ANALYSIS OF PERFORMANCE RESULTING FROM THE DESIGN OF SELECTED HAND-HELD INPUT CONTROL DEVICES AND VISUAL DISPLAYS

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(ABSTRACT)

Since the introduction of graphical user interfaces (GUI), input control devices have become an integral part of desktop computing. When interfacing with GUI s, these input control devices have become the human s primary means of communicating with the computer. Although there have been a number of experiments conducted on pointing devices for desktop machine, there is little research on pointing devices for wearable computer technology. This is surprising because pointing devices are a major component of a wearable computer system, allowing the wearer to select and manipulate objects on the screen. The design of these pointing devices will have a major impact on the ease with which the operator can interact with information being displayed (Card, English, and Burr, 1978). As a result, this research is the first in a series to investigate design considerations for pointing devices and visual displays that will support wearable computer users.

Twenty soldiers participated in an experiment using target acquisition software with five pointing devices and two visual displays. The findings of the research strongly support the use of a relative mode-pointing device with rotational characteristics (i.e. trackball or thumbwheel) over other designs. Furthermore, the results also suggest that there is little difference between pointing devices operated with the thumb and index finger for target acquisition tasks. This study has also showed that there were little differences in pointing and homing time for pointing devices across the two visual displays. Finally, the study demonstrated that the Fitts law model could be applied to hand-operated pointing devices for wearable computers. This is important because it allows the future development of pointing devices to be compared with the devices tested in this research using the Fitts Law Index of Performance calculations.

DEDICATION

This thesis is dedicated to my wife, Sandy, and my two children Kyle (16) and Ryan (13). If it were not for their flexibility to relocate to Virginia from Pennsylvania, my academic goals would have been much more difficult to achieve. Both my sons willingly left schoolmates and friends behind to support me in my academic pursuit. I am especially grateful to Kyle who had to make a significant sacrifice by switching high schools between his freshman and sophomore years. To my wife, who encouraged me to pursue my goals, and willingly left the comforts of our home to join me in Blacksburg, I will forever be grateful.

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CHAPTER I
INTRODUCTION

Rationale for Research.

Since the introduction of graphical user interfaces (GUI), input control devices have become an integral part of desktop computing. When interfacing with GUI s, these devices, along with their techniques, have become the human operators baton (MacKenzie, 1995). Input control devices are necessary to manipulate information presented on the visual display. These devices are diverse and are constantly changing to meet the needs and advancements in computing technology. The recent growth and popularity of wearable computers has broadened the interest in the design and evaluation of pointing devices (Barfield and Baird, 1998).

Although there have been a number of experiments conducted with wearable computers, there is little research on pointing devices for this technology. Pointing devices are a major component of a wearable computer system, allowing the wearer to select and manipulate objects on the screen. The design of these pointing devices will have a major impact on the ease with which the operator can interact with information being displayed (Card, English, and Burr, 1978).

There are currently a variety of commercially available pointing devices, and with the advancing development of wearable computers, there will likely be a growing number of new devices introduced into the marketplace. Determining which device characteristics best support wearable computer users will likely be difficult without a set of recommended design guidelines, which is one of the goals of this thesis. These guidelines can only be established after considering the interaction of a number of factors including the type of device and its operations, the limb used to control the device, the task to be performed, and the skill level of the operator (Douglas and Mithal, 1997).

There has been significant research performed on pointing devices for desktop machines (Card et al. (1978), Epps (1986), MacKenzie, Sellen, and Buxton (1991), Douglas and Mithal, (1997), Ichikawa, Homma, and Umemura (1999)). Most of these studies, however, focused on the evaluating the performance of specific devices. Card et al. (1978), for instance, compared four input devices on a text selection task. Epps (1986) compared six commonly used cursor devices to determine which were best on target acquisition, text editing and graphical tasks. Finally, MacKenzie et al (1991) compared three devices in the performance of pointing and dragging target acquisition tasks. Unfortunately, none of these studies attempted to explain whether the characteristics of the pointing devices contributed to the performance differences or whether the limb used to manipulate the cursor affected performance.

Other studies did investigate pointing device performance with the limb used for controlling the cursor. Zhai, Milgram, and Buxton (1996) found that using the finger to control a pointing device resulted in improved pointing performance over limbs. Hammerton and Tickner (1966) found the wrist to be more effective for pointing tasks than the forearm. However, Balakrishman and MacKenzie (1997) found no significant difference in performance time between the wrist and forearm.

There appears to be no information on performance differences between the digits of the hand (index finger and thumb) for point and selection type tasks while using a pointing device. This is surprising because wearable computer users do not have the benefit of smooth surface space to support a pointing device. The user must therefore hold the device in their hand and simultaneously operate it with one or more of their digits. An alternative would be to develop miniature devices that can comfortably fit on the surface of the soldier s weapon.

Determining if there are differences between the index finger and thumb could be extremely important in the design of novel pointing devices developed for wearable computer users because the lack of surface space will likely lead to hand-held pointing device that are manipulated with these two digits. This information could assist designers with identify implications for computer pointing devices. Filling this gap in the existing knowledge of pointing devices for wearable computers is the intent of this research to analyze soldier performance resulting from the design of selected input control devices where the index finger and thumb are used to control them. Pointing device characteristics, analysis of the user performance, and the subjective data will be used to develop pointing device guidelines that best support the operator. Performance measurements will include movement time, homing time, accuracy and errors. Operational definitions of these measurements are provided in chapter 6.

Research Goals and Objectives.

The broad goal of this research is to enhance wearable computer performance by ensuring the system components (display and pointing device) are compatible with the wearers operations. To achieve this goal, the following questions are addressed. First, are there differences in speed and accuracy between the index finger and thumb when manipulating pointing devices? Pointing devices for wearable computers will likely to be miniaturized and require the wearers to hold the device in their hand while manipulating the controls with a digit of their hand. As a result, it is important to determine if there are speed and accuracy advantages of using one hand digit over another. The second question is whether display-control gain effect pointing performance among pointing devices. To ensure that the pointing devices are tested at their optimum level, the best D-C gain must be determined for each pointing device and display combination. The third question this thesis set out to answer is do specific design characteristics of wearable computer pointing devices enhance performance? Again, the answer to this question can help identify which operational characteristic provides the best performance. Finally, this thesis set out to answer whether pointing devices chosen for this research follow Fitts Law. If these devices do follow Fitts Law, designers, researchers and engineers will be able to compare pointing performance of novel devices against other pointing devices that follow this law. Furthermore, designers will be provided with a prediction tool to assist in estimating trade-off between target size, target distance and pointing time. Most wearable computers include visual displays that are either head or body mounted. Consequently, these visual displays have a limited viewing area to display information. It is important to ensure that the limited viewing space is used efficiently

Besides the above primary goals, there are three secondary goals. The first of these secondary goals include developing a methodology for assessing input control devices so that the results from this experiment can be compared with the results of future experiments that use the identical procedures. The second goal is to determine whether Fitts Law can be applied in comparing the pointing performance of current and novel devices for users. This is important for the future evaluation of input devices. As wearable technology progresses, so will interfaces to this technology. Therefore, it is essential to develop a methodology in which novel devices can be evaluated and compared with data that has been previously collected.

The third goal is to determine if there are significant differences in performance and preference between the two displays. The only display being developed for the LW system is an opaque HMD. However, some of the issues related to the HMD s field-of-view, described in later in this thesis, may preclude that the HMD as an appropriate visual display solution. It is thus important to evaluate pointing devices with an alternative display to verify that the soldiers pointing performance does not degrade. For this research, the Xybernaut flat-panel display (FPD) has been selected as the alternative display (see figure 3.2.).

Project Phases.

The first phase of this research was to identify general tasks that the users will be expected to perform with the wearable computer technology. This is an important consideration because one of the critical factors that have led to inconsistent evaluation of pointing devices is the task to be performed with the device (Baber, 1997).

The second phase of this research will be to conduct a trade study analysis to identify the availability of commercial-off-the-shelf pointing devices that can be used with wearable computers. There are a variety of pointing devices available for desktop computing systems, yet, many of these devices are not usable with wearable computers. The reasons for this are twofold. Many of these devices have been designed for desktop use and require significant surface space in order to use them. With wearable computer users, this surface space is not available, and these devices will not be considered. Second, many devices require that the interface be operated in an upright position. For instance, a mouse cannot be used effectively on its opposing side. This restriction limits its usability for field operations and therefore excludes these devices for this investigation. The trade study identified several commercially available pointing devices that can potentially be used with wearable computers.

The third phase of this thesis was to conduct an experiment to determine if varying the display-control (D-C) gain will effect pointing performance for each input device. Previous studies have tested the effects of D-C gain, but the findings are inconsistent. Epps (1986) reported that different D-C gains for various devices did effect pointing performance of the devices. Buck (1980), on the other hand, reported that changing the D-C gain did not have an effect on pointing performance for different devices. Due to these inconsistencies, an independent experiment was conducted to determine if there is an optimum D-C gain setting for the various devices. If the results show a difference among D-C gain levels, the level that produces the best performance will be used for the follow-on experiment.

The fourth phase of this thesis was to identify appropriate experimental tasks to assess the effectiveness of the pointing devices. These experimental tasks must be susceptible to the pointing devices and visual displays. Applicable tasks must also require the soldiers to rapidly detect targets using the visual displays as well as manipulate and select objects while using the pointing device.

The final phase was to identify whether finger use (index finger vs. thumb) has an effect on speed and accuracy while using the various pointing devices. In addition, the characteristics of the pointing devices were assessed based on their physical operation, speed and accuracy, and fatigue and comfort.

The two devices that provided the best speed and accuracy as well as the highest soldier preference will be used in a follow-on study to investigate the local and global situation awareness of users while using wearable computers. User performance with each device will also be analyzed across the type of display to determine if there is significant difference in performance.

CHAPTER II.
REVIEW OF THE LITERATURE

Wearable Computing.

Wearable computers have been in existence for several decades. The first wearable computer was invented in 1966 by Ed Thorp and Claude Shannon, and was used to predict roulette wheels (Rhodes, 1999). Since that time wearable computing technology has undergone significant progress. A wearable computer differs from a portable computer in that the computer can be worn on the body or placed in clothing, thereby encompassing the personal space of the user. By definition, wearable computers are used in environments that differ dramatically from the normal domains of computer use. They can be exposed to outside environmental conditions, connected to Gobal Positioning System for location awareness, and connected to wireless local area networks for transmission of digital data (Ockerman, Najjar, and Thompson, 1997). At a recent conference, Mann, 1998 presented what he believed to be a significant difference between wearable computers and other portable computing devices. This difference is that wearable computers are constantly powered and accessible at all time. In other words, the wearable computer is always ready , which leads to a new form of interaction between the human and computer.

Wearable computers typically include four standards components. These components include: a miniature computer system containing a central processing unit, motherboard, disk drive, and memory that stores, retrieves, and processes digital information; a visual display system to view the information; an input control system that can be used to manipulate the information; and a wireless communications system (Barfield, Baird, and Cho, 1998). Wearable computing technology has been used in numerous real world applications. For instance, the U.S. Air Force uses wearable computers to assist in Boeing aircraft inspections (Siewiorek and Smailagic, 1997). They have also been used as a factory training tool (Ockerman, Najjar, and Thompson, 1996), and by the medical community for telemedicine applications. Barfield and

Baird (1998) have identified other application areas for wearable computers, including medicine, manufacturing, architecture, face recognition, and intelligent assistants.

A more recent application for wearable computers is for the combat soldier. Designing wearable computers to be used by soldiers in combat situations provide additional challenges. These new challenges include designing for extra durability and designing in a way that soldiers are not overly distracted from their local environment, which may be extremely hostile.

The military has already invested heavily in wearable computer technology, and one of the expected payoffs for this investment is the increase likelihood of soldiers surviving an engagement with the enemy. In order to obtain these payoffs, wearable technology for soldiers must be designed to improve their individual and team effectiveness under stressful and hostile conditions. Furthermore, soldiers will be subject to stresses originating in the environment that may not be experienced by other users of this technology. High ambient noise level will have an impact on the performance of speech recognition and also on the person speaking to the computer (Baber and Noyes, 1996). Variation in illumination and glare could dramatically affect the ease with which head-mounted displays can be read, or inclement meteorological conditions, such as rain, snow or extreme of temperatures will affect both the human and equipment performance (Baber, 1997). While it is clear that environmental factors will play a major role in determining the usability of wearable computers in a combat environment, there has been relatively little work done on how environmental factors interact with computer use. Finally, the soldier using the wearable computer will be subject to stresses arising from the performance of physical work.

Wearable computers are expected in enhance a soldier s combat effectiveness by providing efficient means of distributing command and control information. One such development of this capability is the LW system.

The Infantry s Land Warrior System .

The Army s Land Warrior (LW) is the first integrated fighting system that is being developed for the infantry soldier. In 1991, the Army Science Board Study recommended that the soldier be treated as a complete system. As a result, the Army initiated the Soldier Integrated Protective Ensemble Program. The goal of this program was to integrate the soldier with technology to allow the soldier to become more lethal, while enhancing his chance of survival on the battlefield. The LW project became the first phase in the follow-on soldier modernization effort. Technologies that were proved successful and ready in the SIPE demonstration have been transitioned to the LW System (Gilmore, 1997).

