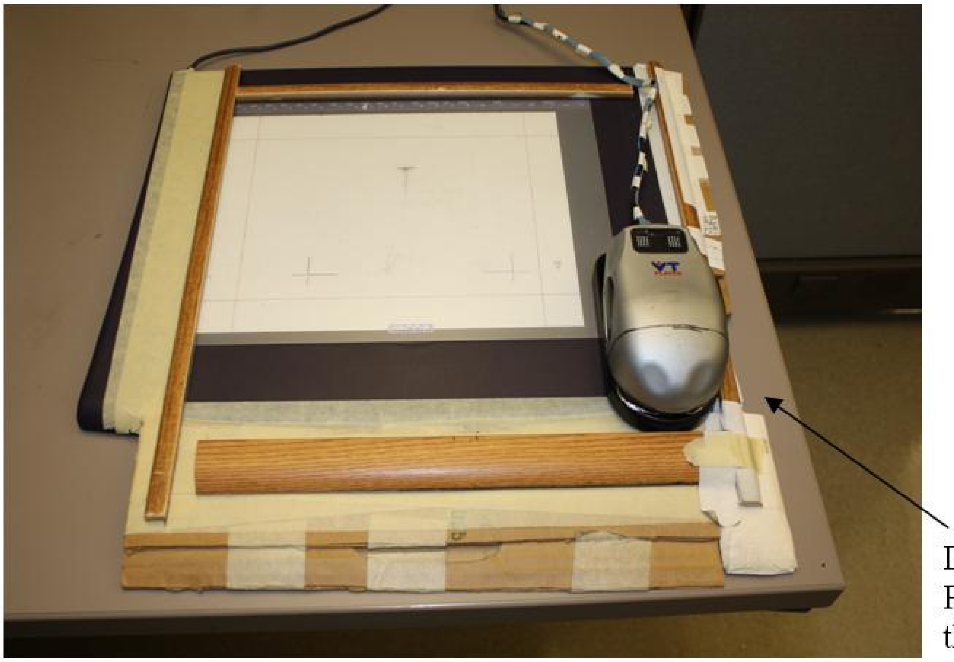


Figure 12: Different locations for the position sensor

This figure shows the VT Player having two tactile pads on the top. Three different positions of the position sensor (shown with white dots) were considered. These are shown in the three figures. (a) Shows the default position of the VT Player optical sensor (white dot at the bottom left). It can be noticed that the position of the optical sensor is skewed to the left of the center line passing through the center line dividing the two tactile pads. (b) Shows the location of the position sensor at the center (white dot) of the two tactile pads of the VT Player. (c) Shows the location of the position senor at the center of the tactile pad.

4.3 DEALING WITH THE BORDERS

Making the VT Player an absolute pointing mouse also solved the problem at the boundaries of the computer screen. However, to prevent users from moving outside the boundaries of the computer screen, resulting in an increase in the exploration time of a graphic, a special enclosure was made around the tactile tablet to restrict the movements of the mouse (Figure 13). The dimension of this *mouse pad* was such that the pointer at the center of the tactile pins remains inside the sensing area of the tablet.



Default
Position of
the Mouse

Figure 13: Special Enclosure for the Mouse Pad

5 VALIDATION OF MODIFIED VT PLAYER

5.1 INTRODUCTION

The main effort of this work was to document whether solving the limitations of the VT Player i.e., 1) switching from a velocity based to an absolute position based device, 2) minimizing the error due to the rotation of the device, and 3) preventing the cursor from overreaching the edge of the screen) would noticeably improve performance. It is the intent of this study to bring attention to the design flaws of the VT Player and document the detriment to performance that they cause, so as to ensure that these mistakes are not repeated in future designs of haptic devices. In this chapter we validate our hypothesis that the VT Player performs significantly worse than our modified VT Player, which corrects for these mistakes, in raised-line drawing tasks. In addition, the modified VT Player will be compared to physical raised-line drawings, the standard goal for all devices.

In order to perform this validation, we used the task of discriminating diagram primitives consisting of angles and lengths lying in the horizontal plan (i.e., on a table). The performance of each device was evaluated in terms of the number of correct answers and time to completion of the task. In addition, a user satisfaction survey was administered for each device.

It should be noted that care has to be taken when designing the discrimination tasks as various factors have been shown to influence the haptic perception of geometric features, such as angles and lengths. Most notably, both tactile and kinesthetic haptic spatial perception has been shown to be anisotropic.

For angles, we chose to examine the response to two main types of angles: acute and obtuse. These could be considered the types of angles with the poorest perceptual discrimination due to the oblique effect, where oblique orientations are perceived more poorly than horizontal and vertical orientations; although whether the oblique effect exists is dependent on which plane the angle is in, whether the same hand or different hands are used for the standard and comparison stimuli, and whether the information is cutaneous or kinesthetic (Jones and Lederman, 2006; Gentaz et al., 2008). What is important for our experiments is to be aware of the effect of these variations and to keep these conditions constant across the different devices and other independent variables.

In addition, Wijntjes and Kappers (2007) also found that angle discrimination thresholds were dependent on the exploration strategy. Rather than have the exploration strategy as one of the variables in our study, we chose to hold it constant to be consistent amongst the two different angles and other experimental variables. We chose the method that was used in Wijntjes and Kappers second experiment as it could be used with both acute and obtuse angles: subjects were instructed to follow the lines of the angle for the exploration of the stimuli. Although this may not be the optimum method for performing discrimination experiments for all angles, by holding it consistent between the devices, we believe we will achieve a good comparison.

In terms of the values of the acute and obtuse angles chosen (i.e., 20 and 135 degrees), from the work of Wijntjes and Kappers (2007), we would expect the angular threshold that could be perceived, at least with physical raised-line drawings, to vary with angular extent, therefore these angles were treated as separate tests. For the choice of the bisector orientation, although Wijntjes and Kappers (2007) found that there was no directional influence of the bisector orientation on the discrimination threshold, we still chose to hold this angle constant: we will hold the lower leg of the angle at zero degrees.

For length differences, two different types of length measurements were used: bar graphs and asymptotes. These tasks measure length in two different ways: bar graphs measure the length by following the contours of a physical entity (i.e., a bar) whereas for an asymptote the gap in between two lines is traversed without guidance. It should be noted that even changing the width of a bar (from a line to a block) can change the magnitude estimation of the length (Armstrong and Marks, 1999). It is therefore likely that using bar graphs and asymptotes are significantly different approaches to length measurements and should be treated as separate tasks. Also, the results of Armstrong and Marks (1999) also highlight the importance of keeping the bar and line widths constant between comparison stimuli in the separate tasks.

Other important effects on the discrimination of a line length include: the location and orientation of the line segment (i.e., the radial-tangential illusion), the path the hand takes from one point to another and the speed of the hand motion (Jones and Lederman, 2006; Armstrong and Marks, 1999). For the first effect, it would be best if the standard and the comparison stimuli for the discrimination task be presented in the same spot. However this is time consuming and also prevents a subject from easily going back and forth between stimuli. We therefore chose to present the standard and comparison stimuli side by side, with the side of the standard randomly chosen between trials. For the second effect, instructions were given to restrict the subject’s hand movements to tracking the lengths upwards and downwards. This was done to ensure that the subjects actually physically explored the lengths and not, for example, the difference between the heights of the bars: subjects were instructed to feel each length separately and then compare. The third effect was controlled by training users to move slowly and at a relatively constant speed during exploration of the figures.

Another possible variable to consider is the effect of practice on performance as the experiment is expected to be lengthy. However, it should be noted that in the experiment on discriminating angles of Voisin and his colleagues (2002), which was also fairly lengthy, practice was not found to improve performance. However, it is possible that without frequent breaks in the experiment, performance could decrease due to fatigue. Therefore, we will allow subjects to take frequent breaks during all experimental tasks.

5.2 GENERAL METHOD

Four discrimination tasks were used in a 2 alternative forced choice design, two for angles and two for lines. They were to discriminate the larger of: 1) a comparison angle and a 20 degree angle standard, 2) a comparison angle and a 135 degree angle standard, 3) a comparison bar and a 60 mm length standard, and 4) a comparison asymptote and a 60mm length standard. For all the tasks, users were blind folded and sitting so that they were facing the back side of the computer screen (Figure 14).

Figure 14: Experimental Setup

Figure 14 a) shows a blindfolded participant using the VT Player facing the back of the computer monitor. b) Shows the participant using a raised line drawing to do the task. c) Shows the participant performing a test task using the Modified VT Player.

5.3 STIMULI

The stimuli used were similar to those in Figures 15-18. The figures containing the stimuli were created to fit within an 11”x8.5” size (with 11” being the horizontal dimension); this constraint was due to the size of the graphics tablet used by the modified VT Player. The pairs of comparison stimuli themselves were always created side by side, each centered on the same position. Half of the time the standard was on the right and half of the time the standard was on the left. Comparison stimuli were created in both the slightly negative direction and in the slightly positive direction.

In terms of the details of the stimuli: for the angles, the bottom legs for all angles were at 0 degrees. For the bar graphs, both bars had a constant width of 7.5mm and rested on the same horizontal line. For the asymptotes, the horizontal lines of the asymptotes were kept parallel to the bottom boundary of the mouse pad, with the bottom boundary of the mouse pad treated as a reference line. For the raised line drawings a physical reference line of 2mm thickness was used as shown in Figure 14b. For all methods, the vertical line in the asymptote was the same length as that of horizontal line. This line was used to aid in exploration while looking for the stimuli in the figures.

In terms of the thickness of the lines for the line drawn stimuli, for the modified VT Player and raised line drawings the thickness was chosen to be 2mm. This is because the center to center pin spacing on the modified VT Player was 2mm: any lines of thicknesses of less than this amount can disappear and reappear from view, resulting in confusion. Using the standard driver for the original VT Player, it was found that the response of the device (i.e., how many pins were raised) for 1mm lines appeared to have a similar response as for the modified VT Player for 2mm lines. Therefore, 1mm was used with the VT Player as this was thought to be more consistent with the other devices.

SolidWorks software (Dassault Systems) was used to create the drawings, which were then saved as JPEG files. The JPEG files were directly presented on the screen for the VT Player using Windows Picture and Fax Viewer. They were then felt using the standard driver provided by Virtouch. For the raised line drawings, the figures were printed on an 8.5”x11” piece of swell paper (American Thermoform Corp.) and then puffed up using a Reprotronics Tactile Image Enhancer. For the modified VT Player a software algorithm (as described below) was used to display the tactile information directly on the tactile pins.

Also, for the modified VT Player and VT Player, the graphics in the JPEG files were sized so that physical distances would be the same on the two devices and puff paper. As the VT Player is a relative and not an absolute positioning device, the scaling factor chosen for it could only be approximated to that of the other two, for the rate of movement at which subjects were trained.