The LW project began development in 1996 and was initially scheduled to be fielded to infantry soldiers in the year 2000. It is expected to significantly improve the lethality, mobility, survivability, command and control, and sustainability of infantry solders by integrating a variety of components and technologies. (USGAO, 1999). One subsystem of the LW is a wearable computer, which will provide substantial tactical information to the soldier about the battlefield.

Marine Corps, Special Forces, Air Force and many foreign countries are interested in the LW system. Land Warrior is currently being advertised as the Army's soldier system for the 21st century. The unique, modular load carrying design enhances the soldier's fighting capability by providing individual mission tailoring. The soldier can select which components of the LW system will be used for a specific mission. This will allow the soldier the flexibility to remove any part of the system that he does not feel will add to his mission requirements.

In addition, the LW system features an open, modular architecture that leverages commercial-off-the-shelf, non-developmental items. This design approach results in a cost-effective, low risk system that can easily accept emerging technologies to maintain the soldier's fighting edge.

Ten prototype Land Warrior systems underwent operational testing during a contractor-conducted experiment at Fort Benning in October-December 1996. The 15 soldiers who used Land Warrior during the experiment said the system enhanced situational awareness, was user-friendly and easy to learn, reduced soldier workload, and improved soldier-to-soldier communications, according to an after-action briefing. The soldiers, however, recommended that the system be made lighter, have a more powerful battery, have better controls, and be made more rugged (Garamone, 1998).

In the USGAO (1999) report, numerous unresolved technical and human factor problems have been identified. These problems include overweight equipment, inadequate battery power, inadequate load-carrying design and equipment comfort. One specific example given was during field tests; soldiers had problems raising their heads to fire their weapons because the backpack would ride up and press against their helmet. This issue, as well as many others, must be resolved before wearable technology can be fielded to the soldiers.

For the dismounted soldier, the need for compatible and reliable wearable computing technology is immediate. Likewise, SOF soldiers also have an immediate need for this technology, but research must first address the concerns for better displays and control devices.

Input Control Devices.

Although there are many different designs for pointing devices, there are only two distinct types of these devices, and they are direct and indirect. Direct input control devices are those devices that do not employ a secondary device for pointing and object selection. An example of a direct input control device is a touchscreen. The operator does not have to make object selections by depressing a key on a secondary device such as a mouse or joystick. He or she can simply touch the icon on the display, and the touched object is selected. An example of this is a kiosk system. Similarly, an operator of a direct input control device can simply press a position on the screen, and that position becomes the active position of the cursor.

An indirect input control device, uses the hand as an effector, which employs a secondary device to position the cursor and to select objects on the screen. Some of these devices include a mouse, joystick, trackball and cursor keys (Baber, 1997). The operator interacts with these devices by applying some form of movement or force control to position the cursor. This is usually followed by a selection action, which is typically performed be depressing an additional device (e.g. mouse button, keyboard key, etc.). Only indirect input control devices can be used with HMDs, and both indirect and direct devices can be used with WMDs. For this research, only indirect input control devices will be considered. The reason for this restriction is HMDs must be a part of this evaluation.

All computer input control devices can also be classified as either zero-order or first-order control devices. Zero-order control devices are those devices that map a given displacement area to a second or remote displacement area. For example, a mouse position on a mouse pad (displacement 1) is mapped to a cursor position on the screen (displacement 2). Mouse devices, touch pads, and lightpens are all examples of zero-order control devices. First-order control devices, on the other hand, maps applied force to cursor velocity and positioning. An example of a first-order control devices is an isometric joystick, which can be found on many new portable computers. Miniature isometric joysticks are commonly positioned between the G, H, and B keys on a portable keyboard. Small forces applied to the isometric joystick results in less cursor speed. As the force is increased, so is the cursor speed (Douglas and Mithal, 1997). For this research, both zero-order and first-order devices will be considered.

Mouse devices, trackballs, and touch pads are all commonly available input control devices. There have been numerous experiments conducted that compared various input control devices (Card et al., 1978); (Thomas, Tyerman, and Grimmer, 1998); (Greenstein and Arnaut, 1987). The results of these experiments are inconsistent as to which input control device provides the best performance for a given task. The likely reasons for this inconsistency are threefold. First, the experimental tasks are usually different from experiment to experiment. One task may measure performance while participants drag and select objects while another experiment measures text input and pointing speed (Baber, 1997).

Second, the environments in which the tasks are performed vary. Much of the research on input control devices has been with desktop computers. With the insurgence of the portable computers, environmental factors must be considered. Unlike the desktop environment, a portable computer may be operated in environments with limited surface space (e.g. on an airplane, in an automobile, or with soldiers, in the field). As a result, there may be limited use for displacement devices like the mouse.

Third, the input control devices tested vary greatly in their design and operations. Some devices require the use of the operators hands and wrists while others require the use of the operators fingers. Psychomotor research on Fitts law has noted differences in human performance based on the limb used for pointing (Langolf, Chaffin, and Foulke, 1976). Langolf (1973) found that certain human muscles have bandwidth limitations. These bandwidth limitations are an upper bound for input control devices. For instance, Langolf reported that the human arm s bandwidth is 9.5 bits/s, the bandwidth for a human wrist is 23 bits/s, and the finger is 38 bits/s. This difference in limb bandwidth would have a direct impact on the performance of the device. With this knowledge, Milner (1988) provided general guidelines for selecting input control devices. He wrote, For fixed choice, low-resolution applications direct input devices are faster and usually the most preferred cursor control device. For quick and accurate selection and manipulation of high-resolution objects, indirect manipulations are better than direct manipulation devices. For quick and accurate selection of high-resolution objects there is inconsistencies in the results to suggest a better indirect device. Cursor keys and function keys perform badly against other devices.

These guidelines, however, had been developed with the general office-computing environment in mind, and are not reliable for input control devices for wearable computers. For instance, soldiers with wearable computers are likely to be carrying a weapon while performing their special mission. Therefore, the input devices used with their wearable computer must be designed with this in mind. Appropriate input devices must allow a soldier to manipulate and interact with objects efficiently while they carry their weapon. Furthermore, the input must not impose a burden that distracts the soldier from the primary task(s). For instance, if a soldier must fumble with a trackball or mouse while navigating through thick terrain, the input design is inadequate. Common factors that must be considered in the design of input devices for soldiers are that they must be unobtrusive, accurate and easy to use in the field (Barfield and Baird, 1998).

In order to determine input control device characteristics that best support the wearable computer user, the interaction of a number of factors must be considered. These factors include the type of device and its operations, the appendage used to control the device, the task to be performed, and the skill level of the soldiers (Douglas and Mithal, 1997).

Advanced Input Control Devices.

Two advanced input control devices that have been recently employed are speech recognition and eye-tracking technology. Speech is one of the most natural ways humans can interact with computers. The state-of —the-art in speech has reach a point where many designers are now considering speech as an alternative to manual input control devices (Yankelovick and Lai, 1998). Using speech as a soldier interface to wearable computers has two advantages. First, speech interfaces do not require the use of the soldiers hands or fingers to interact with the system. This makes speech interfaces extremely attractive because SOF soldiers hands are already occupied with their weapon. Second, speech interfaces do not require extensive use of the operator s visual system to point to and select items on the display. This is extremely beneficial, because the more soldiers focus their attention on the display, the less likely they will be aware of the local and global environment (USDA, 1993).

Unfortunately, there are still many challenges that speech input must overcome before it can be considered as a viable input for wearable computer users. Current speech recognition systems have limited capacity to handle large vocabularies, different voices and continuous speech. As an input source, speech is prone to errors and it is not always easy to correct these errors (Yankelovick and Lai, 1998). Furthermore, background noise interferes with the performance of speech recognition systems (Durlach and Mavor, 1995), and it is likely that wearable computer users will be in environments with high levels of background noise, which is likely to make speech input ineffective. These deficiencies make speech recognition systems inefficient for users of wearable computers.

Eye tracking technology, like speech, is a natural way for users to point and select objects on a display. Eye tracking is an interaction technique where the natural eye movement is tracked and mapped to the visual display (Jacob, 1995b). Users can move their eyes naturally to scan objects on the screen in the same way they scan objects in the real world. Four immediate concerns arise when considering eye-tracking interfaces for wearable computer users. First, eye-tracking equipment is typically bulky and intrusive, which is likely to adversely affect the performance of these users. For instance, many accurate eye-tracking equipment require physical devices to be placed in front of the operator s eyes. This physical placement would interfere with the field-of-view of the operator by obstructing their view of objects in the real world. This obstruction alone would make eye tracking unsuitable. Second, the best eye-tracking equipment is prone to failures. If this equipment frequently fails while a user is attempting to interact with the system, he or she is likely to demand the more common manual input device. Third, people are not accustomed to operating devices by moving their eyes. Although it may seem effortless to train an operator to use eye tracking equipment, the problem of eye tracking goes beyond the simple task of positioning a cursor. The system using the eye tracking equipment must be able to properly interpret the operators eye movements. How will the system interpret an unintentional blink or gaze or prolong stare of the operator? Strategies for handling these natural occurrences have not been defined. Fourth, standard techniques, which would allow for reasonably fast selection of objects or entering text with eye tracking technology has not been established (Jacob, 1995a).

Designing for Hand Digits.

As written earlier, there appears to be little research on performance differences between the digits of the hand (index finger and thumb) for point and selection type tasks while using a pointing device. However, there are numerous studies conducted that report on the force and speed of the various digits of the hand, which can assist in the design of digit-controlled devices. Kroemer, Kroemer, and Kroemer-Elbert (1994) reported that the thumb (83.8 newtons) is significantly stronger than the index finger (60.4 newtons), and this is consistent with the report by Nieble and Freivalds (1999). Nieble and Freivalds (1999) reported that the maximum force of the thumb is 16lbs, and the maximum force of the index finger is 13lbs. Nieble and Freivalds (1999) also reported that the index finger is capable of moving the fastest of the digits. The information reported by Nieble et al, and Kroemer et al suggests that the characteristics of the device as well as the digit used to control the device contribute to cursor movement performance. For instance, a device that includes moving parts (i.e. trackball) may be fastest when controlled by the index finger. Likewise, a device that incorporates force (i.e. isometric joystick) as a means for moving the cursor may be fastest when operated with the thumb. However, this speculation was not supported in a study by Mehr (1973).

Mehr (1973) conducted a study that compared the pointing speed with two different types of joysticks. The joysticks were finger and thumb-operated controls that included both spring-loaded and isometric designs. The findings show the mean pointing time was significantly fastest with the finger-controlled isometric joystick. The second fastest time was with the isometric joystick, which was controlled by the thumb. The results further show that the displacement joystick was faster when controlled by the finger than the thumb. However, the isometric joystick was faster when controlled by the thumb than the displacement joystick when finger-operated. Although Mehr s findings suggest that both the hand digit and control design characteristics contribute to the overall performance, it does not suggest that devices where force is applied is best when controlled by the thumb.

Visual Displays.

One of the key issues involved in developing interfaces for users of wearable computers is whether the interfaces can be effectively used while they perform their primary mission. One of the interfaces in question is the visual display. The optimum visual display must not interfere with the visual senses needed for the users primary visual task. Specifically, a soldier s primary visual task may involve reconnaissance and surveillance actions to obtain or verify information concerning the capabilities, position, intentions, and activities of an actual or potential enemy. This action may involve the search, detection, identification and reporting of enemy locations and hazardous areas. It may also involve locating and attacking targets of opportunity. The visual display being developed for the LW system is a head-mounted display (HMD) with a monocular eyepiece. The HMD is the primary display system used with wearable computers (Barfield and Baird, 1998). This display occludes peripheral vision and may inhibit the SOF soldier s performance during their special missions.

In the NRC (1995) report on tactical displays for infantry soldiers several key issues and findings were reported. The authors wrote a device that assists a solider under one task in one environment may detract from the soldier s performance on a different task or in a different environment. To yield valid predictions about the effectiveness of HMDs, the devices must be tested under realistic field conditions as well as in the laboratory.

The report identified several issues related to opaque monocular displays. These issues include temporary blindness in the unrestricted eye, loss of stereoscopic depth perception, restriction of field of view, and attentional narrowing (i.e. paying exclusive attention to one source of information at the expense of other channels of information). These are all issues that are of concern to SOF soldiers.

Because of these potential consequences, an alternative display, a WMD, will also be included in this experiment. This alternative display will help determine if a body-worn-display can be as effective as a HMD for pointing and homing tasks.

Fitts Law as a Predictive Model for Input Control Devices.

Fitts (1954) and Fitts and Peterson (1964) conducted experiments that led to the discovery that movement time is a logarithmic function of distance to a target and target size. Fitts

formulated his discoveries into what is known as Fitts Law. Fitts law is a relation derived from information theory, which models human movement (Soukoreff and Mackenzie, 1996).
The Fitts Law equation follows:

$$MT = a + b \log_2\left(\frac{2A}{W}\right) \quad (1)$$

$$ID = \log_2(2A/W)$$

Where: MT = Movement time.

a & b = Empirically derived constants (Y intercept and slope).

A = Distance of movement from the start position to target (amplitude).

W = Width of target.

Note that the distance-width ratio is multiplied by 2 to avoid negative logarithms when the target width is greater than the distance of movement. Also note that log is base 2, which is related to the information theory unit of measurement (e.g. bits) contained in the movement ($H = \log_2 N$). In addition, $\log_2(2A/W)$ is also used to define the index of difficulty (ID) for specific movements. Thus, as distance to a target increases and/or as the width of the target decreases the index of difficulty will increase. A derived version of the Fitts Law ID was proposed by MacKenzie (1989). He proposed the following equation:

$$MT = a + b \log_2\left(\frac{A}{W}+1\right) \quad (2)$$

$$ID = \log2\ (A/W+1)$$

MacKenzie provided three reasons why he believes his formula is an improvement over all other variations for input control devices. These three reasons are as follows: First, he states that his formula always yields a positive ID. Second, this equation, according to MacKenzie, provides a slightly better fit with empirical data than the other formulations, and third, it exactly reflects the

Shannon-Hartley information theory (equation 3), which Fitts' Law is based. Variations of Fitts Law has been used to successfully test pointing devices, and for this thesis the MacKenzie formula will be used.

$$C = B\log_2\left(\frac{S}{N}+1\right) \quad (3)$$

Where: C = Information channel capacity

B = Available bandwidth

S = Signal power

N = Noise power

Fitts also describes an index of performance (IP), which is used to describe the channel capacity from Shannon s theorem. The IP can be calculated by using formula 4. The results of this calculation can be used to compare to pointing performance of different pointing devices.

$$IP=\left(\frac{ID}{MT}\right) \quad (4)$$

Where: ID = Index of difficulty described in equation 2.

MT=Movement time.

Several experiments have demonstrated the generality of Fitts Law. For example, Fitts and Peterson (1964) found that the law applies to single, discrete movements, or reciprocal tapping between targets. Langolf et al. (1976) have also verified Fitts Law for peg insertion tasks performed under a microscope. However, one of the difficulties of using Fitts Law for interaction devices is defining a common IP value for specific devices. Different studies have reported different IP values for identical devices (see table 2.0), which makes it difficult if not impossible to use these results across experiments. As seen in the table below, three studies note three different pointing speeds for the same device. Card et al. (1978) recorded mouse pointing time as 1290ms. MacKenzie et al. (1991) reported mouse pointing time at 674ms, and Douglas and Mithal (1997) reported mouse pointing time at 1123ms. Although the IP values for the mouse were calculated using the same formula, the differences in pointing speed had an effect on the IP values, and the resultant IPs were significantly different. The cross-experiment differences may be due to the experimental tasks, the D-C setting for each device, or the tested devices may have been acquired from different manufacturers. For whatever reason, it would not be reliable to use the IP results across experiments. Furthermore, most of these experiments were performed with conventional desktop input devices. As written earlier, many of these devices would not be feasible for wearable computing use.

Table 2.0

Comparison of different control devices.

Study	Devices	Pointing		Dragging		Homing to Keyboard	Homing to Pointing Device
		Time (ms)	Error Rate	Time (ms)	Error Rate	Time (ms)	Time (ms)
Card et al. (1978)	Mouse	1290	5%				360
	Joystick	1570	11%				260
	Text Keys	1950	9%				320
	Step Keys	2310	13%				210
MacKenzie et al. (1991)	Tablet	665	4.0%	802	13.6%		
	Mouse	674	3.5%	916	10.8		
	Trackball	1101	3.9%	1284	17.3		
Rutledge and Selker (1990)	Mouse	760					
	Pointing Stick	1180					
Douglas and Mithal (1997)	Mouse	1123	6.9%	966	3.7%	667	
	Key joystick	1779	10.3%	1407	6.2%	438	

Table from Douglas & Mithal (1997) p. 79

Even if there were no inconsistencies in the above experiments, the results could not be generalized to wearable computer pointing devices for several reasons. The first reason is that these studies were conducted using desktop systems where adequate surface space was available to test devices such as a mouse. Wearable computers, on the other hand, are likely to be operated in environments where surface space is limited or non-existent. Therefore, the results from these tests would not accurately predict performance for devices designed to be used with wearable computers. Second, the input control devices selected for these experiments are standard size devices that are commonly used with desktop systems (i.e. mouse, trackball, joystick etc). For wearable computer systems, the size and weight of these devices must be reduced to limit their effect on soldiers. There will likely be no surface space to support these devices, which will require the wearable computer operator to hold and operate them using their hands. Because of these operational constraints, most standard desktop devices are not feasible for usage in field environments. Third, each of the experiments list above used different display resolutions. Card et al (1978) used a 14 monitor with a resolution of 420x640. Douglas et al (1997) used a 16 monitor with a resolution of 800x600. Rutledge and Seller (1990) used a 15 monitor with a resolution of 640x480, and MacKenzie et al (1991) did not describe the display used in their experiment. Curry, Hobbs, and Toub (1996) found that there is no statistically significant difference in pointing performance between subjects equipped with a head-mounted display and those using a desktop display. Barfield, Rosenberg, and Lotens (1995), on the other hand, reported that display resolution does have an impact on visual acuity and will thus impact performance. Barfield et al (1995) writes that a display resolution of 720x480 pixels in a 60^{o} field of view is equivalent to 20/200 visual acuity. As a result, it is expected that there would be differences between the results from studies using desktop machines with higher resolution and results from studies using a HMD with a lower resolution of 640x480.

For this research, the IP value will be calculated and compared to the final data analysis. If there is a strong correlation between the IP value and the analysis, the pointing devices will be rank ordered based on the IP value. The higher the value of the IP, the greater the soldier s performance using that input control device.

Literature Review Conclusion.

As shown in the literature review, the use of wearable computers have advanced significantly over the past few years. Industries, universities, and government organizations alike have contributed significantly to the development of this technology. Government leaders have recognized that wearable computer technology can significantly benefit infantry soldiers by providing them with the latest available C4I capabilities. One of the biggest challenges, however, is to develop this technology so that soldiers can effectively use wearable computers in combat environments.

Providing soldiers will an effective input control device is a step towards overcoming the challenges facing the acceptance of wearable computer technology by soldiers. An input control device is the main tool soldiers will use to interact with the computer and the displayed information. Therefore it is essential that the design of the device meet all the usability requirements of soldiers.

Simply comparing input control devices and making a selection, however, will have little benefit for the development of novel devices. As written, wearable computers and components have may significant advancements. It is not unreasonable to believe that these advancements will continue into the future. It would not be cost effective or feasible to test each innovative device against all others. For this reason it is important to develop a model that can be used to predict the performance of novel devices.

Past research has shown that Fitts law has been used successfully for input control devices used with desktop computers. However, no literature was found for applying Fitts law to miniaturized input control devices. This research will test whether pointing devices for wearable computer follow Fitts law. If this proves successful, the methodology used in this experiment can by used as a standardize procedure to effectively test and predict the performance of future devices.

CHAPTER III.

METHODOLOGY STUDY 1

Display-Control (D-C) Experiment.

Experimental Goals.

The first goal of this initial experiment was to determine the optimal D-C gain for each of the COTS input devices. The D-C gain controls the velocity of the display cursor. This was necessary to ensure that each of the devices were set at their optimal D-C level for the target acquisition tasks and to assure that an unbiased analysis of the pointing device could be performed. The second goal of this experiment was to estimate the number of multi-directional blocks required in order for the participants to become well practiced with the different devices. This estimate was then used as a training criterion for the main experiment described later.

Methodology.

Participants.

Ten students, seven males and three females, from the Virginia Polytechnic Institute and State University were recruited for this experiment. The participants were unpaid volunteers recruited through personal contacts and announcements and were taken from the graduate population of the Industrial and Systems Engineering Department. All participants were between the age of 25 and 53 years old, and were required to meet visual acuity requirements of 20/40 corrected or uncorrected vision and had their visual acuity verified using a Bausch & Lomb Vision Tester prior to the experiment. In addition, all participants who consented to participating in this experiment were required to sign a Volunteer Agreement Affidavit (Appendix B). Each of the participants reported being well experienced with using a computer, and only one participant was left-handed.

Experimental Equipment.

The equipment consisted of the Xybernaut wearable computer (figure 3.0) with two visual displays and five input devices. The Xybernaut wearable computer used for this experiment was model MA IV¤ which included a Intel Pentium MMX 233 MHz processor with 64MB of memory. The MicroSoft Windows95 operating system was installed.

Figure 3.0 Xybernaut CPU
(Photo from Xybernaut, http://www.xybernaut.com.)

A trade study was performed to identify available COTS input control devices that could be used with wearable computers. The findings of this trade study are shown in Appendix A. Five of these devices were chosen for this experiment. The rational for choosing these five devices was that each requires a unique method for controlling the cursor with either the index finger or thumb, and collectively these devices adequately represented the characteristics of many pointing devices available for wearable computers. All the selected devices were compatible with the standard MicroSoft Windows mouse driver that was used as the default driver. A description of each of the five selected devices along with their unique design and operational features follows.

DuraPoint® Device. The DuraPoint® is a isometric device (i.e. does not move) developed by Interlink Electronics, Inc. The device includes a pressure-sensing mouse button that is operated with the index finger. The device senses the magnitude and direction of the force applied to it, and moves the cursor with a velocity proportional to the force, and in the direction that the force is applied. Participants were instructed to operate the DuraPoint device with their index finger.

Thumbelina® Thumbwheel. The Thumbelina is a mini trackball that is designed to be used as a hand-held device. A miniature trackball is positioned in the center of the device which measures 0.9 H x 1.7 W x 1.7 L. The device senses the rotation of the thumb- controlled trackball and moves the cursor with a velocity proportional to the rotation and direction of the trackball. Participants were instructed to operate the mini trackball with their thumb.

Mouse-Trak® Trackball. The trackball was developed by ITAC Systems, Inc and consists of a 2 diameter freely rotating ball. The ball rests on three wheels that rotate as the ball rotates. The wheels are positioned at 90◦ from each other so that cursor can be positioned at any X-Y coordinates on the display. Similar to the thumbwheel, the cursor moves with a velocity proportional to the rotation and direction of the trackball. Although the trackball is the large pointing device, it remains in a fixed position and the participants found it easy to rotate with only their index finger.

VersaPad™. The VersaPad™ is a touchpad developed by Interlink Electronics and has the dimensions of 4.0 x 5.5 x 0.7 . To move the cursor, the participant were instructed to place the tip of their index finger on the main pad area, and while retaining contact with the pad, move their finger in the same direction they wished to move the cursor. The participants were also instructed to use the touchpad button, rather than double tapping the touchpad, to end a trail. Although the sensitivity for horizontal and vertical movements can be set at different levels, they were set at the identical level for this experiment.

Palm Mouse™. The Fujitsu Palm Mouse™ is a hand-held device that is controlled by the thumb. Like the Dura Point, the Palm Mouse senses the magnitude and direction of the forced applied to it, and moves the cursor with a velocity proportional to the force, and in the direction that the force is applied. Participants were instructed to use the Palm Mouse with their thumb.

One of the most common input control devices, the mouse, was not chosen because of its requirement for surface space. This is unfortunate because the mouse device is one of the most studied pointing device and is known for its ease of use, fast pointing speed and low error-rate (Douglas and Mithal, 1997).

Two visual displays will also chosen for this experiment. The displays include a monocular HMD and the Xybernaut s forearm mounted flat-panel display. The HMD (figure 3.1) consists of an occluding, monocular display developed by Xybernaut.

Figure 3.1 Xybernaut HMD
(Photo from Xybernaut, http://www.xybernaut.com.)

The HMD has a monochrome active matrix liquid crystal display (AMLCD) with 640H X 480V resolution. Focus and brightness-controls are integrated into the headset. The display slides left or right along the top of the unit to accommodate the desired viewing eye. The monocle assembly rotates on its arm and can be manipulated vertically to provide adjustment for eye relief (fore-aft) and display stowage. In this investigation, the display was positioned over the eye that is not used to aim the M16 rifle. The weight of the HMD is approximately 0.45 kilograms (1.0 pound).

The second display is a wrist-worn flat panel display (FPD) by Xybernaut. The FPD is a 640H X 480V resolution with a 6" (152 mm) viewable diagonal display. The weight of the FPD is 520g, and is depicted in figure 3.2.

Figure 3.2. Xybernaut s Flat Panel Display
(Photo from Xybernaut, http://www.xybernaut.com)

Experimental Design.

Independent Variables.

This experiment is a four-factor, mixed design. The between-subject factor was the type of visual display, and the three within-subject factors included the three levels of D-C gain, trial blocks and the five input devices. The linear statistical model for the experiment is as follows:

$$Y_{ijklmn} = \mu + B_i + D_j + G_k + I_l + S_{m(j)} + BD_{ij} + BG_{ik} + BI_{il} + BS_{im(j)} + DG_{jk} + DI_{jl} + IS_{lm(j)}$$
$$+ GS_{km(j)} + BDG_{ijk} + BDI_{ijl} + BGI_{ikl} + BIS_{ilm(j)} + DGI_{jkl} + DGS_{jkm(j)} + GIS_{klm(j)} + BDGI_{ijkl}$$
$$+ BGIS_{iklm(j)} + \varepsilon_{n(ijklm)}$$

Where,

Y_{ijklmn} = Dependent variable (home time, pointing time and error) measured under the i^{th} type of visual display and j^{th} input device, t^{th} trial and response for the l^{th} subject.

B = i^{th} trial blocks (k=1, 2, 3) Block

D = j^{th} level of visual display (i=1, 2).