For the software algorithm for the modified VT Player, first the JPEG files were converted to binary format (*.bin) files in preparation for use. The algorithm itself loaded in each binary file for use by a particular task. For each task, the location of the cursor was determined using a Windows API. Then a mathematical transform was used, assuming that the VT Player was oriented vertically (note the maximum error due to this assumption was 1.9mm in the horizontal direction and 1.1mm in the vertical direction, see Table 1), to determine the individual positions of the pins in the virtual world corresponding to the location of the cursor on screen. Then the corresponding pixel information at the locations of the pins was used to drive the individual pins of the VT Player. For this, all the grey scale values were converted to black (0) and white (255) using a standard threshold (127). For black pixel values (0), the corresponding pins was raised up, and, for white pixel values (255), pins were lowered.

Two additional modifications were necessary for the VT Player as it was found that, due to its inherent problems, the search time to find the stimuli, in the first place, over repeated trials could be extremely long. As we wanted to evaluate the discrimination of lengths and angles with the VT Player and not its search time to find the stimuli, we made modifications to ensure that the stimuli were found more easily. It should be noted that, if this search time is taken into account, performance in terms of time increased up to 4 minutes; often, subjects even had problem completing the task and guessed the response! The two modifications that were made were: (1) physical boundaries, similar to that used with the modified VT Player, were used so as to prevent unnecessary movements of the mouse beyond the borders of the figure (figure 14a); and (2) a marked start position for each task was used (figure 19), where, between tasks, the VT Player was moved and then the position "zeroed" on the figure. It should be noted that without the second modification, the position error between the mouse position and cursor position became far too large over time. To be consistent, the same start position was used for the raised line drawings and the modified VT Player, although no "zeroing" was performed.

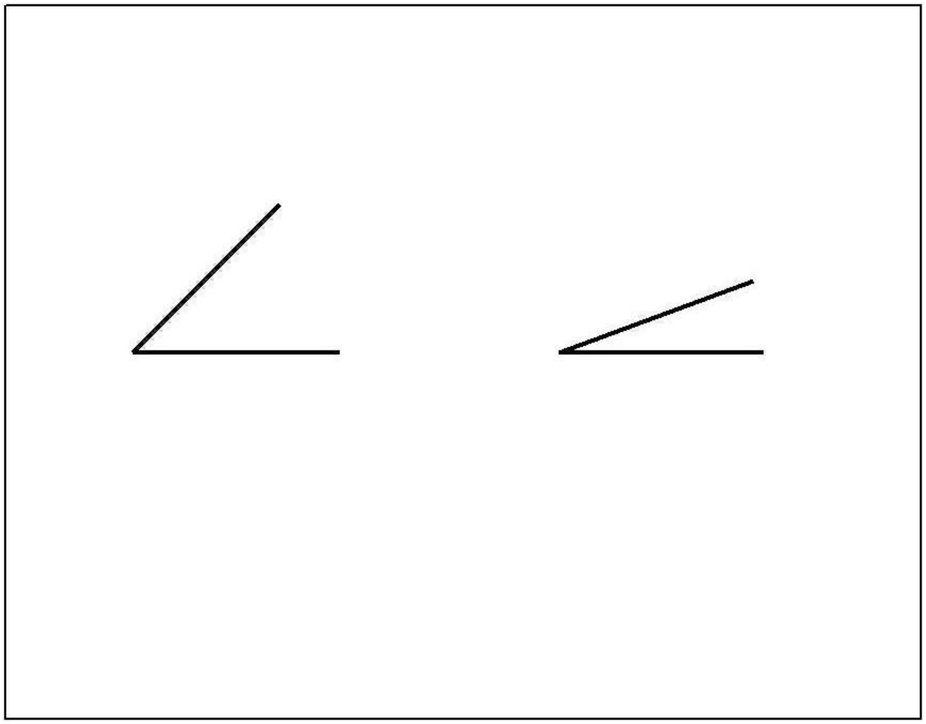


Figure 15: Angle perception: 20˚ Standard

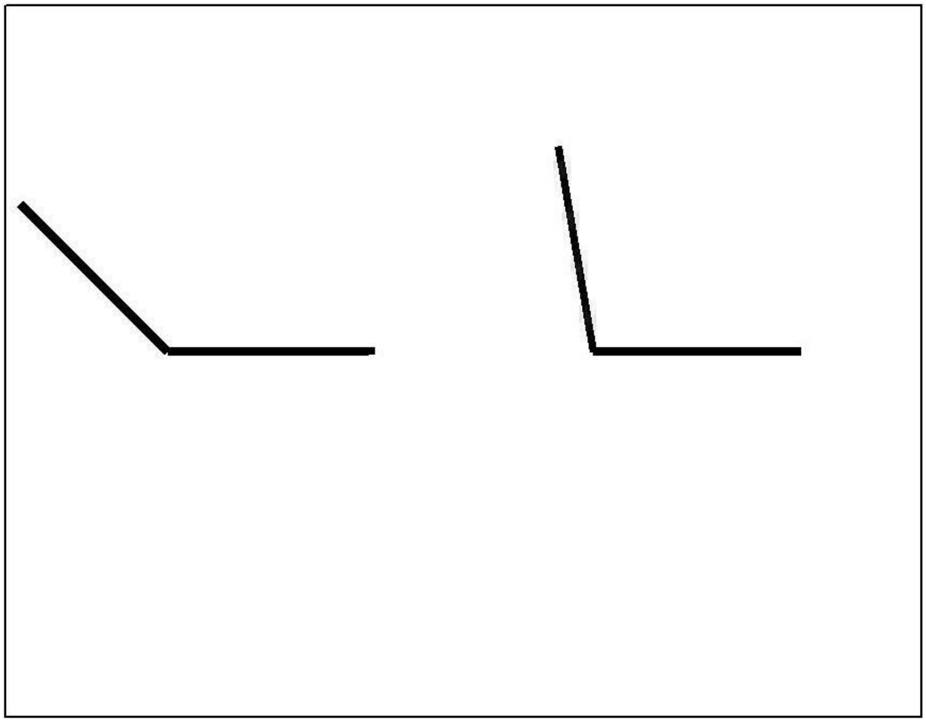


Figure 16: Angle perception: 135˚ Standard

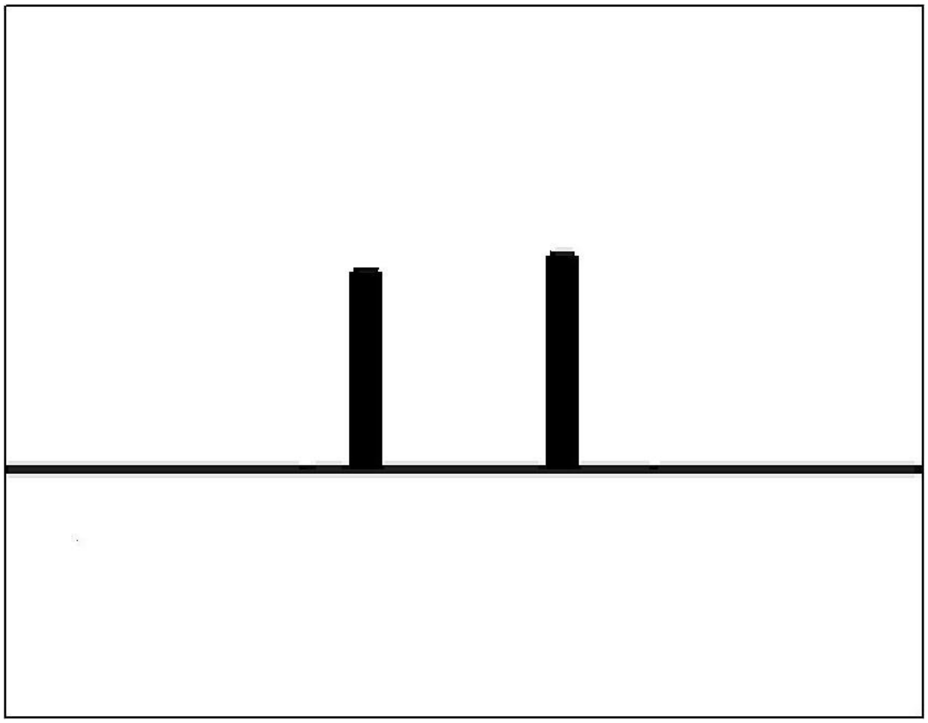


Figure 17: Length Perception: Bar-graph

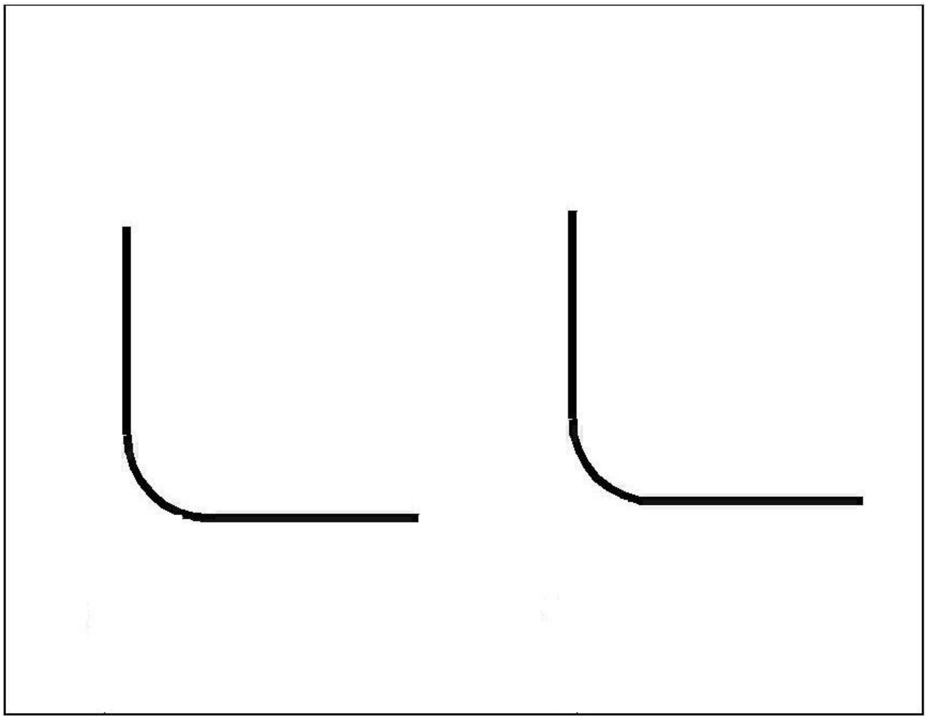


Figure 18: Length Perception: Asymptote

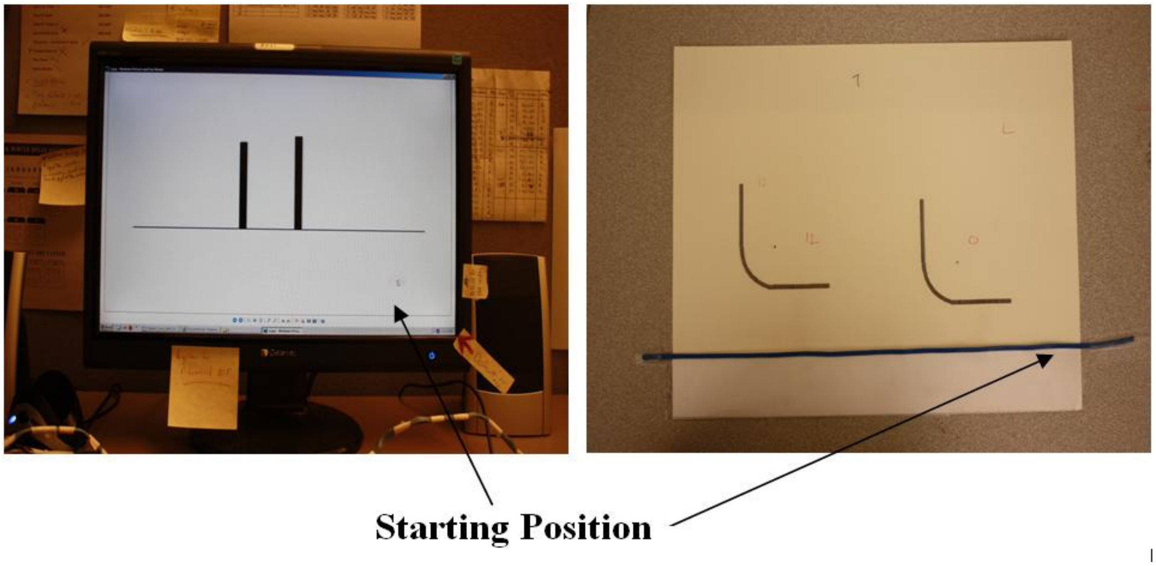


Figure 19: Start positions of the VT Player and Raised line drawing

5.4 INSTRUCTIONS

All participants were instructed to start exploring the tactile graphic from the start position and to return to the start position after giving the answer.