G = k^{th} D-C gain (k=LO (1), MED (2) , HI (2))

I = l^{th} level of input device (j=1, 2, ,5).

S = m^{th} subject (j=1, ,10).

ε = n^{th} response for the m^{th} subject, i^{th} trial block, j^{th} visual display, k^{th} gain and l^{th} input device.

Dependent Variables.

The two dependent variables for this experiment were the pointing time (PT) and the accuracy (AC) for target selection. The accuracy was based on the absolute difference between the center of the target position and the position of the cursor when the target was selected.

Experimental Procedures.

Participants were initially screened using the Bausch & Lomb™ model 14019 machine to verify that they have at least 20/40 vision corrected. Upon successful completion of the vision test, participants were permitted to participate in the experiment.

Participants were seated at a table and provided an adjustable chair. Before the subjects began the first test, they were provided written instructions about the experiment. After reading the instructions, any questions the subjects had were answered.

Each participant received training on the target acquisition software and they were allowed to practice until they felt comfortable with the software. This practice was done to help minimize the effects of learning for the tasks. The participants were given a detailed explanation on the operations of the input devices and how they are used to move the display cursor. Once all their questions have been answered, the participants proceeded with the main portion of the experiment.

The participants were asked to perform six blocks of pointing-type tasks, which included 36 fully crossed combinations of target width, distance and angle of approach. The participants were also instructed to perform the task as quickly as possible while maintaining accuracy.

One of the main experimental concerns of the study was to control for the effects of learning by the participants. For this experiment, learning is described as a significant improvement in performance time between the blocks of 36 trails. Performance time was measured as the time it took the subject to move the cursor from the home target to the objective target and depress the device key. Since each subject performed the same tasks using all pointing devices, it was necessary to design the experiment to minimize the learning effect. The two steps that were taken to control the effects of learning were to allow all participants to practice the tasks and to randomize the order of the pointing devices.

The first control measure was accomplished by allowing the participants to practice three blocks of multiple combinations of target width, distance and angle trails for each pointing device before beginning the test. The three practice blocks were chosen based on previous research by Douglas and Mithal, (1997) that showed no significant improvement in pointing time after the third block. Practicing the pointing tasks for three blocks also helped to ensure that each participant began the testing phase at approximately the same level of pointing ability before beginning the test. The second method was to randomize both the treatment order and the three level of the C-D gain, and was accomplished through a partially balanced Latin square.

After the initial questionnaire and training, each subject performed the task using one of the visual displays, which was determined by a random number generator. If the generated number was even, the participant was assigned the HMD. Otherwise, the participant was assigned the WMD. All participants were required to use the five input control devices, with the order of presentation counterbalanced with a partially balanced Latin square design. The experimental design is shown in Table 3.0, and the partially balanced Latin square in Table 3.1. The participants were informed that they should move the cursor as quickly as possible to the target and position the cursor as accurately as possible to the center of the target before depressing the device button. They understood that speed and accuracy were equally important and that they should not spend too much time attempting to center the cursor on the target.

Table 3.0.

<u>C-D Gain Experimental Design.</u>

(Input Control Devices)

Between Subjects (Visual Displays)	INPUT 1	INPUT 2	INPUT 3	INPUT 4	INPUT 5
HMD	$S_1...S_5$	$S_1...S_5$	$S_1...S_5$	$S_1...S_5$	$S_1...S_5$
WMD	$S_6...S_{10}$	$S_6...S_{10}$	$S_6...S_{10}$	$S_6...S_{10}$	$S_6...S_{10}$

Table 3.1.

C-D Gain Balanced Latin Square Design.

	Subjects 1	Subjects 2	Subjects 3	Subjects 4	Subjects 5
Presentation Order of Input Control Devices	Input 1 Input 2 Input 5 Input 3 Input 4	Input 2 Input 3 Input 1 Input 4 Input 5	Input 3 Input 4 Input 2 Input 5 Input 1	Input 4 Input 5 Input 3 Input 1 Input 2	Input 5 Input 1 Input 4 Input 2 Input 3

	Subjects 6	Subjects 7	Subjects 8	Subjects 9	Subjects 10
Presentation Order of Input Control Devices	Input 4 Input 3 Input 5 Input 2 Input 1	Input 5 Input 4 Input 1 Input 3 Input 2	Input 1 Input 5 Input 2 Input 4 Input 3	Input 2 Input 1 Input 3 Input 5 Input 4	Input 3 Input 2 Input 4 Input 1 Input 5

Experimental Tasks.

Pointing tasks.

The Generalized Fitts Law Model Builder (GFLMB) version 1.1 software developed by William Soukoreff and Scott MacKenzie, University of Guelph, Ontario, Canada was used for the pointing tasks. Each participant was presented with a multiple combination of targets, which varied in height, width and amplitude (distance between the home position and the center position of the target). Furthermore, the angle at which the targets appeared also varied. Both the pointing time (ms) and errors were recorded for each trial. An error was recorded when the participants pressed the device button to indicate the end of a trial while the cursor was outside the target boundaries.

The size, amplitude and angle of the targets were varied but remained constant across subjects. For this study, three target sizes were chosen to represent large, medium and small targets. The values for the target sizes were 2.5mm, 5mm and 10mm. Likewise, three amplitudes (long, medium and short) were used. These distances included 60mm, 100mm and 160mm. Finally, the four angle positions that were specified were 45^{o}, 135^{o}, 225^{o} and 315^{o}.

Pointing Movement.

Pointing tasks refer to moving the cursor from the home position to the center position of the target. Two objects simultaneously appeared on the screen, one in the middle of the screen (home) and another one at some prescribed angle and distance (target). After depressing the spacebar on the keyboard, the participant initiated a cursor movement, which began in the center of the home position. Movement began when the participant moved or applied pressure to the input control device. Once the system detected that the input control device had been activated, the pointing time (ms) began. The ending time was recorded when the participant positioned the cursor in the center of the target and depressed the input control key.

CHAPTER IV.

RESULTS (DEVICE OPTIMIZATION)

This chapter presents the results obtained during the device optimization experiment, and the results were used to optimize each of the five input devices for study that took place later in the same month.

For each of the five devices, the overall means for pointing time and accuracy were calculated. Since the motivation of this experiment was to determine which D-C gain contributed to the best performance for all conditions (i.e. target size, distance, and angle of approach), the interaction between the main effect and these variables were unimportant. As a result, the general approach used to determine which D-C gain level contributed to the best performance follows. An examination of the mean pointing time and accuracy were calculated. If the examination of the data showed that both the shortest pointing time and best accuracy were produced at the same D-C level, that level was chosen as the optimum gain setting for that specific device and display. However, if the shortest pointing time and best accuracy resulted from different D-C levels, a paired-sample t test was performed to determine if there were significance between the two D-C levels for accuracy. If the analysis of the t test resulted in significance, the D-C level that resulted in the best accuracy was chosen as the optimum gain setting. Otherwise, the D-C level which produced the shortest pointing time was selected. The rationale for focusing on accuracy over pointing time for D-C gain selection was due to the likelihood that an error in accuracy

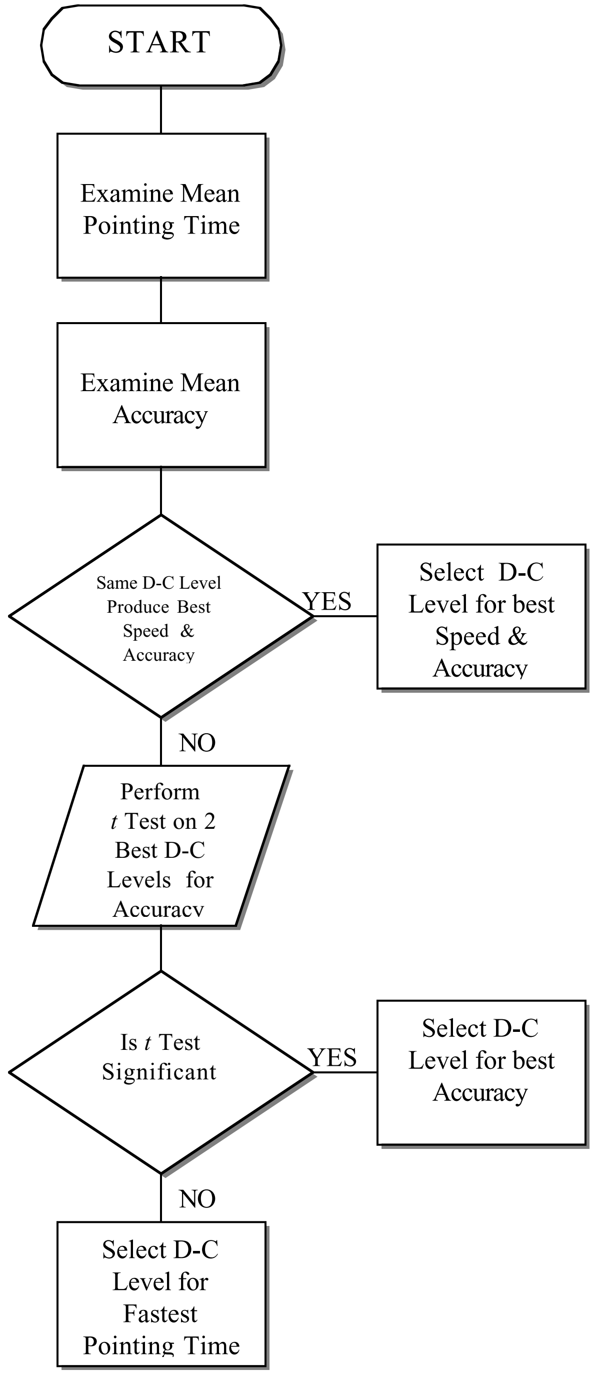

Figure 4.0. Decision process for determining the optimum D-C gain for each pointing device.

would increase pointing for real-world applications. In real-world applications, recovery from accuracy errors would likely lead to an increase in the number of pointing and selection tasks; thus increasing the overall pointing time. For this reason, better accuracy is preferred over shorter pointing time. The diagram in figure 4.0 illustrates the decision flow for determining the best D-C level for each device.

DuraPoint Results.

An examination of the data for the HMD shows that the mean pointing times for the three D-C levels are 4065ms, 3828ms and 3909ms respectively. In addition, the standard deviation for the second D-C gain was smaller than those for the first and third levels (Table 4.0).

Table 4.0.

Description Statistics for Pointing Time on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	4065	861
2	5	Pointing Time	3828	636
3	5	Pointing Time	3909	704

An examination of the accuracy data for HMD, however, shows that the mean accuracy for the three D-C levels was the worst for levels two and three and best for level one (Table 4.1.). Since the best speed and accuracy performance were not achieved at the same D-C level, a paired-samples t test was performed on the first two D-C levels to determine if there is a significant difference in accuracy. The analysis revealed a no significant difference between mean levels of accuracy for D-C level one and two, $t(4) = 0.31$; $p = 0.07$.

Table 4.1.

Description Statistics for Accuracy on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	1.60	0.64
2	5	Accuracy	1.91	0.87
3	5	Accuracy	1.94	0.57

A review of the data for the FPD shows that the mean times for the three D-C levels are 3864ms, 3449ms and 3698ms respectively. Similar to the results found for the HMD, the standard deviation for the second D-C gain was smaller than those for the other two (Table 4.2).

Table 4.2.

Description Statistics for Pointing Time on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	3864	975
2.	5	Pointing Time	3449	467
3	5	Pointing Time	3698	568

Likewise, an examination of the accuracy data for FPD found that the D-C level two resulted in the highest accuracy level while D-C gain level one resulted in the lowest accuracy (Table 4.4). The results indicate that D-C gain 2 is best for the FPD and DuraPoint combination.

Table 4.4.

Description Statistics for Accuracy on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	2.50	0.33
2	5	Accuracy	2.31	0.27
3	5	Accuracy	2.58	0.30

Hand Mouse Results.

An examination of the data for the HMD shows that the mean pointing times for the three D-C levels are 3834ms, 3712ms and 3841ms respectively. In addition, the standard deviation for the first D-C gain was smaller than those for the second and third levels (Table 4.5).

Table 4.5.

Description Statistics for Pointing Time on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	3834	535
2	5	Pointing Time	3712	898
3	5	Pointing Time	3841	957

An examination of the accuracy data for HMD shows that the mean accuracy for the three D-C levels was the highest for levels one and two and lowest for level three (Table 4.6). The results indicate that D-C gain 2 is best for the HMD and Hand Mouse combination.

Table 4.6.

Description Statistics for Accuracy on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	1.83	0.79
2	5	Accuracy	1.83	0.72
3	5	Accuracy	2.45	0.77

A review of the data for the FPD shows that the mean times for the three D-C levels are 3718ms, 3606ms and 3660ms respectively. The results also show that D-C level two had the lowest standard deviation. (Table 4.7).

Table 4.7.

Description Statistics for Pointing Time on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	3718	860
2.	5	Pointing Time	3606	553
3	5	Pointing Time	3960	1011

An examination of the accuracy data for FPD (Table 4.8) found that the D-C level one resulted in the highest accuracy level while D-C gain level two resulted in the lowest accuracy. Thus a paired —sample t test was performed was determine if there was a significant difference in accuracy for the D-C gain main effect. This analysis revealed no difference between mean values of accuracy, $t(4) = 0.69$; $p = 0.25$. The results indicate that D-C gain 2 is optimum for the FPD and Hand Mouse combination.

Table 4.8.

Description Statistics for Accuracy on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	2.30	0.42
2	5	Accuracy	3.02	1.21
3	5	Accuracy	2.65	0.32

Trackball Results

An examination of the data for the HMD and Trackball combination shows that the mean pointing times for the three D-C levels are 2291ms, 2139ms and 2424ms respectively. In addition, the standard deviation for the first D-C gain was smaller than those for the second and third levels (Table 4.9).

Table 4.9.

Description Statistics for Pointing Time on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	2291	250
2	5	Pointing Time	2139	269
3	5	Pointing Time	2424	447

An examination of the accuracy data for HMD shows that the mean accuracy for the three D-C levels was best at level two. As a result, D-C gain 2 is optimum for the HMD and Trackball combination.

Table 4.10.

Description Statistics for Accuracy on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	2.80	1.01
2	5	Accuracy	1.43	0.70
3	5	Accuracy	1.89	0.54

A review of the data for the FPD and Trackball combination shows that the mean times for the three D-C levels are 2528ms, 2318ms and 2522ms respectively. The results also show that D-C level two had the lowest standard deviation. (Table 4.11).

Table 4.11.

Description Statistics for Pointing Time on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	2528	332
2.	5	Pointing Time	2318	311
3	5	Pointing Time	2522	398

An examination of the accuracy data for FPD and Trackball combination found that the D-C level two resulted in the highest accuracy level while D-C gain level three resulted in the lowest accuracy. As a result, D-C gain level 2 was chosen as the optimum level for the FPD and Trackball combination

Table 4.12.

Description Statistics for Accuracy on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	1.65	0.31
2	5	Accuracy	1.61	0.40
3	5	Accuracy	2.19	0.35

Thumbwheel Results.

An examination of the data for the HMD and Thumbwheel combination shows that the mean pointing times for the three D-C levels are 3094ms, 3044ms and 3356ms respectively. In addition, the standard deviation for the second D-C gain was smaller than those for the first and third levels (Table 4.13).

Table 4.13.

Description Statistics for Pointing Time on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	3094	651
2	5	Pointing Time	3044	214
3	5	Pointing Time	3354	467

An examination of the accuracy data for HMD and Thumbwheel combination also shows that the mean accuracy was best for level one. As a result a paired-sample t test was performed on the mean accuracy for the first two D-C gain levels. This analysis revealed no significant differences between these two levels, $t(4) = 0.81$; $p = 0.19$. As a result, D-C gain level 2 was chosen as the optimum level for the HMD and Thumbwheel combination.

Table 4.14.

Description Statistics for Accuracy on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	1.62	1.06
2	5	Accuracy	2.43	1.35
3	5	Accuracy	2.06	0.50

A review of the data for the FPD and Thumbwheel combination shows that the mean times for the three D-C levels are 3612ms, 3977ms and 4803ms respectively. The results also show that D-C level two had the smallest standard deviation. (Table 4.15).

Table 4.15.

Description Statistics for Pointing Time on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	3613	738
2.	5	Pointing Time	3977	461
3	5	Pointing Time	4803	665

An examination of the accuracy data for FPD and Trackball combination found that each of the D-C levels were extremely close for accuracy (Table 4.16). Thus, D-C gain 1 was chosen as the optimum level for the FPD and Thumbwheel combination.

Table 4.16.

Description Statistics for Accuracy on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	2.69	1.03
2	5	Accuracy	2.69	0.47
3	5	Accuracy	2.63	0.47

Touchpad Results.

An examination of the data for the HMD and Touchpad combination shows that the mean pointing times for the three D-C levels are 2264ms, 2737ms and 2796ms respectively. Thus the shortest pointing time was recorded with D-C level two. In addition, the standard deviation for the second D-C gain was smaller than those for the first and third levels (Table 4.17).

Table 4.17.

Description Statistics for Pointing Time on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	3264	501
2	5	Pointing Time	2737	315
3	5	Pointing Time	2796	454

An examination of the accuracy data for HMD and Touchpad combination, however, shows that the mean accuracy for the three D-C levels was the highest for level one and lowest for level two (Table 4.18). Since the fastest pointing time and best accuracy were not achieved at the same D-C level, a paired-samples t test was performed to determine if there was a significant difference in accuracy between levels one and two. The results revealed no significant difference between the two levels, t(4) = 0.37; p = 0.56. Therefore, D-C gain 2 was chosen as the optimum for the HMD and Touchpad combination.

Table 4.18.

Description Statistics for Accuracy on HMD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	2.59	1.52
2	5	Accuracy	2.97	2.57
3	5	Accuracy	4.06	2.27

A review of the data for the FPD shows that the mean times for the three D-C levels are 3312ms, 2976ms and 2842ms respectively. The results also show that D-C level three had the lowest standard deviation. (Table 4.19).

Table 4.19.

Description Statistics for Pointing Time on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Pointing Time	3312	679
2.	5	Pointing Time	2976	688
3	5	Pointing Time	2842	610

An examination of the accuracy data for FPD found that the D-C level three resulted in the highest accuracy level while D-C gain level one resulted in the lowest accuracy (Table 4.20). Since the fastest mean pointing time and highest accuracy were produced by D-C gain level 3, this level was chosen as the optimum level for the FPD and Touchpad combination.

Table 4.20.

Description Statistics for Accuracy on FPD.

GAIN	N OBS	VARIABLE	MEAN	STD DEV
1	5	Accuracy	8.96	6.60
2	5	Accuracy	6.98	6.18
3	5	Accuracy	4.08	2.31

Summary of Device Optimization.

Table 4.21. presents the overall results based on the above analysis. The D-C gain selection will be used to assess the soldiers performance in the next experiment described in Chapter V.

Table 4.21.

D-C Gain for Selected Devices and Visual Display

DEVICE	HMD GAIN	FPD GAIN
DuraPoint	2	2
Hand Mouse	2	2
Trackball	2	2
Thumbwheel	2	1
Touchpad	2	3

Effect of Learning on Pointing Time.

As described earlier, learning for this experiment is described as a significant improvement in performance time between trail blocks. All participants were require to practice 4 trial blocks which included 36 fully crossed trial combinations of target width (3), distance (3) and angle of approach (4). The data from the first trial was practice data and was discarded. The data from the other three blocks are presented in Table 4.22.

Table 4.22.

Change in Mean Block Time as a Result of Practice, n=5.

		Mean trial time in ms and SD by block number		
Device	Display	1	2	3
DuraPoint	HMD	3456 (800)	3500 (713)	3827 (679)
	FPD	4231 (776)	4093 (753)	4189 (939)
Palm Mouse	HMD	3484 (577)	3381 (720)	3538 (460)
	FPD	3942 (626)	4013 (519)	4105 (644)
Trackball	HMD	2215 (276)	2199 (163)	2403 (255)
	FPD	2537 (302)	2476 (357)	2495 (325)
Touchpad	HMD	2726 (347)	2908 (420)	3292 (400)
	FPD	3468 (782)	3518 (478)	3494 (528)
Thumbwheel	HMD	2954 (673)	3165 (698)	3368 (850)
	FPD	3659 (500)	3690 (515)	3488 (509)

A review of the above table shows that there was an improvement in pointing time for the DuraPoint and FPD combination; the Hand Mouse and HMD combination; the Trackball with both visual displays; and the Thumbwheel and FPD combination. Mean pointing time across the three blocks for each combination are displayed in Figures 4.0 and 4.1. Results were analyzed using one-way analysis of variance (ANOVA), repeated-measures design. This analysis revealed no significant effect for pointing time.

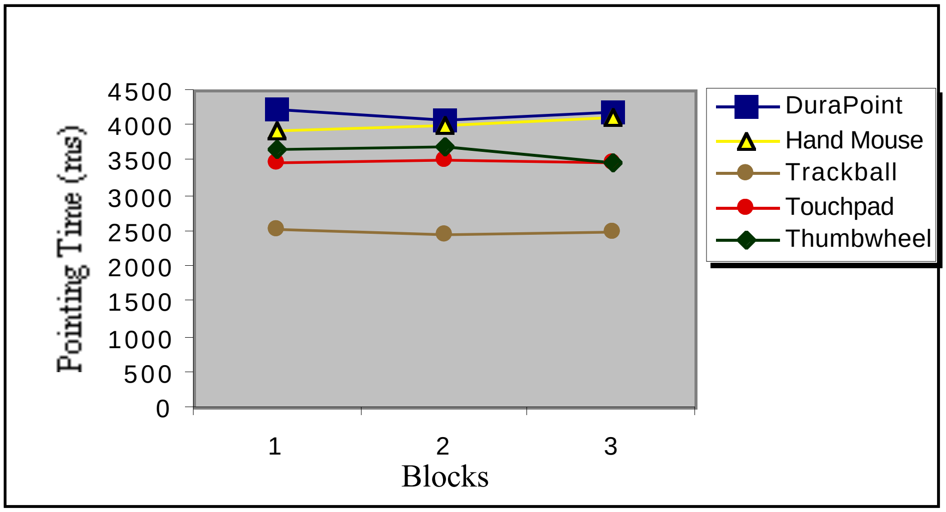

Figure 4.0: Mean Pointing Time (ms) with HMD by block across participants, n=5.

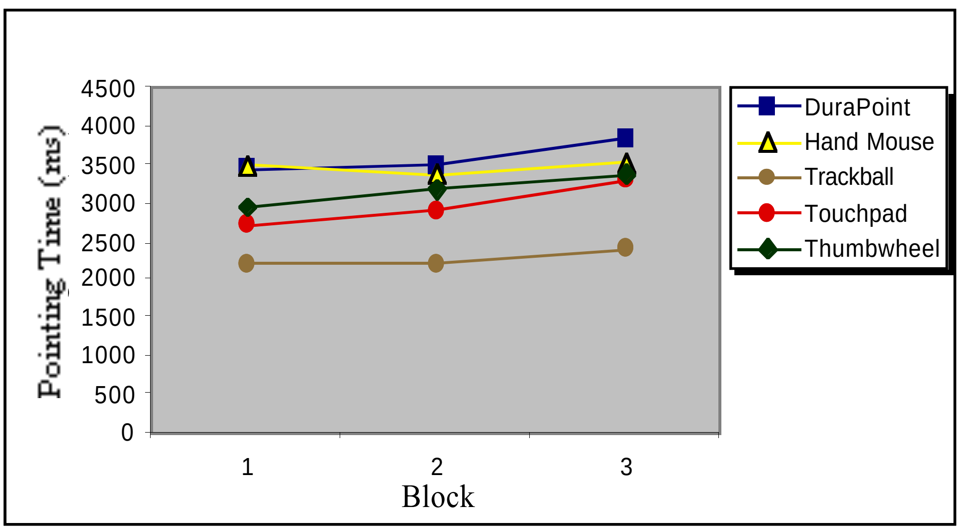

Figure 4.1: Mean Pointing Time (ms) with FPD by block across participants, n=5.

The explanation for the lack of learning effect could possibly be due to the fact that the pointing task was not complex and each participant became well-practiced after the first practice block. In addition each of the test participants reported to have a minimum of ten years experience and good ability with using a computer. This experience could account for the ease of learning how to use each of the pointing devices. It is expected that SOF soldiers will not have equivalent experience. Thus, it may take them longer to become well practiced with the various devices.

CHAPTER V

EXPERIMENTAL METHODS 2

Pointing Devices & Visual Display Experiment.

Experimental Goals.

This experiment was supported by the U.S. Army Special Operations Command (USASOC), and the results will be used to support their preparation of a requirement document for wearable computer components. The objectives of this study were to (1) compare soldiers performance while using five different COTS input devices with two different visual displays; (2) determine if Fitts Law can be used to assess the future design of input control devices; and (3) identify soldier s preference for visual displays.

Methodology.

Participants.

Twenty male soldiers from the USASOC at Ft. Bragg, North Carolina were recruited for this experiment. Since only male soldiers can be awarded a combat military occupational specialty positions for the SOF, this experiment excluded female soldiers from participating. The SOF soldiers were briefed on the purpose of the study, the procedures to be followed during its conduct, and any risks involved. All soldiers who consented to participate were required to sign a Volunteer Agreement Affidavit (Appendix B). All participants completed a questionnaire to obtain demographic information (Appendix C). For this study, the soldiers were asked to fill out the questionnaire describing their experience with miniature input control devices. This experience was assessed upon review of the questionnaire and prior to any test conditions given. If any of the 20 soldiers indicated that he had had prior experience using these miniature devices, then he was excluded from participating in this study and was replaced by a soldier who had no previous experience with miniature input control devices.

Experimental Equipment.

The experimental equipment used in this second experiment is a same as the equipment described in the experiment above.

Experimental Design.

Independent Variables.

This experiment is a three-factor, mixed design. The between-subject factor is the type of visual display, and the two within-subject factors are the five input devices and the blocks for each trail. The linear statistical model for the experiment is as follows:

$$Y_{ijkl} = \mu + D_i + I_j + S_{k(i)} + DI_{ij} + IS_{jk(i)} + \varepsilon_{l(ijk)}$$

Where,

Y_{ijkl} = Dependent variable (home time, pointing time and error) measured under the i^{th} type of visual display and j^{th} input device, k^{th} subject.