For both angle perception tasks, participants were instructed to use a line following method when they found the stimuli, following each line of the angle individual, and not to try to feel both lines at once. Figure 20 shows the exploration strategy used. In more detail, subjects were asked to first find the horizontal base line at 0° and follow it until they reached the apex. Then they were to follow the other line which completed the angle. They could repeat these motions as many times as they like but were instructed to always start from the horizontal line to get a better reference of the base line.

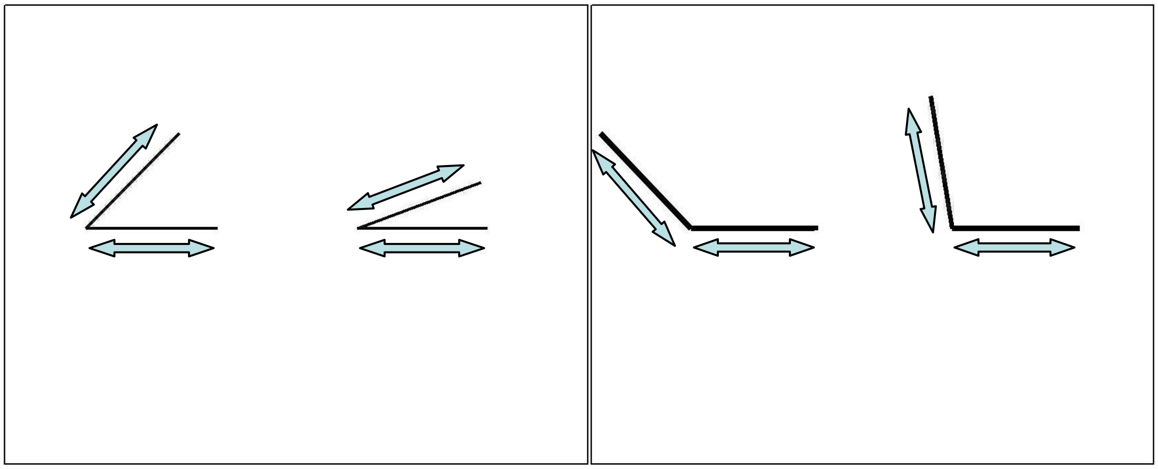


Figure 20: Exploration Procedure for Angle Perception Testing

For bar graph stimuli subjects were instructed to feel the lengths of the lines separately by moving upward and downward on the graph to feel the individual heights (figure 21a). Similarly, for asymptotes, they were instructed to move upward and downward on the graph to feel the gap between the reference line and the bottom edge of the asymptote (figure 21b). They could perform these movements as many times as they liked but were required not try to actually move between the figures to feel height differences.

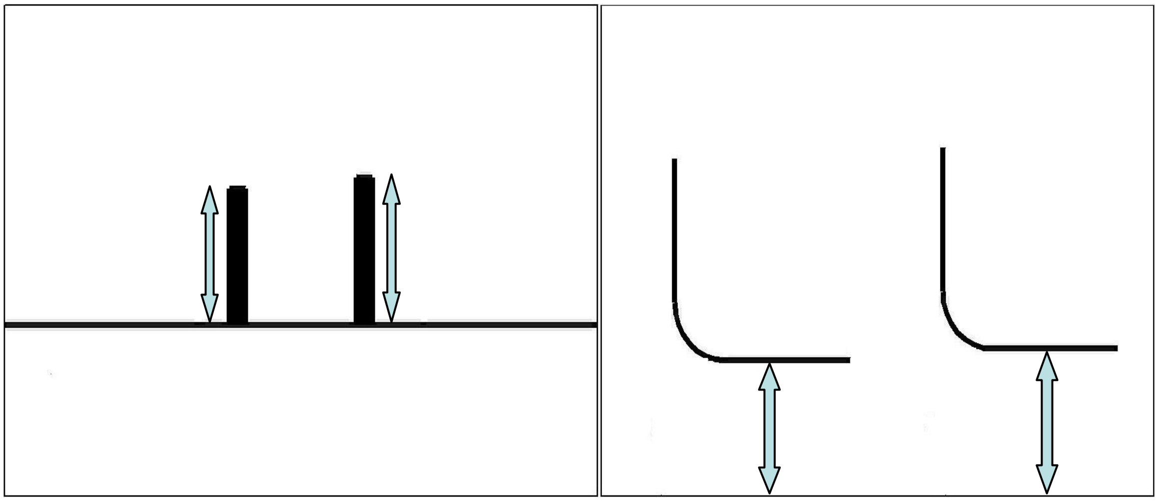


Figure 21: Exploration strategy for Length Perception Testing

For all tasks, subjects were instructed to move slowly during exploration to compensate for the delay between updating of tactile pins of the VT Player. They were given practice figures with which they were taught the exploration strategy. When subjects seemed to learn the strategy and felt comfortable, the actual testing began. For the actual testing, instructions were given for users not to deviate from the exploration strategy and to determine the answer to the task in the least amount of time.

5.5 TRAINING

All participants were given practice in performing each discrimination task before the actual testing commenced for that particular task. Practice figures were produced based on three difficulty levels: easy, medium and hard comparisons. See table (2) for more details. These three difficulty levels were given in series. Easy level discriminations were used to provide information to the participants about: the shape and size of the stimuli and environment, and the exploration procedure. For this level, participants were guided through the figure by passive exploration and were told the answer to the question beforehand. For medium level discriminations, the participants practiced the exploration procedure taught and were provided with answers only when requested. For hard comparisons, they were asked to give an answer and told to continue exploring the graphic again if they gave an incorrect answer.

Table 2: Testing Values for Practice Images.

Stimuli	File no	Difficulty Level	Value difference on Left	Value difference on Right
Asymptote	1	Easy	0	15
	2	Easy	15	0
	3	Medium	0	8
	4	Medium	8	0
	5	Medium	0	-8
	6	Medium	-8	0
	7	Hard	0	4
	8	Hard	4	0
	9	Hard	0	-4
	10	Hard	-4	0
Bar graph	11	Easy	0	15
	12	Easy	15	0
	13	Medium	0	8
	14	Medium	8	0
	15	Medium	0	-8
	16	Medium	-8	0
	17	Hard	0	4
	18	Hard	4	0
	19	Hard	0	-4
	20	Hard	-4	0
Angle 20	21	Easy	0	25
	22	Easy	25	0
	23	Easy	0	-12
	24	Easy	-12	0
	25	Medium	0	9
	26	Medium	-9	0
	27	Hard	0	6
	28	Hard	-6	0
Angle 135	29	Easy	0	-35
	30	Easy	-35	0
	31	Easy	0	25
	32	Easy	25	0
	33	Medium	0	-20
	34	Medium	20	0
	35	Hard	-15	0
	36	Hard	0	15

All Values in mm

All Values in Degrees

In this table, the standard for the Asymptote and Bar graph stimuli is 60mm and is represented as a difference of 0mm. Similarly, for acute angle stimuli, the standard is 20°

and, for obtuse angle stimuli, the standard is 135°. Both of these values are represented as a difference of 0°.

5.6 PILOT TESTING

For the discrimination tasks of the main experiment, the comparison stimuli needed to be chosen to obtain meaningful results; the requirement being that they needed to be able to differentiate between the performance of the three devices (i.e., the VT Player, modified VT Player and raised line drawings) if any existed. Although discrimination thresholds could be obtained for the four tasks with each device and then compared, these experiments would be incredibly lengthy, being 5 hours for one device, and not very tractable. Instead, it was decided that comparison stimuli would be chosen that would maximize the amount of information that could be gained from the main experiment without having to perform a complete set of threshold tests.

In order to do this, six comparison stimuli were used for each task, being centered on a value that produced a discrimination threshold of 75% for the modified VT Player. This would mean that on average, assuming S-shaped psychometric function, the performance on the six comparison stimuli would be 75% for the modified VT Player. This value was chosen as the performance of the modified VT Player was expected to be between that of the VT Player and the raised line drawings. Choosing a 75% performance level would enable the main experiment to capture equal amounts of maximum deviation in performance for the VT Player and the raised line drawings (although it is true that this design does not guarantee that performance will not show ceiling for the raised line drawings or flooring for the VT Player, we still felt that the results would be informative as even a 25% change in performance would still be considered very large).

For choosing the value of the comparison stimulus to be centered on, a pilot test was used to obtain an average 75% discrimination threshold for subjects using the modified VT Player. Although it would have been more ideal to determine the 75% discrimination threshold for each subject used in the main experiment and then use their own threshold, the discrimination threshold experiment, even for one device, was not tractable to perform on a large number of people. Therefore, to avoid any undue sensitivity to the particular value selected that could result in flooring or ceiling effects even for the modified VT Player for a particular subject, values for the comparison stimuli were chosen not only to be the standard +- the average threshold, but the standard +- the average threshold +- the standard deviation in the threshold between subjects. This resulted in six different comparison stimuli.

A pilot study was therefore conducted to determine the average and standard deviation of the 75% discrimination threshold value for each discrimination task using a tractable number of subjects.

5.6.1 Participants

A total of four strongly right handed sighted students (3 male and 1 female) at Virginia Commonwealth University participated in the study. In addition, three strongly right handed blind participants (2 female and 1 male) also participated. None of participants had any neurological disorders or any history of diabetes. The first participant who was blind (female) was legally blind, with some traces of vision. The second participant (male) who was blind was totally blind from an early age. The third participant (female) was congenitally blind. All the participants both sighted and blind were blindfolded during the pilot testing.