D = i^{th} level of visual display (i=1, 2).

I = j^{th} level of input device (j=1, 2, , 5).

S = k^{th} subject (j=1, ,20).

ε = l^{th} response for the k^{th} subject, i^{th} visual display and j^{th} input device.

Dependent Variables.

The dependent variables for this experiment were the pointing time, homing time, the number and types of errors made when clicking on a target, and responses to a questionnaire for evaluating the usability of the pointing devices and displays.

Experimental Procedures.

Participants were initially screened using a Rosenbaum vision screener to verify that they have at least 20/40 vision corrected. Only one soldier was unable to pass the vision test due to recent eye surgery. The soldier was dismissed from the experiment and a replacement soldier was added. Upon successful completion of the vision test, participants proceeded to the main part of the experiment.

Participants were seated at a table in a classroom and provided an adjustable chair for height. Before the subjects began the first condition, they were provided written instructions about the experiment. After reading the instructions, any questions the subjects had were answered. Next, each subject received training on the target acquisition software, which include one block of completely crossed combination of target size (3), target distance (3), and angle of approach (4) for a total of thirty-six trials. This training was done to help minimize the effects of learning for the task. The experimenter explained the functionality of the input devices and how they were used to manipulate the display cursor. After the participants complete one complete block of trials, they performed five complete blocks of 36 trials per pointing device.

As noted above, one of the main experimental concerns of the study was to control for the effects of learning by the participants. Since each subject performed the same tasks using all pointing devices, it is imperative to design the experiment to minimize the potential learning effect. The two steps that were taken to control the effects of learning were to allow all participants to practice the tasks and to randomize the treatment order. The first control measure was described above allowing the soldiers to practice one complete block of trials. The second method taken was the randomization of the treatment order. This was accomplished through a partially balanced Latin square.

After the initial questionnaire and training, each subject performed the task using one of the visual displays, which was determined by a random number generator. If the generated number was even, the participant was assigned the HMD. Otherwise, the participant was assigned the WMD. All participants were required to use the five pointing devices, with the order of presentation counterbalanced with a partially balanced Latin square design. The experimental design is shown in Table 5.1, and the partially balanced Latin square in Table 5.2.

To increase to power of the partially balanced Latin square, two participants from each between-subject variable (visual display) received the same order of presentation of the five different input control devices (Howell, 1997). The participants were given as much time as they needed to complete the task.

Upon completion of the tasks, participants were asked to complete a post-test questionnaire (Appendix D) to determine their subjective preference for visual display and the usability of the various control devices.

Table 5.1.

Experimental Design

Between Subjects / Visual Displays	Within Subjects (Input Control Devices): INPUT 1	INPUT 2	INPUT 3	INPUT 4	INPUT 5
HMD	$S_1 \ldots S_{10}$	$S_1 \ldots S_{10}$	$S_1 \ldots S_{10}$	$S_1 \ldots S_{10}$	$S_1 \ldots S_{10}$
WMD	$S_{11} \ldots S_{20}$	$S_{11} \ldots S_{20}$	$S_{11} \ldots S_{20}$	$S_{11} \ldots S_{20}$	$S_{11} \ldots S_{20}$

Table 5.2

Balanced Latin Square Design

Presentation Order of Input Control Devices	Subjects 1 & 11	Subjects 2 & 12	Subjects 3 & 13	Subjects 4 & 14	Subjects 5 & 15
	Input 1	Input 2	Input 3	Input 4	Input 5
	Input 2	Input 3	Input 4	Input 5	Input 1
	Input 5	Input 1	Input 2	Input 3	Input 4
	Input 3	Input 4	Input 5	Input 1	Input 2
	Input 4	Input 5	Input 1	Input 2	Input 3

Presentation Order of Input Control Devices	Subjects 6 & 16	Subjects 7 & 17	Subjects 8 & 18	Subjects 9 & 19	Subjects 10 & 20
	Input 4	Input 5	Input 1	Input 2	Input 3
	Input 3	Input 4	Input 5	Input 1	Input 2
	Input 5	Input 1	Input 2	Input 3	Input 4
	Input 2	Input 3	Input 4	Input 5	Input 1
	Input 1	Input 2	Input 3	Input 4	Input 5

Experimental Tasks.

Pointing tasks.

The Generalized Fitts Law Model Builder (GFLMB) version 1.1 software, developed by William Soukoreff and Scott MacKenzie, University of Guelph, Ontario, Canada, was used for the target acquisition tasks. Each participant was presented with a predetermined number of targets that varied in height, width and amplitude (distance between the home position and the center position of the target). Furthermore, the angle at which the targets appeared also varied. Five blocks per participant were recorded for each of the five pointing devices. Each trail measurements included the amplitude (mm), the target size (mm), the movement time (ms) and the homing time (ms). Longitudinal change in performance time as a function of practice was computed to measure learning.

The size, amplitude and angle of the targets were varied but remained constant across subjects. For this study, three sizes were chosen to represent large, medium and small targets. The value for the target sizes were 2.5mm, 5mm and 10mm. Likewise, 3 amplitudes (long, medium and short) were chosen. These distances included 60mm, 100mm and 160mm. Finally, four angles of approach were specified. The angles of approach were 45^{o}, 135^{o}, 225^{o} and 315^{o}. The times for each trial were summed, and the mean was calculated. This mean value was then used to calculate the Fitts law ID.

There were two timing measurements that were recorded and are homing and pointing times. In addition, accuracy and errors were also recorded. A description of these measurements are defined in the following section.

Homing Movement.

Homing is referred to as the time it took a participant to physically switch from the keyboard to the pointing device. Douglas and Mithal (1997) refer to this movement as device switching. For this experiment, homing time was the time it took a participant to initiate movement of the pointer (cursor) with the pointing device after depressing the space bar on the keyboard. For some devices, switching between the keyboard and pointing device may be time consuming and may significantly affect the overall task time. As a result, it was critical to capture and include this homing time in this assessment because soldiers will likely have to switch between the pointing device and other equipment used for their mission.

Before beginning each pointing condition, the participants were required to depress the spacebar on the keyboard to initiate the pointing task using the same hand. The time between depressing the spacebar and initiating a pointing movement was recorded. The homing time was then be added to the pointing time to assess the input control devices.

Pointing Movement.

Pointing tasks refers to moving the cursor from the home position to the center position of the target. For the pointing task, two objects appeared on the screen simultaneously. One appeared in the middle of the display (home target) and another object (objective target) appeared at a prescribed angle and distance from the home target. After depressing the spacebar on the keyboard, the participant initiated a cursor movement, which began in the center of the home target. Movement began when the participant moved or applied pressure to the input control device. Once the system detected that the input control device had been engaged, the pointing time (ms) began. The ending time was recorded when the participants positioned the cursor in the center of the target and depressed the input control key.

Pointing Accuracy.

Accuracy was recorded as the position of the cursor, (X, Y) coordinates, relative to the center of the target when the subject depressed the device key indicating the end of the trial (Soukoreff and Mackenzie, 1996). The absolute values of the X and Y coordinates are summed, and the result is used to as the pointing accuracy value.

Trial Error.

An error is recorded when a participant depresses the device button while the cursor is outside the boarder of the target. When this happens, the participant is notified by an audible beep from the computer, and the trial is recorded as an error.

CHAPTER VI

RESULTS

Quantitative Analysis.

Outliers.

A review of the data for each of the pointing devices was performed using the SAS plot and normal commands. This review was performed to examine the dispersion of the data, and to screen the data for errors and potential problems. The review revealed two outliers for errors and accuracy with the thumbwheel device, and one outlier for accuracy with the touchpad. Further review of the plots identified subjects 14 and 9 as the outliers. An examination of their data verified that no recording errors had been made. Furthermore, subject 9 reported on the questionnaire that moving the cursor from home position to the target was difficult with both the touchpad and thumbwheel devices. Likewise, subject 14 reported that moving the cursor from the home position to the target was difficult with the touchpad device. Their responses to the accuracy questions for these devices suggests that they were likely to have made significantly more errors than the other subjects. Therefore, the decision was to retain both subjects data. The results of the SAS output can be found in Appendix E.

Effect of Learning on Pointing Time.

As noted in Chapter V, the effect of learning on performance time is an important consideration. Learning is described as a significant improvement in performance time between trial blocks. A practice session for each device was performed, which included 36 trials, and the data from this practice session was discarded. Table 6.0 presents the mean and standard deviations for each pointing device over the five blocks of 36 trials for all subjects. The mean pointing the homing times were also grouped by visual display.

Table 6.0.

Mean performance time for each pointing device & visual display over the 5 blocks, n=10.

			Mean trial time (ms) and SD (ms) by block number				
Device	**Task**	**Display**	**1**	**2**	**3**	**4**	**5**
DuraPoint	Pointing	FPD	3905 (578)	3953 (678)	3985 (724)	3961 (758)	3827 (626)
		HMD	4264 (616)	4338 (760)	4340 (797)	4413 (841)	4295 (676)
	Homing	FPD	867 (216)	912 (263)	902 (207)	852 (187)	880 (240)
		HMD	989 (109)	1014 (164)	1032 (198)	1003 (156)	988 (146)
Hand Mouse	Pointing	FPD	4239 (1240)	4202 (1476)	4277 (1220)	4316 (1335)	4314 (1317)
		HMD	4109 (876)	4162 (765)	4131 (745)	4202 (887)	3989 (819)
	Homing	FPD	639 (124)	649 (99)	669 (111)	665 (127)	643 (118)
		HMD	703 (108)	698 (99)	710 (128)	686 (93)	738 (107)
Trackball	Pointing	FPD	2709 (338)	2794 (410)	2851 (343)	2856 (470)	2799 (470)
		HMD	3066 (735)	3014 (736)	2996 (754)	3052 (793)	3005 (844)
	Homing	FPD	672 (170)	645 (142)	663 (175)	654 (142)	666 (156)
		HMD	693 (121)	694 (135)	692 (123)	679 (105)	694 (117)
Touchpad	Pointing	FPD	4116 (779)	3948 (670)	3970 (627)	4025 (742)	4015 (753)
		HMD	3757 (801)	3847 (787)	3785 (668)	3844 (796)	3604 (568)
	Homing	FPD	956 (146)	944 (133)	945 (139)	918 (158)	919 (133)
		HMD	989 (222)	1006 (150)	992 (188)	1018 (167)	1003 (180)
Thumbwheel	Pointing	FPD	3561 (803)	3536 (775)	3423 (847)	3652 (965)	3483 (734)
		HMD	3435 (764)	3545 (1035)	3395 (549)	3488 (960)	3437 (891)
	Homing	FPD	460 (103)	465 (66)	482 (135)	500 (118)	472 (74)
		HMD	532 (79)	540 (43)	532 (43)	528 (43)	540 (70)

A review of the above table shows that there was an improvement in pointing time for the

Hand Mouse, Touchpad and Thumbwheel when combined with the FPD. There was also an improvement in pointing time for the Trackball and HMD combination. To determine if there was statistically significant learning from block to block, a paired-samples *t* test was performed on successive blocks. The results are presented by visual display in Tables 6.1 and 6.2. This analysis revealed no significant effect for Pointing Time x Block interaction, $t(359) = 137.86$; $p > .05$. Thus, there was no significant learning effect for pointing time among pointing devices.

Table 6.1.

Pair-samples t test between successive blocks for pointing device x HMD, n=10.

		Block			
Device	**Task**	**1-2**	**2-3**	**3-4**	**4-5**
Dura Point	Pointing	0.52	0.98	0.59	0.43
	Homing	0.41	0.55	0.32	0.26
Hand Mouse	Pointing	0.63	0.82	0.44	0.06
	Homing	0.81	0.46	0.47	0.03*
Touchpad	Pointing	0.46	0.53	0.41	0.10
	Homing	0.57	0.45	0.22	0.46
Trackball	Pointing	0.61	0.75	0.23	0.13
	Homing	0.96	0.95	0.13	0.34
Thumb Wheel	Pointing	0.52	0.58	0.71	0.71
	Homing	0.65	0.56	0.81	0.47

$t < .05$ for increase in performance time between successive blocks. As a result there is no learning effect for homing time.

Table 6.2.

Pair-samples *t* test between successive blocks for pointing device x FPD, n=10.

		Block			
Device	**Task**	**1-2**	**2-3**	**3-4**	**4-5**
Dura Point	Pointing	0.66	0.81	0.75	0.20
	Homing	0.07	0.76	0.002*	0.32
Hand Mouse	Pointing	0.79	0.64	0.71	0.99
	Homing	0.73	0.58	0.87	0.35
Touchpad	Pointing	0.28	0.77	0.65	0.93
	Homing	0.63	0.96	0.04*	0.95
Trackball	Pointing	0.27	0.46	0.94	0.54
	Homing	0.37	0.61	0.73	0.43
Thumb Wheel	Pointing	0.80	0.36	0.10	0.20
	Homing	0.77	0.52	0.34	0.14

The analysis revealed no significant difference between successive blocks for mean pointing times. However, the results do reveal a significant difference for mean homing time between blocks 3 and 4 for the FPD and DuraPoint combination, $t(9) = 12.47$; $p < .05$. In addition, there is a significant difference for mean homing time between blocks 3 and 4 for the FPD and Touchpad combination, $t(9) = 27.58$; $p < .05$.