5.6.2 Experimental Design

The experimental method, stimuli, instructions and training were used as described in Sections 5.2-5.5. For each task, participants were presented with comparison stimuli that spanned eight different deviation values (table 3). Eight repetitions of these comparison stimuli were presented such that, for half the trials, the standard was on the left side and, for the other half, it was on the right. In addition, four questions were posed which had the standard on both sides. For each task, this resulted in 68 questions, which were presented in random order. Subjects were given one minute for each question (i.e., to explore both the standard and comparison, and then give an answer).

Table 3: Testing Threshold values for pilot experiment.

Serial no	Stimuli	Deviation values
1	20° Standard	+/- 3,6,9,12
2	135° Standard	+/- 5,10,15,20
3	Bar-graph: 60mm standard	+/- 1,2,4,8
4	Asymptote: 60 mm standard	+/- 1,2,4,8

For the sighted subjects, all participants were tested on the four tasks in a different sequence. In general, two participants received the tasks involving angles first, and two participants received the tasks involving lengths first. Both blind subjects were asked to perform the angle tasks before the length tasks.

For each discrimination question with a different deviation value, responses were transformed into a fraction indicating the number of times the comparison stimuli were judged as larger than the standard. Then for each discrimination task, a normalized cumulative Gaussian distribution was fit to the data to describe the psychometric function. Both the fit and the 75% threshold values were determined in MATLAB using the programming code provided by Hill (http://bootstrap-software.org/psignifit/, accessed Oct., 2008)).

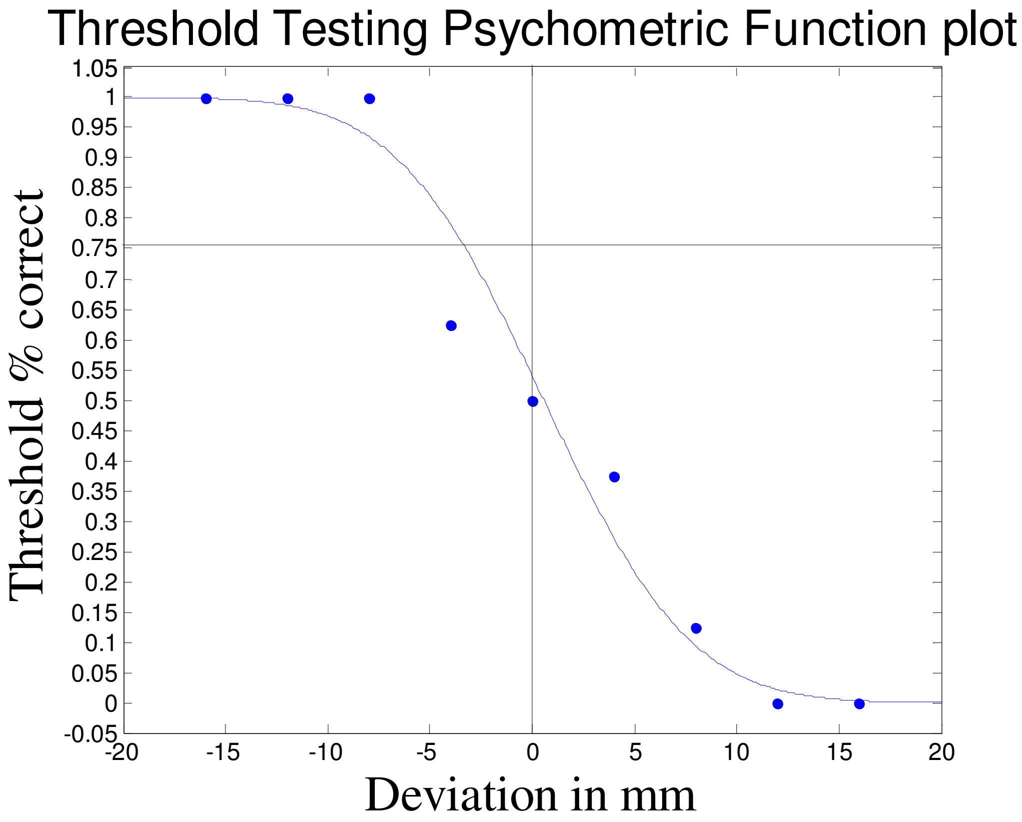


Figure 22: Plot of fit of psychometric function

5.6.3 Results

The psychometric curves were fit for all the tasks and all subjects as shown in Figures 23-26.

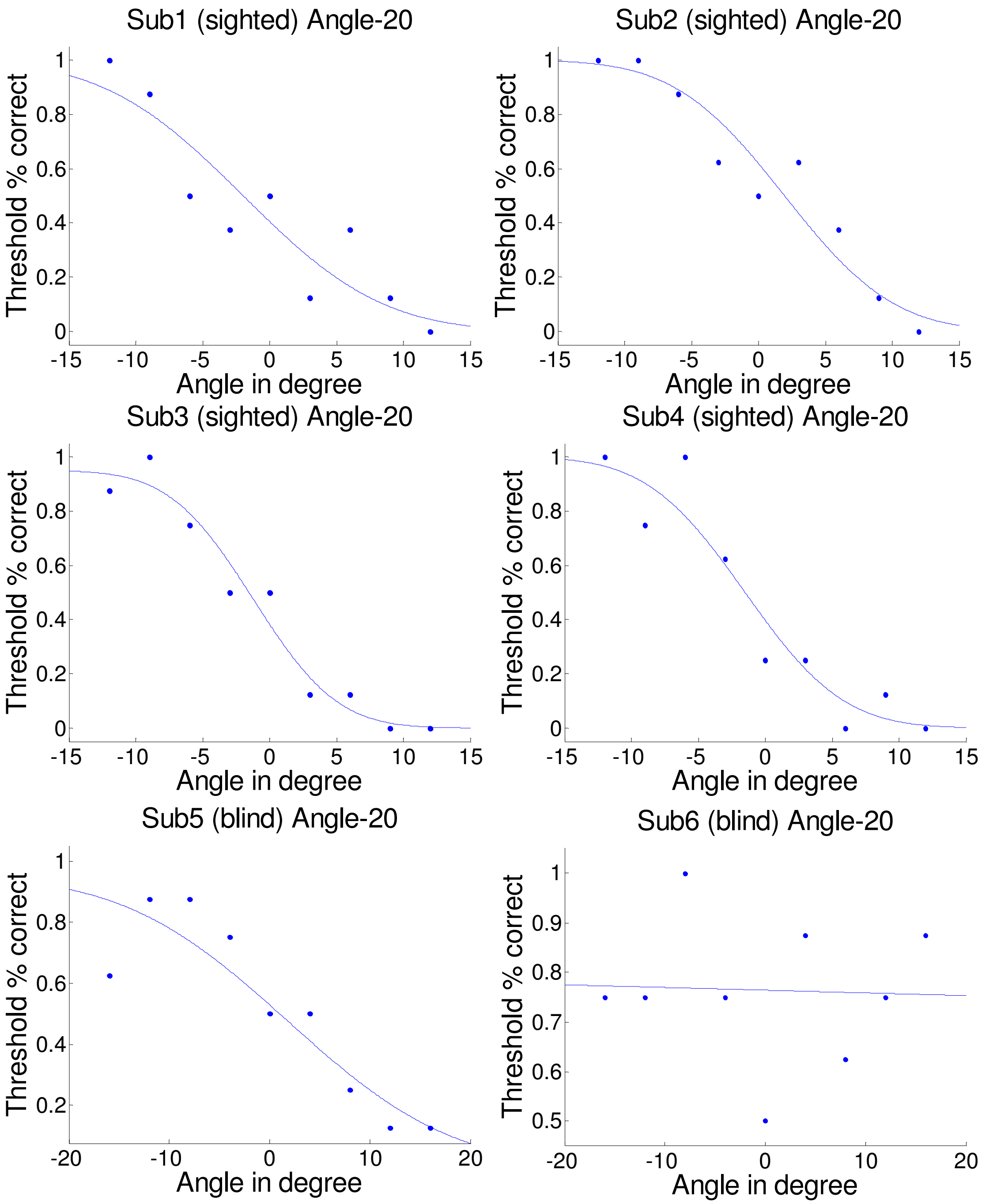


Figure 23: Psychometric curve fitting of the subjects for angle testing stimuli (20 degree standard)

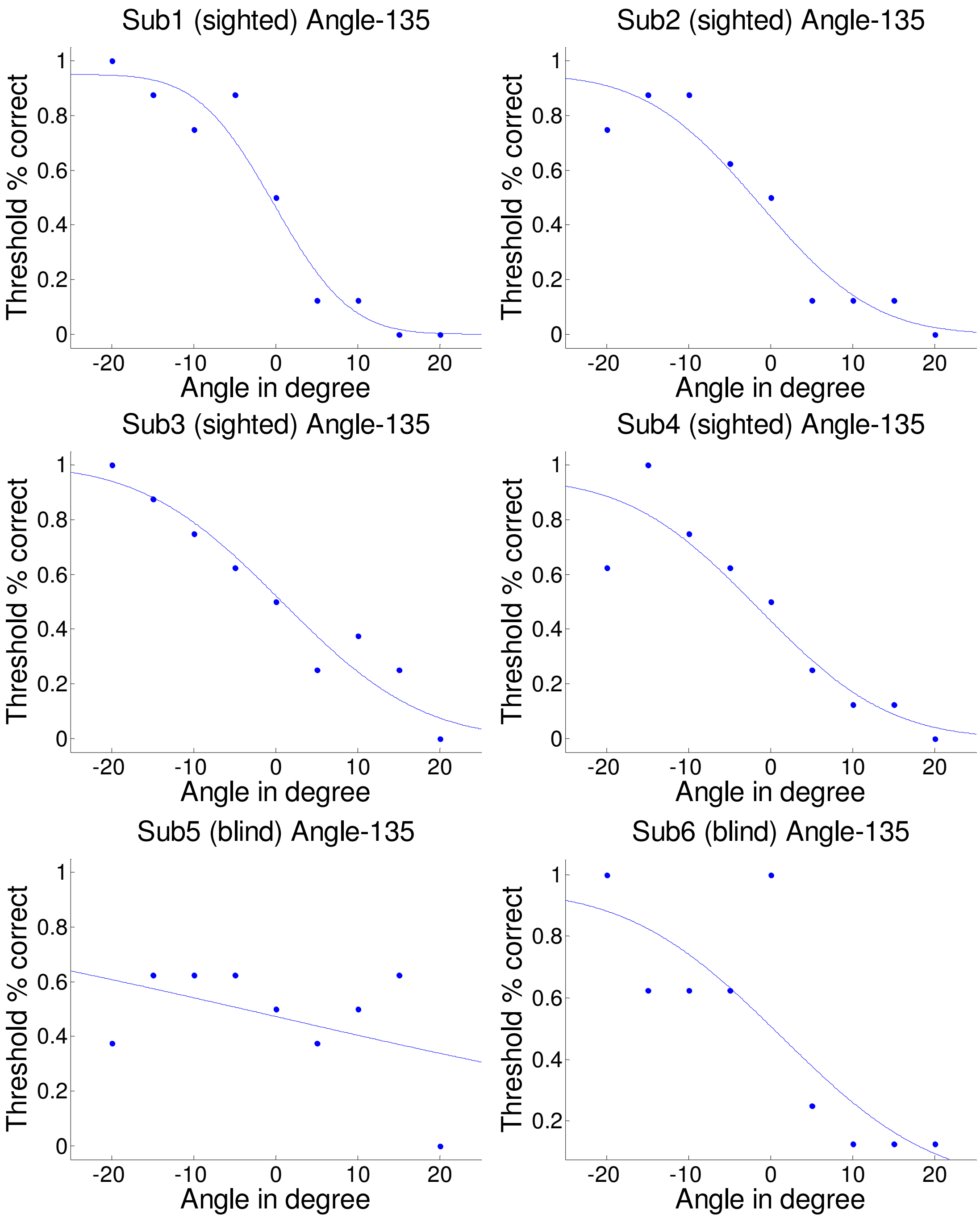


Figure 24: Psychometric curve fitting of the subjects for angle stimuli (135 degree standard)