Figures 6.0 through 6.3 are plots of the pointing and homing data for each pointing device by visual display. As expected, the plots confirm that there is no significant improvement in pointing time by block across participants. As a result of the analysis, the mean trial times from the last two blocks (4 & 5) will be used for the rest of the analysis.

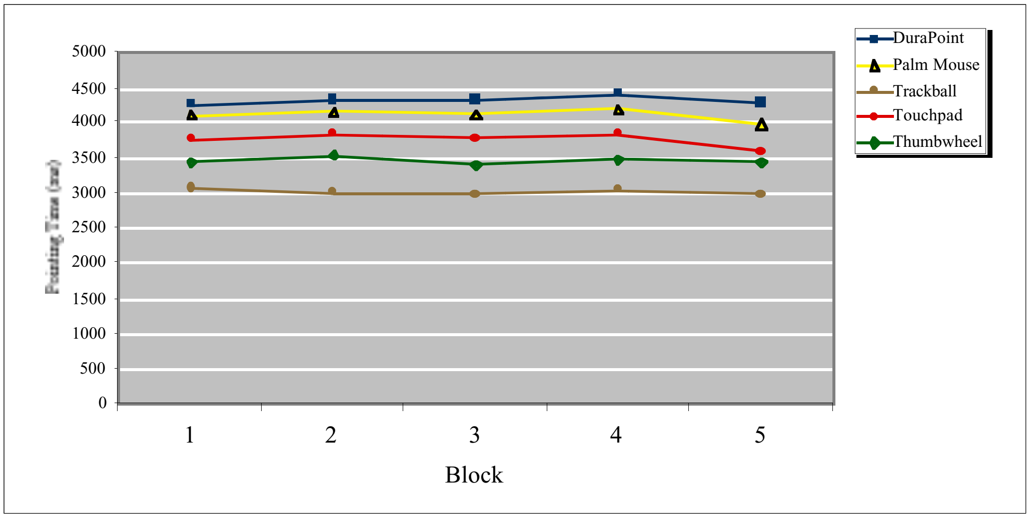

Figure 6.0. Pointing Time (ms) with HMD by block across subjects. n=10.

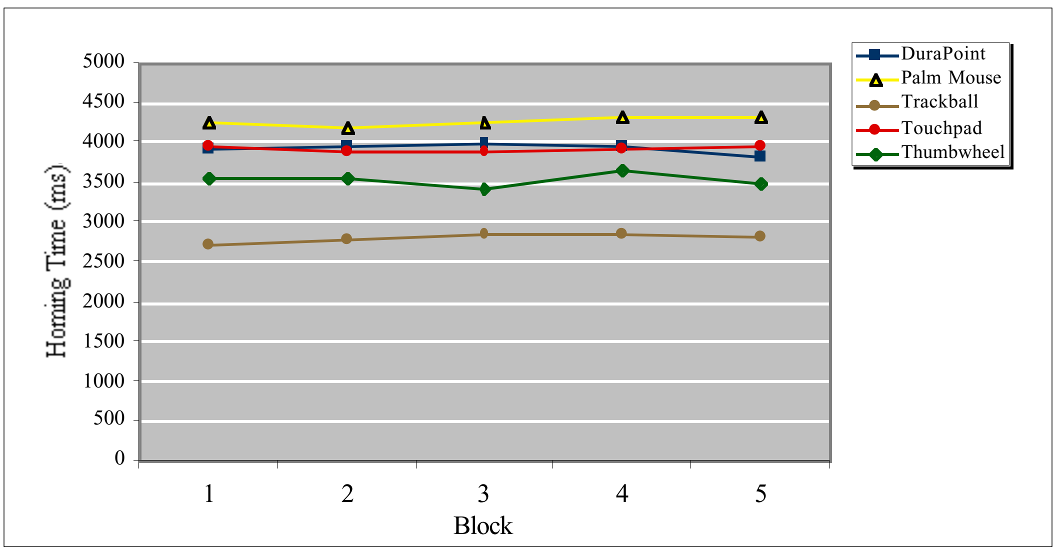

Figure 6.1. Pointing Time (ms) with FPD by block across participants. n=10.

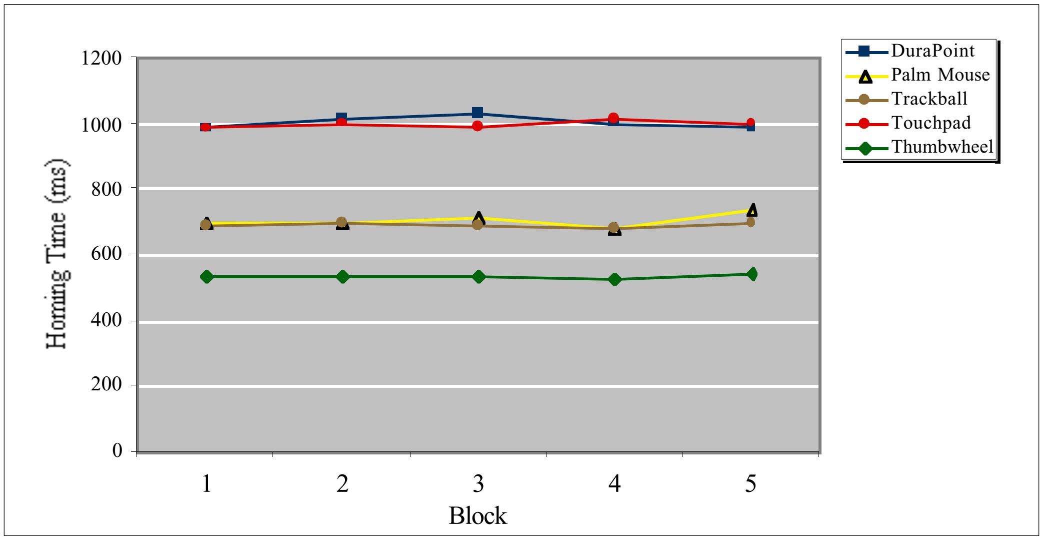

Figure 6.2. Homing Time (ms) with HMD by block across participants. n=10.

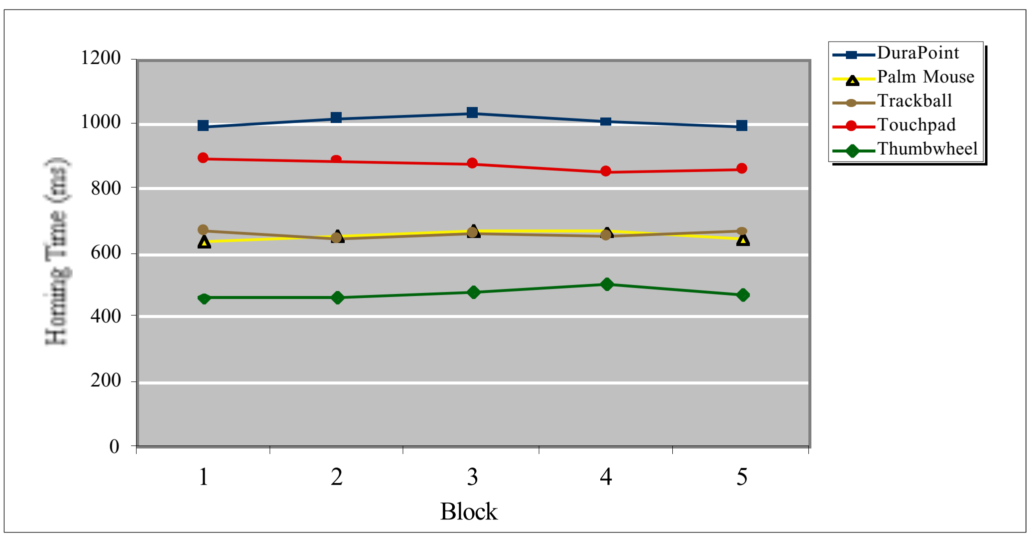

Figure 6.3. Homing Time (ms) with FPD by block across participants. n=10.

Pointing Device and Visual Display Analysis.

Pointing Time.

The mean pointing times for each device during the last two blocks are presented in Figure 6.4. The results were analyzed using a two-way ANOVA, with repeated-measures on one factor (pointing device). The Display X Pointing Device interaction was not significant, $F_{(4, 72)}$ = 1.18, $p > .05$. The main effect of display also was not significant, $F_{(1, 18)} = 0.00$, $p > .05$. This analysis did reveal a significant effect for pointing device, $F_{(4, 72)} = 12.87$, $p < .05$. Post-hoc contrasts found that pointing time was significantly faster with the trackball than the other devices (device 3) ($p < .0001$). In addition, the pointing time for the thumbwheel device was significantly faster than the hand mouse ($p < .01$) and durapoint ($p < .007$) devices but not significantly faster than the touchpad ($p = .06$). Finally, the pointing time with the touchpad was not significantly faster than either the hand mouse ($p = .10$) or durapoint ($p = .23$).

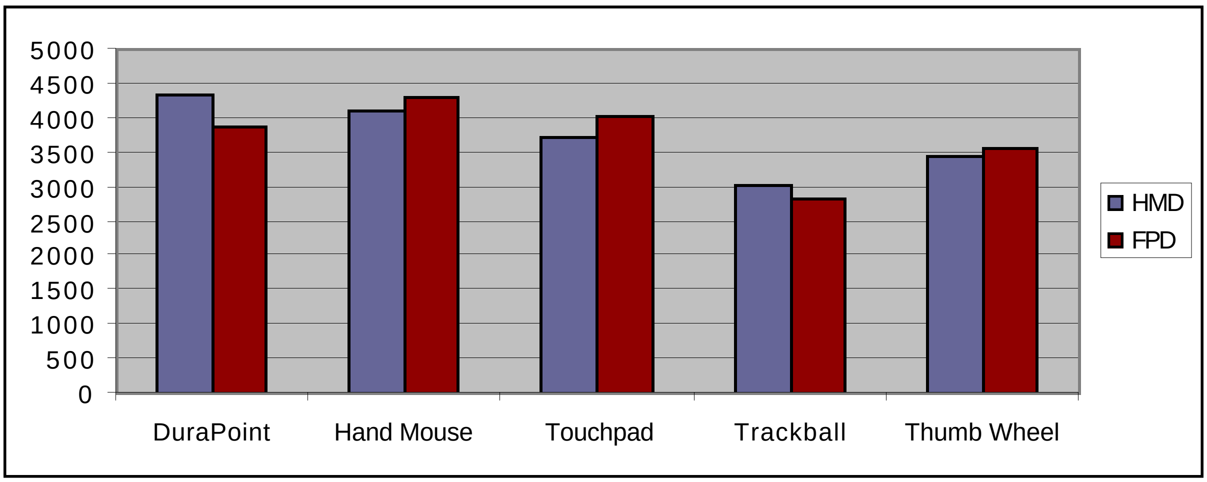

Figure 6.4. Mean pointing time (ms) for each device during last two blocks.

Table 6.2

ANOVA Summary Table for Pointing Time (ms) Pointing.

Source	df	S S	MS	F
Between Subjects	19	30364561		
Visual Display (A)	1	1576	1576	0.00
Residual	18	30362985	1686832	
Within Subjects	80	54325997		
Pointing Devices (B)	4	21813460	545365	12.87 *
A X B Interaction	4	1994809	498702	1.18
Residual	72	30517728	423857	
Total	99	84690558		

Note: N= 20.
* p < .0001

Homing Time.

The mean homing time for each device during the last two blocks are presented in Figure 6.5. The results were analyzed using a two-way ANOVA, with repeated-measures on one factor (pointing device). The Display X Pointing Device interaction was not significant, F(4, 72) = 0.53, p = .72. The main effect of display also was not significant, F(1, 18) = 4.04, p = .06. This analysis did reveal a significant effect for pointing device, F(4, 72) = 47.77, p < .05. Post-hoc contrasts found that homing time was significantly faster with the thumbwheel than the other devices (device 5) (p < .0001). In addition, the homing time for the trackball was significantly faster than the both the durapoint and touchpad (p < .0001) devices but not significantly faster than the hand mouse (p = .77). Likewise, the homing time with the hand mouse was significantly faster than both the durapoint and touchpad (p < .0001). There was, however, no significant difference in homing time between the durapoint and touchpad (p = .50).

Table 6.3

ANOVA Summary Table for Homing Time (ms).

Source	df	S S	M S	F
Between Subjects	19	679683		
Visual Display (A)	1	124608	124608	4.04
Residual	18	555075	30838	
Within Subjects	80	4073615		
Pointing Devices (B)	4	2935208	733802	47.77 *
A X B Interaction	4	32460	8115	0.53
Residual	72	1105947	15360	
Total	99	4753298		

Note: N= 20.