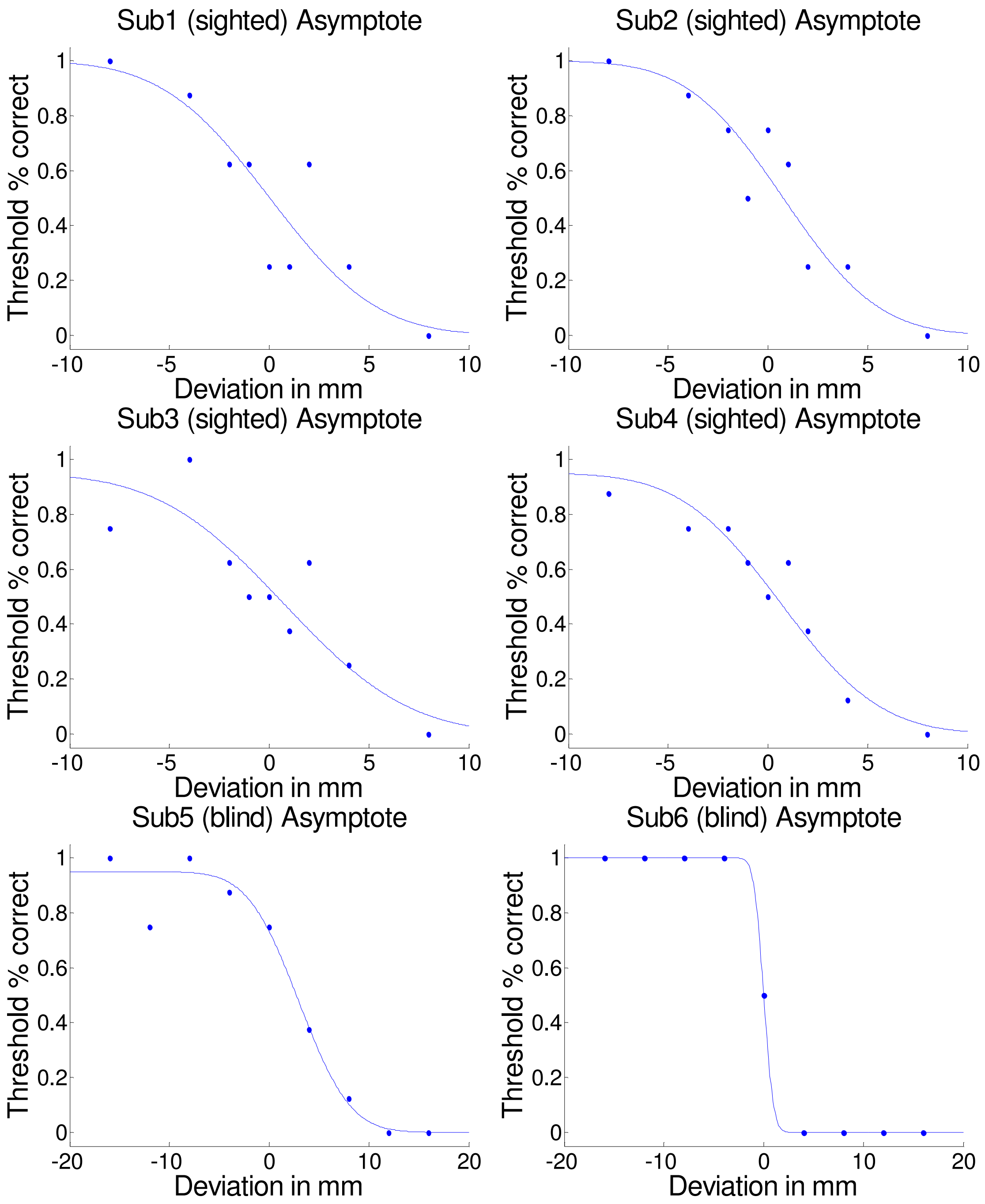


Figure 25: Psychometric curve fitting of the subjects for length stimuli (60 mm bar standard)

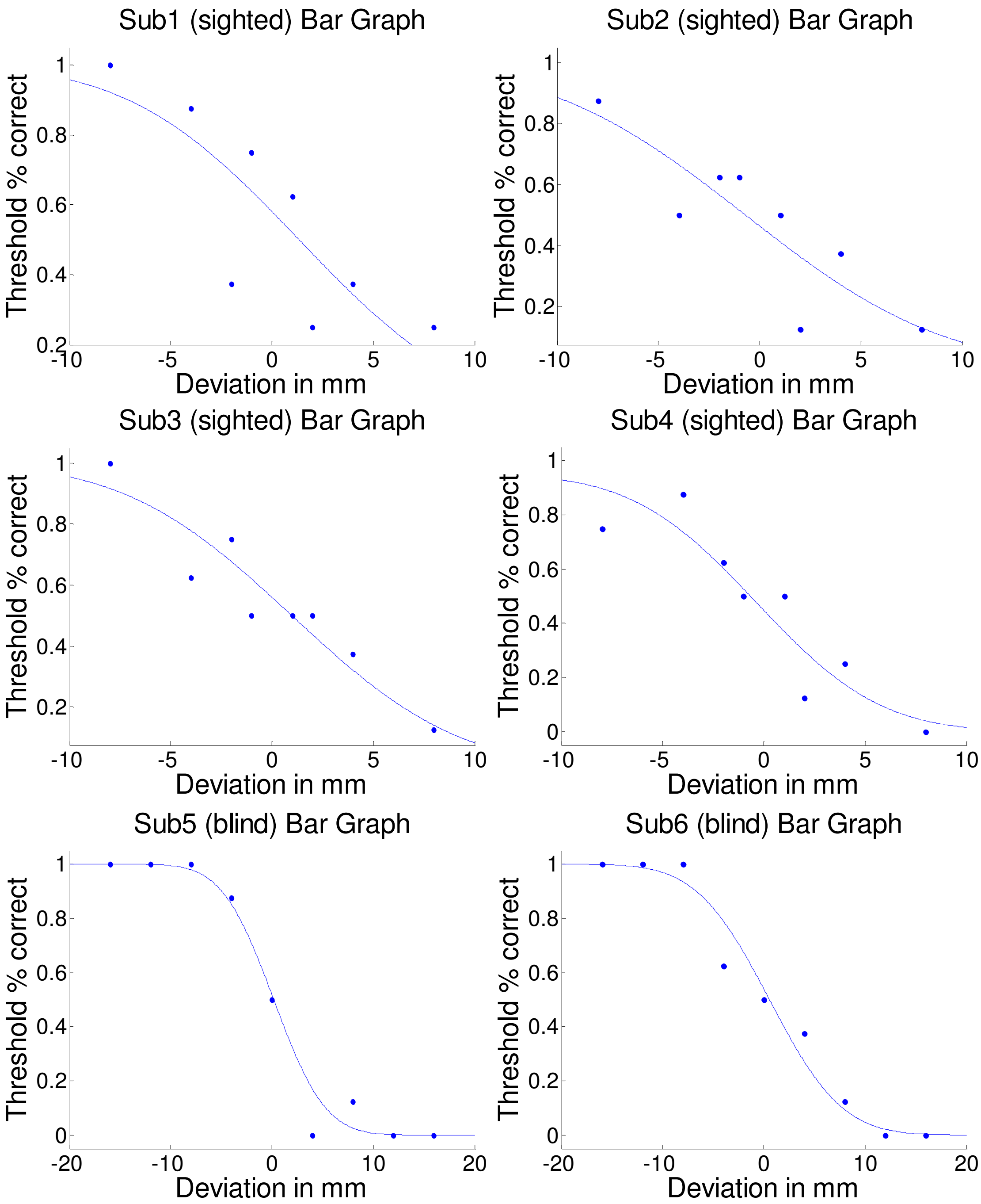


Figure 26: Psychometric curve fitting of the subjects for length stimuli (60 mm asymptote standard)

Figures 27a-d show the individual threshold values for a 75% correct response for all the subjects for all the tasks. Each bar in a figure represents different subjects, one to four number participants are sighted and, five to seven are blind participants. Threshold was not obtained for one of the blind subject (represented as number 7 participant in figure 27) for the angle discrimination task with a standard of 20 degrees and, for the other, with a standard of 135 degrees, due to the unreliability of the data.

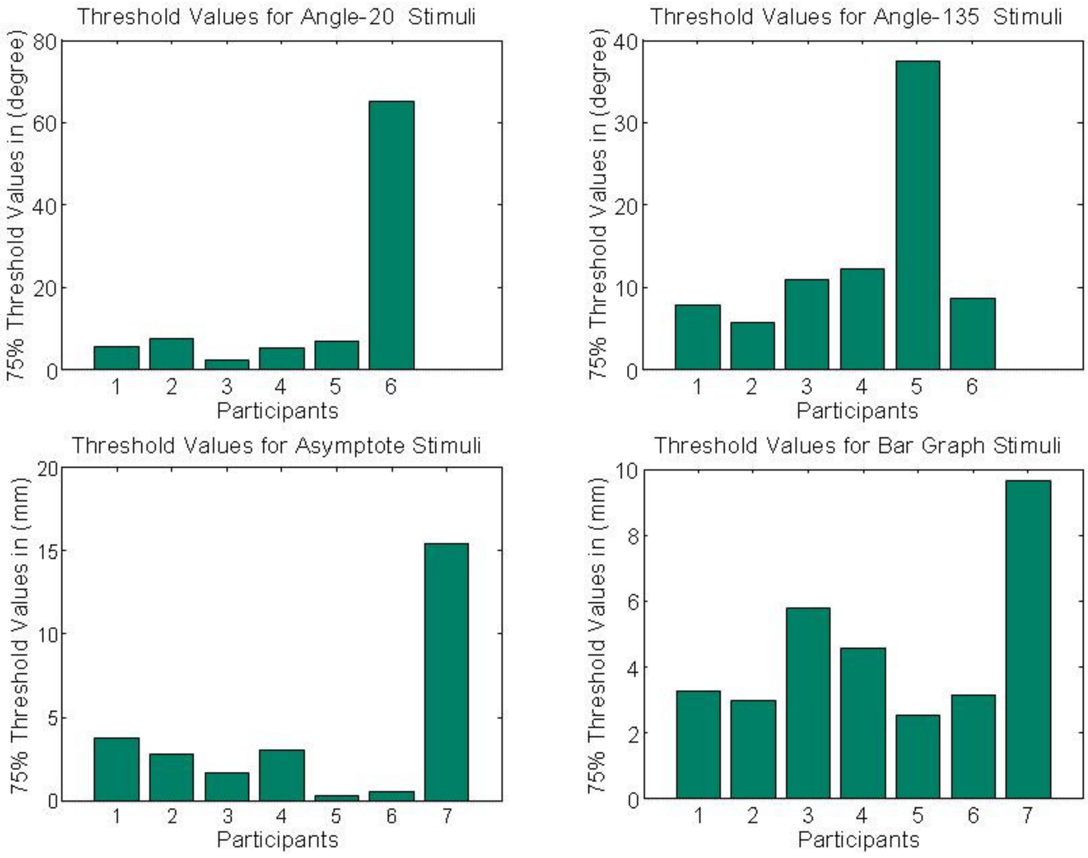


Figure 27: Shows the individual threshold Values all the participants (Sighted and Blind)

5.6.4 DISCUSSION

Originally we were intending to perform pilot testing only with subjects who were blind, and then continue using subjects who are blind with the main experiment. However, due to the inability to get reliable threshold measurements for half of the angle data for blind subjects and the lack of availability of participants who are blind, sighted subjects were used. As the thresholds for sighted and blind participants are likely to be different, only the threshold values for the sighted subjects were averaged to choose the comparison stimuli. Also, as such, only sighted subjects will be used in the main experiment.

Averaged threshold values and the standard deviations of the sighted participants are as shown below in table 4.

Table 4: Threshold values for 75% correct responses of all the discrimination tasks.

	Asymptote	Bar Graph	Angle 20	Angle 135
Th	2.78	4.15	5.0875	9.1625
SD	0.837	1.27	2.12	2.96

For the participants who were blind, we expect that the way we asked the questions about angles might have confused them. In contrast, Kappers and her colleagues (2008), while testing for haptic orientation perception, asked participants to interpret the orientations of the figures with the minute hand of the clock. This made the task easier as all the participants were easily able to understand the concept. The better performance of the sighted participants compared to the blind participants was also likely due to the fact that the sighted subjects all had much more experience with graphics in general.

Although we used a limited number of subjects, due to our pilot experiment being very lengthy and only a prelude to the main experiment, it is interesting to make comparisons between the discrimination thresholds we obtained with the modified VT Player to that of the literature. One such comparison is to the experiments of Wijntjes and Kappers (2007), upon whose work we based our angle discrimination tasks. Of most relevance was their experiment in which subjects used the same exploration strategy that we used, with standards of 20 degrees and 135 degrees, and for which the apex of the angle was present or absent. They found a difference in the discrimination thresholds for the two different types of stimuli (apex present/absent) and posited that the apex was primarily a cutaneous information source and the arms of the angle were primarily a kinesthetic information source.

The 75% correct response threshold for Wijntjes and Kappers (2007) experiments (if we use their conversion factor) were 4.0 degrees for a 20 degree standard with an apex, 5.0 degrees for a 20 degree standard without an apex, 7.2 degrees for a 135 degree standard with an apex, and 10.1 degrees for a 135 degree standard without an apex. For the modified VT Player, we obtained an average 75% correct response threshold of 5.1 degrees for the 20 degree standard and 9.2 degrees for the 135 degree standard. As can be seen, our results are most comparable to the results of Wijntjes and Kappers without an apex, rather than with one. This suggests that, potentially, the information obtained through the distributed pin array is still primarily kinesthetic in nature. This is supported by the observation that even with the pin array, subjects made transverse motions across the lines to explore them, similar in manner to what we have observed subjects do with a single point of contact device; in contrast to raised line drawings where the motion is primarily along the line.

5.7 MAIN EXPERIMENT

The objective of the main experiment was to compare the performance of the VT Player, the modified VT Player and raised line drawings for two angle discrimination tasks and two length discrimination tasks.

5.7.1 METHOD

5.7.1.1 PARTICIPANTS

A total of 19 strongly right handed sighted subjects (9 females and 10 males) participated in the study. All were aged between 20-30 years. All participants either worked or studied at Virginia Commonwealth University. None of the subjects had neurological disorders or diabetes. All the participants were naïve to the experiment and had no experience using the VT Player.

5.7.1.2 EXPERIMENTAL DESIGN

The experimental method, stimuli, instructions and training were used as described in Sections 5.2-5.5. In addition, before the instructions and training began, participants were shown drawings of an example figure for each task on a white board.

Each participant received the four discrimination tasks in 3 different conditions: with the VT Player, with the modified VT Player and with the raised line drawings. The experiment was blocked on condition, where the order of conditions was presented in a counterbalanced design between subjects. Within each condition, the order of presentation of the discrimination tasks was also counterbalanced between subjects and between conditions. For each discrimination task, 6 comparison stimuli were used (table 4) as chosen in Sections 5.6. Each comparison stimulus had 2 repetitions: the repetitions were balanced so that half the time the standard was on the right and half the time it was on the left. This resulted in 12 questions per discrimination task within condition and which were presented in random order. Subjects were given two minutes for each question (i.e., to explore both the standard and comparison, and then give an answer), although they were told to answer as quickly as possible. The time to response was recorded in fractions of minutes.

Table 5: Six comparison stimuli used for the all the testing stimuli.

Testing Stimuli	S+Th	S+Th+SD	S+Th-SD	S-Th	S-Th+SD	S-Th-SD
Angle 20 (in degree)	25.08	27.2	22.96	14.92	17.04	12.8
Angle 135 (in degree)	144.16	147.12	141.2	125.84	128.8	122.88
Asymptote (in mm)	62.78	63.617	61.943	57.22	58.057	56.383
Bar Graph(in mm)	64.15	65.42	62.88	55.85	57.12	54.58

Outcome measures for the experiment were number of correct answers and the time to respond.

In addition, the System Usability Scale (Digital Equipment Corp, 1986) survey was administrated at the end of the experiment to quantify the perceived usefulness of the VT Player and modified VT Player. All participants were asked to respond to the statements on a Likert scale of one (strongly disagree) to five (strongly agree), three being neutral or no answer. In the survey, question 1, 5 and 10 were not asked, so the responses were marked as neutral (3) for all the participants.

5.7.1.3 STATISTICAL METHODS

The two variables which were use to quantify performance were: 1) the probability of a correct response and 2) the time to respond. A generalized linear mixed effects model was used to estimate the probability of a correct response as a function of device, discrimination task, task “difficulty”, order and time using a logit link and assuming a binomial distribution for the response. The model included main effects for device, task, task difficulty, order, and time, as well as interaction effects for device by task and device by time. A generalized linear mixed effects model was fit to model the time to respond as a function of the device, discrimination task, task difficulty and order. The model included main effects for device, task, task difficulty and order, as well as the interaction effect for device by task. The models also assumed that responses from the same subject are correlated and responses from different subjects are independent.

5.7.2 Results

5.7.2.1 PROBABILITY OF CORRECT RESPONSE

For the linear mixed effects model of the probability of a correct response, the tests for the model effects are summarized in Table 6.

Table 6: Analysis of Model Effects for the Probability of a Correct Response.

Effect	F-statistic	(NDF, DDF)	p-value
Order	5.79	(2, 36)	0.0066
Task Difficulty	4.63	(5, 90)	0.0008
Task	2.34	(3, 54)	0.0831
Device	19.68	(2, 36)	< 0.0001
Time	13.13	(1, 2696)	0.0003
Device × Time	3.19	(2, 2696)	0.0412
Device × Task	1.08	(6, 108)	0.3787

The most relevant result was that, after adjusting for order, discrimination task, task difficulty and response time, there was evidence of a very significant device effect. However, the effect depended to some degree on task type (and we will show the results for the different tasks separately below) and on the response time. There was also a statistically significant main effect of order, task difficulty and response time.

The estimated proportion of correct responses for each of the devices based on the developed linear, mixed effects model is shown in Table 7. Results are shown across all tasks and for each task separately. The associated 95% confidence intervals and standard error are also given. Figures 28 and 29 show these results in graphical form; error bars indicate the 95% confidence intervals.

Table 7: Estimates for the proportion of correct responses by device, and device and task.

Device	Proportion	95% CI	Task	Proportion	95% CI
VT Player	0.6628	(0.6150, 0.7074)	T1	0.6392	(0.5582, 0.7130)
			T2	0.7053	(0.6320, 0.7693)
			T3	0.5981	(0.5272, 0.6651)
			T4	0.7027	(0.6319, 0.7651)
Modified VT Player	0.7424	(0.7027, 0.7784)	T1	0.7898	(0.7269, 0.8414)
			T2	0.7527	(0.6870, 0.8085)
			T3	0.6964	(0.6267, 0.7581)
			T4	0.7245	(0.6565, 0.7835)
Raised Line	0.8099	(0.7577, 0.8530)	T1	0.8316	(0.7541, 0.8882)
			T2	0.8092	(0.7315, 0.8684)
			T3	0.7905	(0.7122, 0.8519)
			T4	0.8066	(0.7328, 0.8637)

CI= Confidence Interval

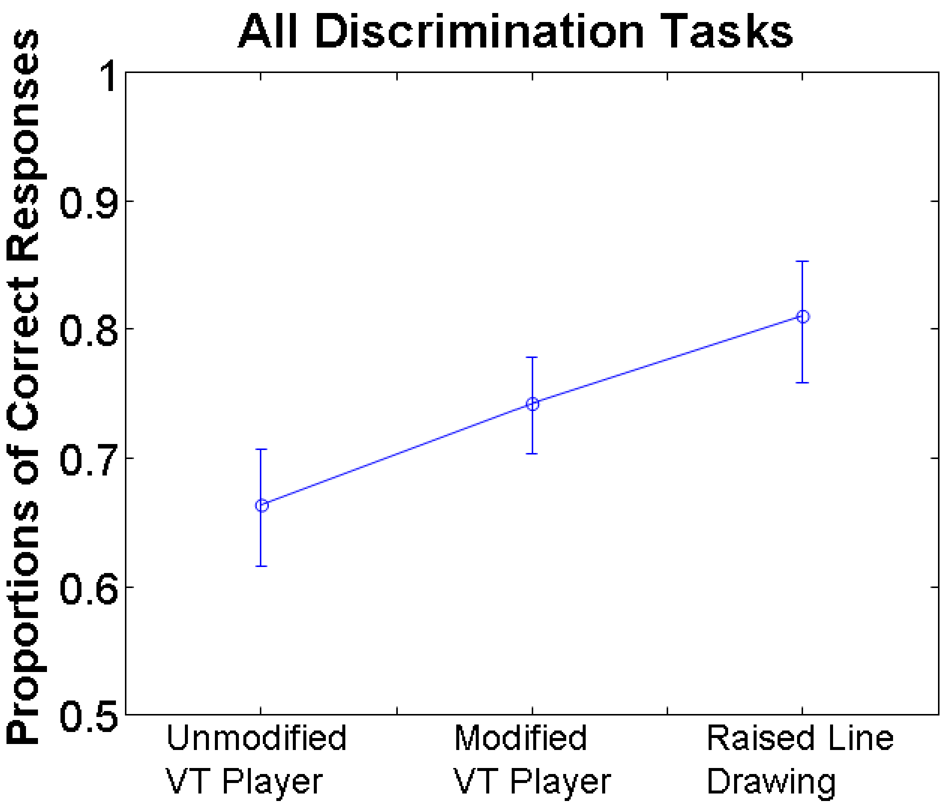


Figure 28: Shows the estimates for the proportion of correct responses for each of the devices across all discrimination tasks. Error bars indicate the 95% confidence intervals

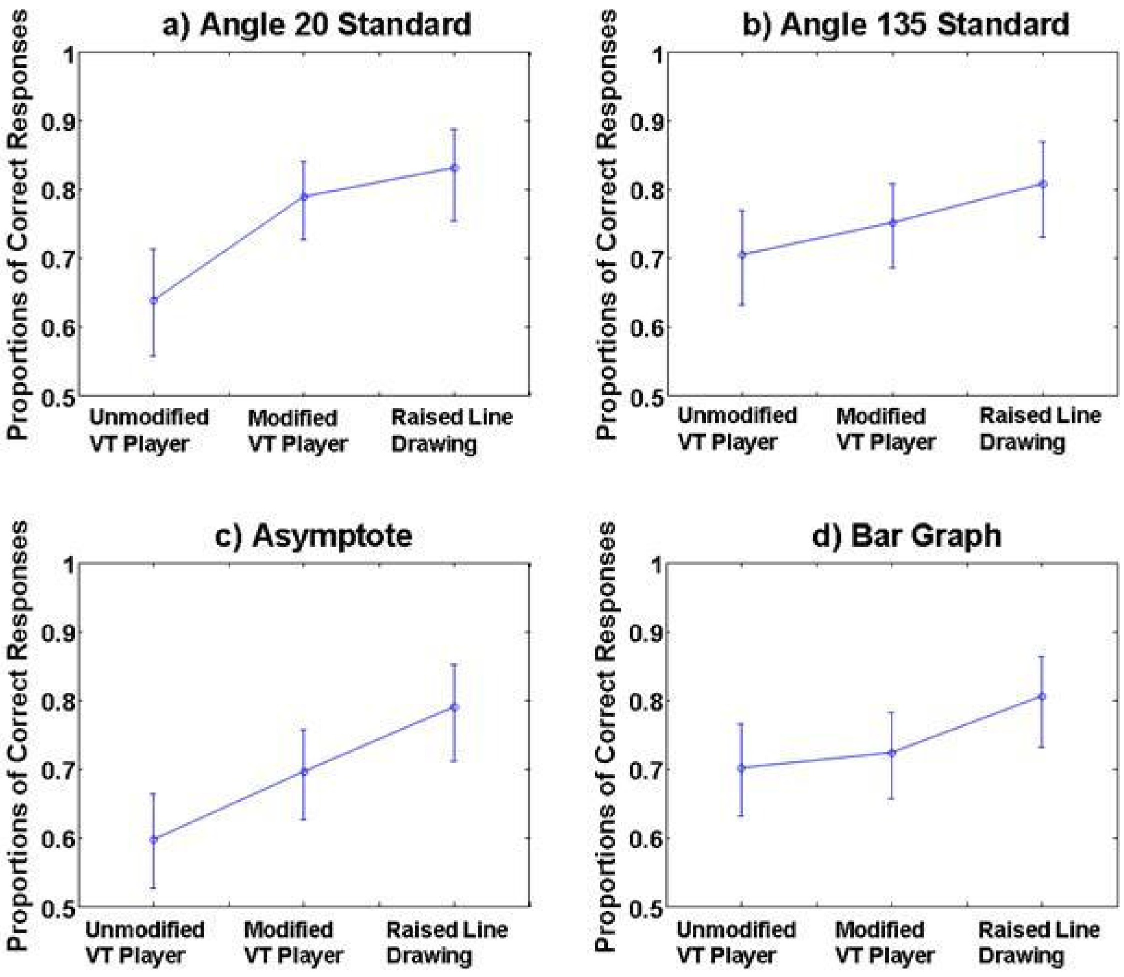


Figure 29: Shows the estimates of the proportion of correct responses for each of the devices for each discrimination task. Error bars indicate the 95% confidence intervals

Perhaps the best way to convey the effect size of the device effect is to look at the odds ratio between devices (Table 8). We are particularly interested in comparing the modified VT Player to the unmodified VT Player to validate that correcting the limitations in the VT Player improves the odds of a correct response. We are also interested in comparing the modified VT Player to the raised line drawings to determine how close performance with this new device is to the goal of being able to replicate the performance accuracy that is obtained with actually continuous raised line drawings.

Table 8: Estimated Odds Ratios for the Modified versus the Unmodified VT Player and the Raised Line Device versus the Modified VT Player.

	Modified vs. Unmodified VT Player		Raised Line Device vs. Modified VT Player	
	Odds Ratio	95% CI	Odds Ratio	95% CI
All tasks	1.7992	(1.1716, 2.7631)	2.0045	(1.3442, 2.9891)
T1 and T2	2.0152	(1.2163, 3.3387)	1.8345	(1.1551, 2.9134)
T3 and T4	1.6064	(1.0444, 2.4709)	2.1902	(1.3925, 3.4449)

CI = Confidence Interval

In comparing the modified VT Player to the original VT Player, we found a large improvement in the odds of a correct response when using the modified VT Player. Considering all four discrimination tasks together, we found that the odds of a correct response were increased by 79.9%. The increase in the odds was also noticeably greater for the angle discrimination tasks (with an increase in the odds by 101.5%) than for the length discrimination tasks (with an increase in the odds of 60.6%).

However, we also found a large improvement in the odds of a correct response when using the raised line drawings as compared to the VT Player. Considering all four discrimination tasks together, we found that the odds of a correct response were increased by 100.5%. In this case, the increase in the odds was notably greater for the length discrimination tasks (with an increase in the odds of 119.0%) than for the angle discrimination tasks (with an increase in the odds of 83.5%)

In terms of the other main effects of the model, order, the level of difficulty of the task, and response time were also statistically significant in terms of the estimated probability of a correct response. The level of difficulty of the task is not surprising as we would expect the probability of a correct response to decrease with increasing difficulty of discrimination. In terms of the order effect, the odds of a correct response were significantly higher at period 1 as compared to period 2 (odds ratio = 1.40, 95% confidence interval = [1.11,1.77]) and period 3 (odds ratio = 1.43, 95A confidence interval = [1.13,1.80]). In terms of the response time effect, increasing the amount of time was found to increase the likelihood of a correct response for the modified VT Player (for a 10 second increase in time, the odds ratio became 1.07, 95% confidence interval [1.01, 1.14]) and the VT Player (also for a 10 second increase in time, the odds ratio became 1.16, 95% confidence interval [1.05,1.29]), but not the raised line drawings.

5.7.2.2 TIME TO RESPONSE

For the linear mixed effects model of the time to respond, the tests for the model effects are summarized in Table 8.

Table 9: Model effects for time to respond by the devices.

Effect	F-statistic	(NDF, DDF)	p-value
Order	30.67	(2, 2699)	<0.0001
Task Difficulty	1.76	(5, 2699)	0.1176
Device	863.86	(3, 2699)	<0.0001
Task	63.01	(2, 2699)	< 0.0001
Device × Task	35.71	(6, 2699)	< 0.0001

The most relevant result was that, after adjusting for order, discrimination task and task difficulty, there was evidence of a very significant device effect. However, the effect depended on task type. There was also a statistically significant main effect of order and task.

The estimated time to respond (given in minutes) for each of the devices based on the developed linear, mixed effects model is shown in Table 9. Results are shown across all tasks and for each task separately. The associated 95% confidence intervals and standard error are also given.

Figures 30 and 31 show these results in graphical form; error bars indicate the 95% confidence intervals.

Table 10: Estimates for the Time to respond with the 95% Confidence Interval (CI) by Device and, Device and Task.

Device	Time†	95% CI	Question	Time†	95% CI
VT Player	0.964	(0.870, 1.058)	T1	1.219	(1.117, 1.321)
			T2	1.063	(0.961, 1.165)
			T3	0.631	(0.528, 0.733)
			T4	0.943	(0.841, 1.045)
Modified VT Player	0.675	(0.582, 0.769)	T1	0.683	(0.581, 0.785)
			T2	0.710	(0.608, 0.812)
			T3	0.520	(0.418, 0.622)
			T4	0.788	(0.686, 0.890)
Raised Line	0.267	(0.174, 0.361)	T1	0.228	(0.126, 0.331)
			T2	0.260	(0.158, 0.362)
			T3	0.270	(0.168, 0.373)
			T4	0.310	(0.208, 0.412)

CI = Confidence Interval
† = (in minutes)

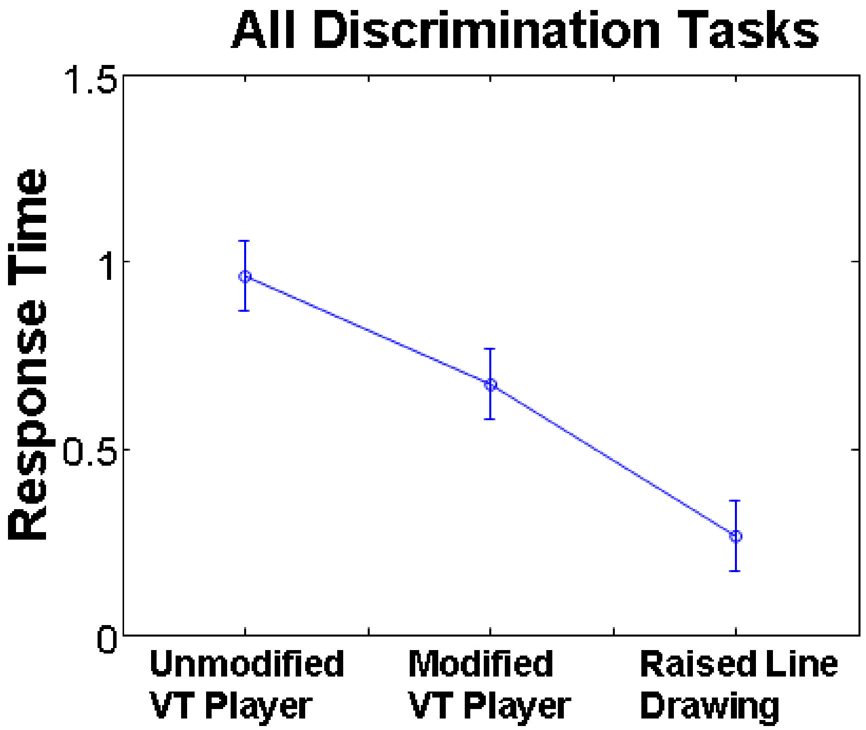


Figure 30: Shows the estimates for the response time for each of the devices across all discrimination tasks. Error bars indicate the 95% confidence intervals

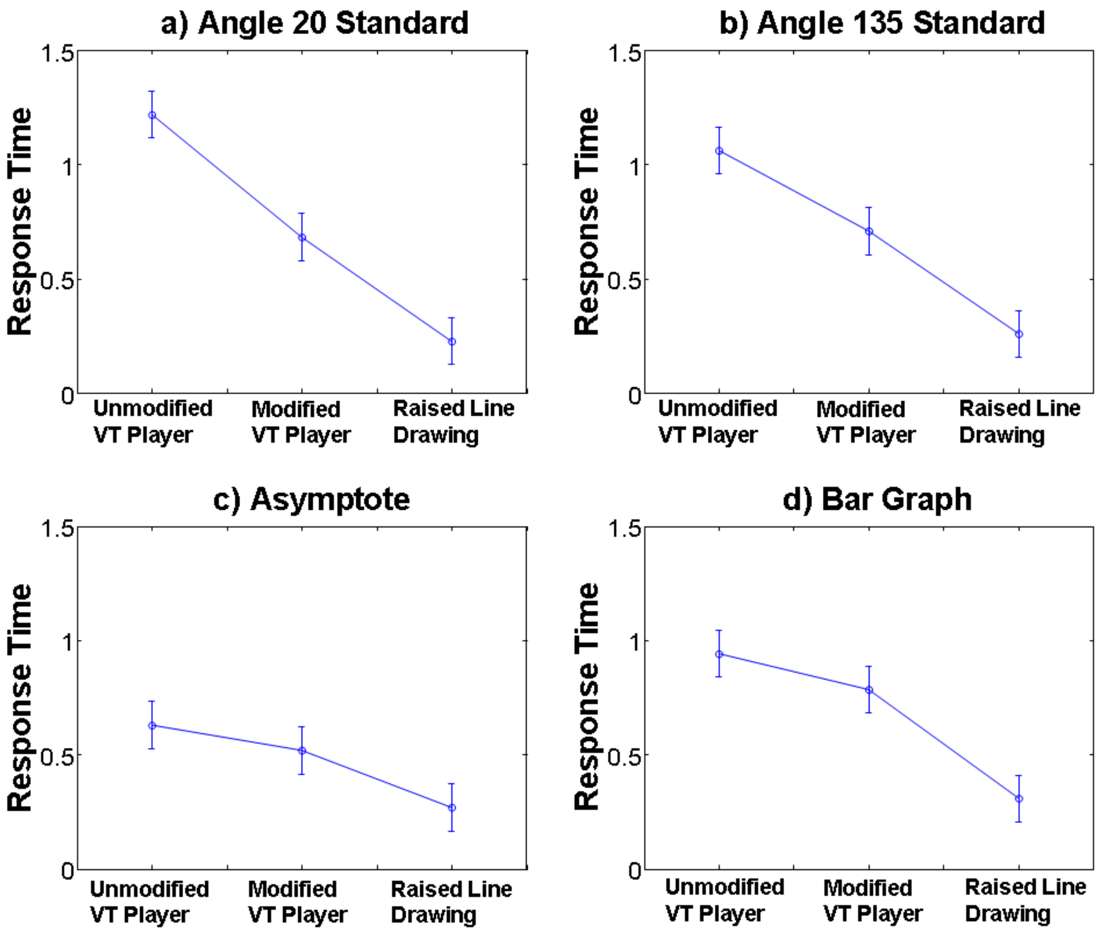


Figure 31: Response time of all devices for individual questions. Error bars indicate the 95% confidence intervals

We are particularly interested in comparing the modified VT Player to the unmodified VT Player to validate that correcting the limitations in the VT Player improves the response time, in addition to the odds of a correct response. We are also interested in comparing the modified VT Player to the raised line drawings to determine how close performance with this new device is to the goal of being able to replicate the performance accuracy that is obtained with actually continuous raised line drawings. For these questions we will look at the differences in response times (Table 10).

Table 11: Estimated Differences in Response Time for the Unmodified VT Player minus the Modified VT Player, and the Modified VT Player minus Raised Line Drawings.

	VT Player minus Modified VT Player		Modified VT Player minus Raised Line Device	
	Difference	95% CI	Difference	95% CI
All tasks	0.289	(0.256, 0.322)	0.408	(0.375, 0.441)
T1 and T2	0.444	(0.397, 0.491)	0.453	(0.406, 0.499)
T3 and T4	0.133	(0.086, 0.180)	0.364	(0.317, 0.410)

In comparing the modified VT Player to the original VT Player, we found that the time to respond is significantly lower (quicker) for the modified VT Player than the original VT Player (p-values for across all tasks, task 1 and 2, and task 3 and 4 are all < 0.0001). On average, across all tasks, we found the difference in response time to be 0.289 minutes. There was more of a difference for angle discrimination tasks (0.444 minutes) than for length discrimination tasks (0.133 minutes).

However, we also found significant differences in the response in comparing the modified VT Player compared to raised line drawings. On average, across tasks, we found the response time to be 0.408 minutes faster for raised line drawings than for the modified VT Player. Again, there was more of a difference for angle discrimination tasks (0.453 minutes) than for length tasks (0.364), although not to the degree as the differences for the two versions of the VT Player.

In terms of the other main effects of the model, order was also statistically significant. Specifically, the time to respond was significantly higher at period 1 as compared to period 2 (difference = 0.113, CI = [0.080,0.146]) and as compared to period 3 (difference = 0.116, CI = [0.083,0.149]. The time to respond was not statistically significant between periods 2 and 3 (p=0.8682).

5.7.2.3 SYSTEM USABILITY EVALUATION

The scores for the System Usability Scale survey were determined for the Modified VT Player and the VT Player; the raised line drawing method was not considered for this survey as it is not device. The devices could be rated from 0 (not usable) to 100 (highly acceptable). We found very large difference between the mean scores between the two devices. The scores for the Modified VT Player had a mean of 69.08 and a standard deviation of 8.42. The scores for the original VT Player had a mean of 39.87 and a standard deviation of 14.8.

5.7.3 Conclusions and Discussion

The results of the experiment clearly confirm that there is a significant improvement in performance when using the modified VT Player as compared to the original VT Player. The odds of a correct response, considering all four discrimination tasks, were increased by 80% and the amount of time taken decreased by 30%. In addition, the results of administering the System Usability Scale showed that the subjects found the modified VT Player much more usable (by an increase in usability of 73%) than the original VT Player. Informal comments by the subjects also indicated that they did not experience the frustration with the modified VT Player that they did with the original VT Player.

One issue that is important to note is that the performance differences obtained are also very conservative. During the experiment, the performance of the original VT Player was actually maximized in such a way that would not be realistic during normal usage; namely, the starting position for the original VT Player was re-aligned between the screen and the desk top *every* trial. Without this re-alignment, the time taken using the original VT Player would have been much greater: in practice, we found that subjects would often not even be able to find the stimuli in the two minute time limit. In contrast, the modified VT Player did not have this problem at all, due to its absolute position sensing.

Our choice to realign the starting position of the original VT Player every trial was based on our desire to obtain a measurement for the odds of a correct response for the discrimination tasks, while making the experiment tractable. Among other possible beneficial effects, re-aligning the start position enabled subjects to find the stimuli for comparison much faster and, thus, able to complete the experiment in a reasonable amount of time. In a real use situation, we would expect the time taken to be greater and measurement errors to be cumulative because of the relative position information provided by the original VT Player.

Two other contributions to the conservative estimate of the difference in performance between the original and modified VT Players were that for some subjects: 1) flooring effects in the number of correct responses were observed with the original VT Player but not with the modified VT Player, and 2) the time limit was reached on trials with the original VT Player but not the modified VT Player. Both these effects would contribute to an underestimation of the performance difference. It should be noted though that we did achieve our target of placing the performance of the modified VT Player in the middle of the performance range (at approximately 75% correct), which maximized the allowable variation in both directions.

The results of the experiment also showed that performance was still better with the actual raised line drawings than even with the modified VT Player. The odds of a correct response, considering all four discrimination tasks, were increased by 100.5% and the amount of time taken decreased by 60%. In addition, some subjects exhibited ceiling effects on the number of correct responses, indicating that the odds of a correct response were conservatively estimated. This was likely not due to any issues with the kinesthetic feedback, which was made much more accurate by the modified VT Player, but with the cutaneous information due to the limited spatial resolution of the VT Player as compared to raised line drawings.

In addition, to the main effect of the device used, when the device was used in the order of presentation also had an effect. The first device presented to subjects, regardless of which one it was, tended to have higher odds of a correct response. However, this did not seem due to fatigue as the response time was actually longer for the device presented first than for the remaining devices. It was likely that subjects were more attentive with the first device than with the remaining devices, which made the counterbalanced design essential to the analysis.

6 CONCLUSIONS

The uses of tactile mice to interpret outline drawings have several advantages over physical raised line diagrams: they are more interactive, cheaper and more portable, and do not wear as easily. Although these devices have widespread applications, we have suggested that there are some serious design problems with them that have prevented tactile mice from being usable. In this thesis, we proposed cheap modifications to a particular tactile mouse, the VT Player, that can solve these problems and significantly improve performance.

The modifications performed on the VT Player were: (1) turning it from a relative velocity based device (inherent in all tactile mice) to an absolute positioning device using an electromagnetic position sensor; (2) adding a physical border to prevent the device from going past the borders of the screen; and (3) moving the position sensor to the center of the tactile pins to reduce position mismatches between the kinesthetic and tactile information due to rotation of the device.

Previous chapter described the validation experiment performed to show how these modifications to the VT Player improved performance. As most tactile diagrams can be thought to be made up of lines and angles, discrimination of these primitives, in terms of line length and angular extent, were performed. The modified VT Player showed significantly improved performance over the original VT Player, both in terms of the odds in obtaining a correct response and time to perform the task. Greater performance improvements were observed for the angle discrimination tasks than the length discrimination tasks. This was possibly due to the angle discrimination tasks being more complex than the length discrimination tasks (with each angle consisting of two tracked lines that converged) which could have led to more cumulative errors for these tasks when using the original VT Player.

It should also be acknowledges that the main experiment described in this previous chapter also showed that the modified VT Player still has a ways to go to achieve the performance of raised line drawings. The most likely reason that we are aware of is that the tactile pin matrices of the VT Player, which have pins spaced 2mm apart, still do not provide an accurate enough depiction of an edge like a raised line drawing does. Unlike a raised line drawing, where lines are tracked by following along them, the user needs to move the VT Player back and forth across the line. This is similar to what we observed with a tactile display with a single point of contact.

Thus, it seems that the spatial resolution of the tactile display component of the tactile mouse needs to be improved as well to achieve the performance of raised line drawings. However, it is likely that the same size of the contact area needs to be maintained as well (which currently covers approximately the pad of one finger), which would result in an increase in the number of pins. This would be much more difficult to incorporate into a hand-sized portable device, as well as being more costly and harder to maintain. We, therefore, with the modified VT Player, feel that we have reached the tradeoff point between design issues and performance.

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