* p < .0001

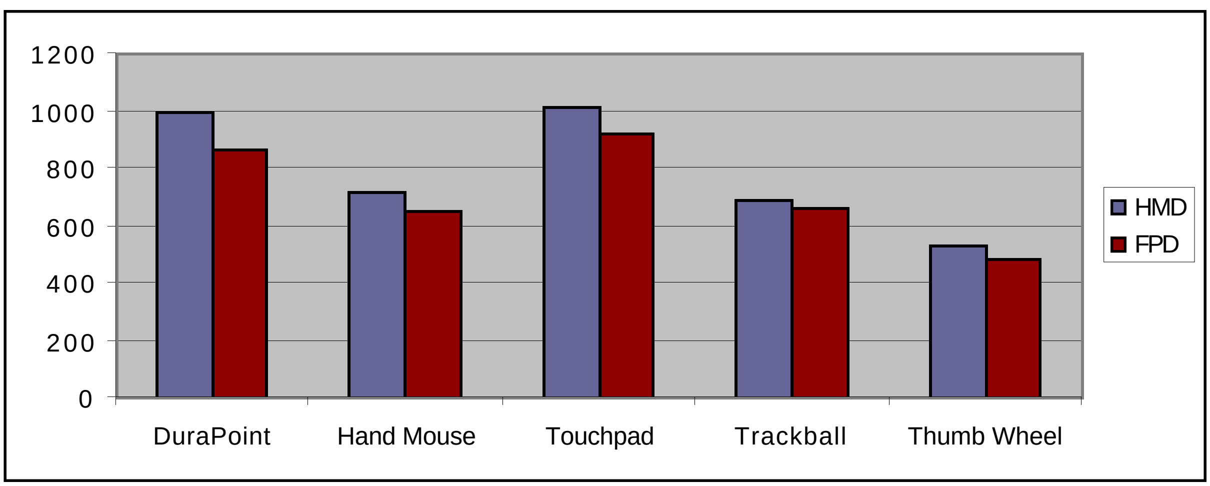

Figure 6.5. Mean homing time (ms) for each device for the last two blocks.

Accuracy.

The mean level of accuracy for each device during the last two blocks are presented in Figure 6.6. The results were analyzed using a two-way ANOVA, with repeated-measures on one factor (pointing device). The Display X Pointing Device interaction was not significant, $F_{(4, 72)} = 0.48$, $p = .75$. The main effect of display also was not significant, $F_{(1, 18)} = 0.31$, $p = .58$. This analysis did reveal a significant effect for pointing device, $F_{(4, 72)} = 10.32$, $p < .05$. Post-hoc contrasts found that pointing accuracy was significantly better with the trackball than the other devices (device 3) ($p < .0077$). In addition, the pointing accuracy with the durapoint was significantly better than the both the handmouse ($p < .02$) and touchpad ($p < .001$) devices but not significantly faster than the thumbwheel ($p = .48$). There was, however, no significant difference in pointing accuracy between the handmouse and touchpad ($p = .066$).

Table 6.4

ANOVA Summary Table for Accuracy.

Source	df	S S	MS	F
Between Subjects	19	33.112		
Visual Display (A)	1	0.055	0.055	0.03
Residual	18	33.057	1.84	
Within Subjects	80	1105990.34		
Pointing Devices (B)	4	40.93	10.232	12.01 *
A X B Interaction	4	2.41	0.603	0.71
Residual	72	1105947	0.852	
Total	99	1106023.452		

Note: N= 20.

* p < .0001

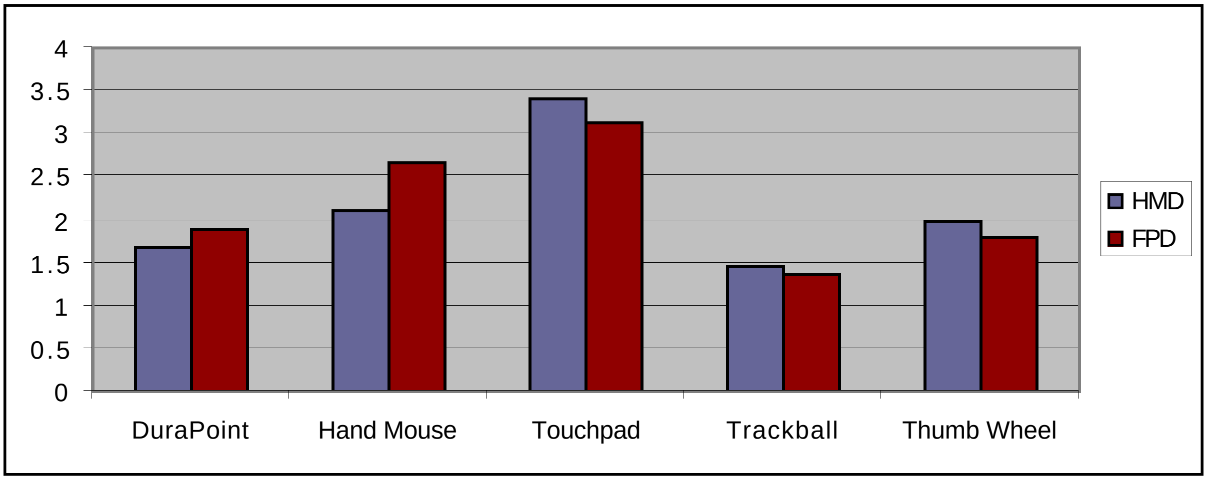

Figure 6.6. Mean accuracy value (mm) for each device for the last two blocks.

Errors.

The mean numbers of errors for each device during the last two blocks are presented in Figure 6.7. Because the number of errors were so small, it was decided that a statistical analysis would be inappropriate. However, a review of Figure 6.7 indicates that the pointing task with the trackball resulted in less errors than the other devices, and pointing with the touchpad resulted in the highest number of errors.

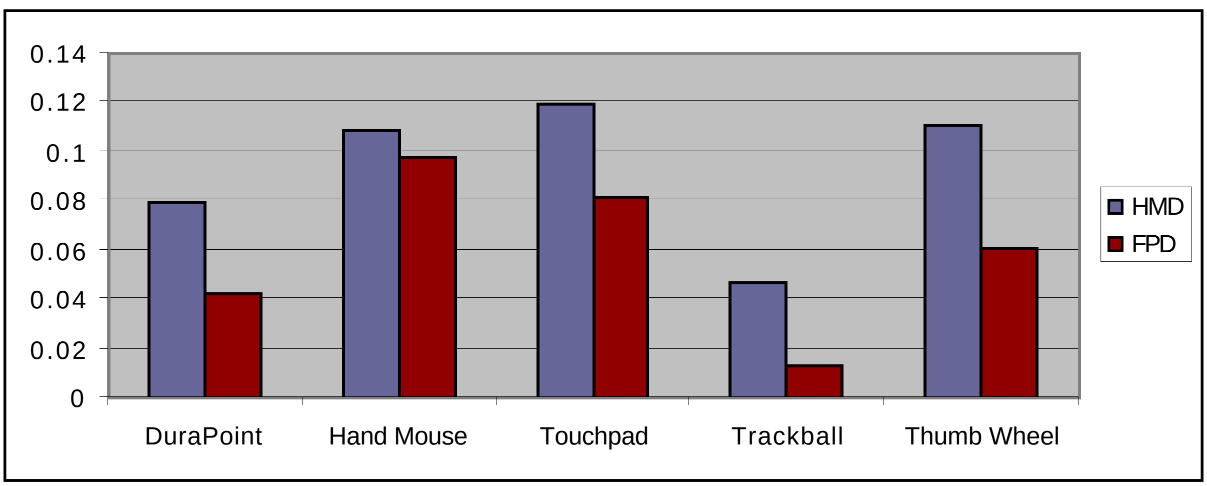

Figure 6.7. Mean number of error for each device for the last two blocks.

Composite Results.

A composite of the standardized results is presented in Figure 6.8 and Figure 6.9 for all input devices by HMD and FPD. This was done to better illustrate that lack of difference between pointing devices across visual display, and to better illustrate the differences between pointing device for error, homing time, pointing time and accuracy.

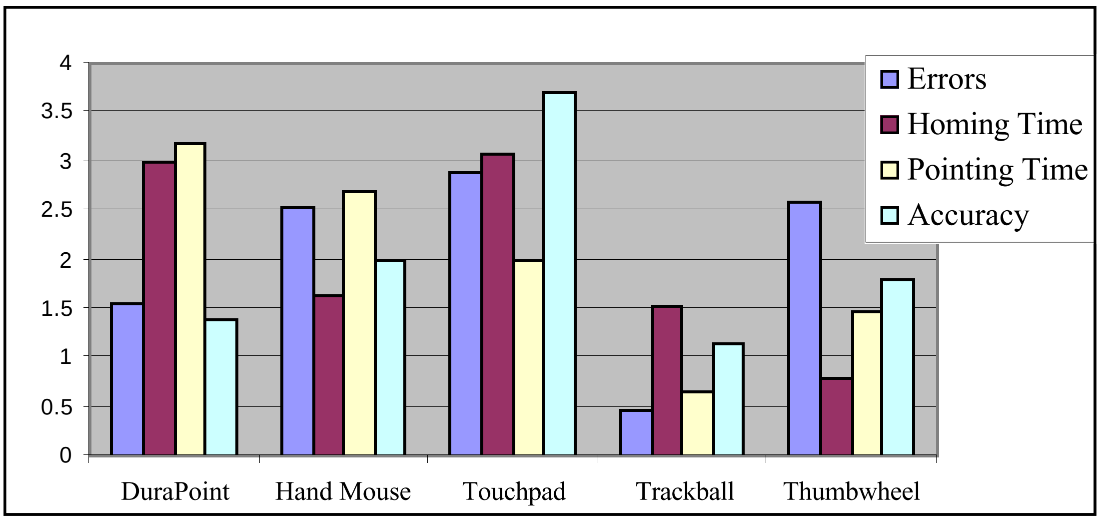

Figure 6.8. Composite results for each device with the HMD.

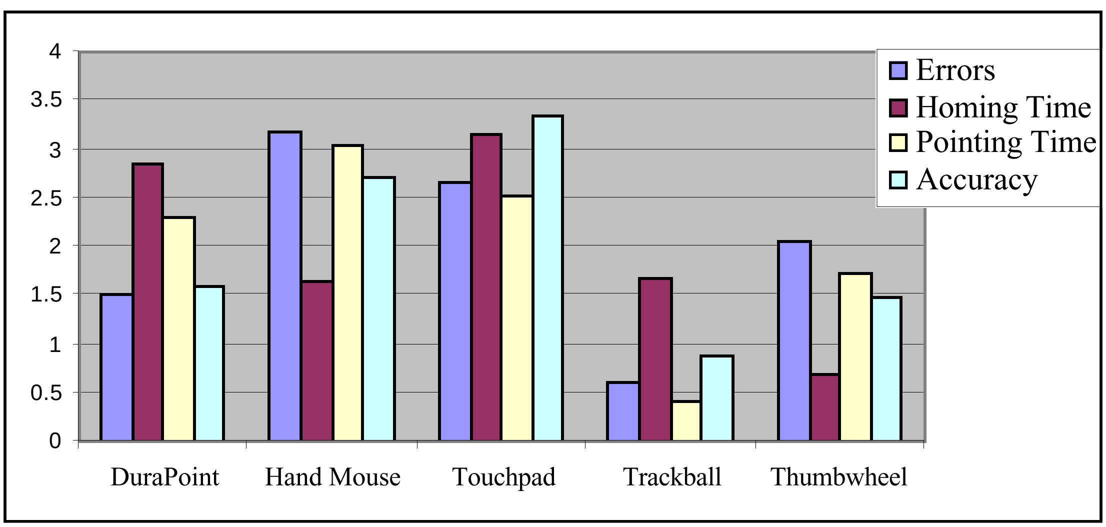

Figure 6.9. Composite results for each device with the FPD.

Fitts Law Analysis.

To determine if the pointing devices follow Fitts Law the trail completion times were plotted for each device. If the pointing devices follow Fitts Law the completion times should show an effect based on the target distance and size. The mean trail times from the last two blocks were used and Figures 6.10 shows that the times decrease as target width increases. Figure 6.11 shows that pointing time increases as the distance increases.

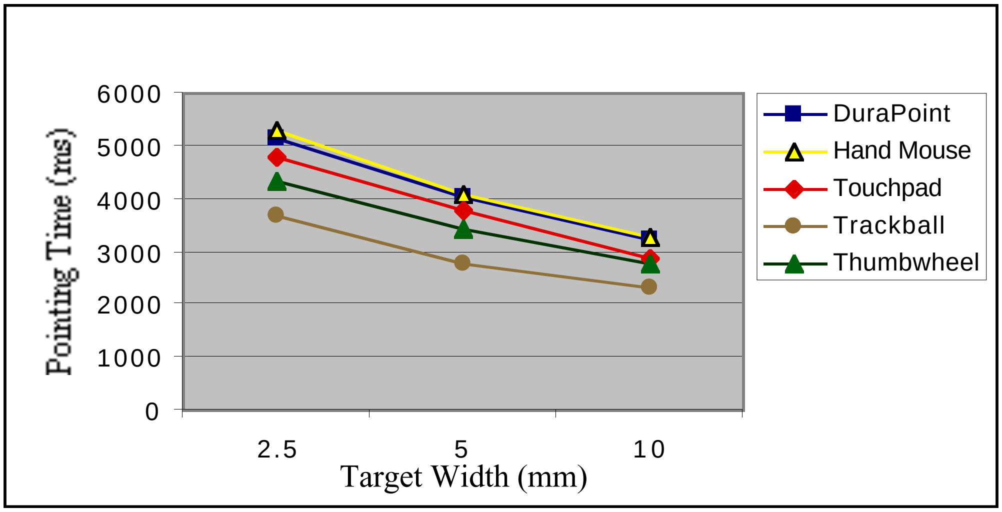

Figure 6.10. Effect of target width on pointing time, n=20.

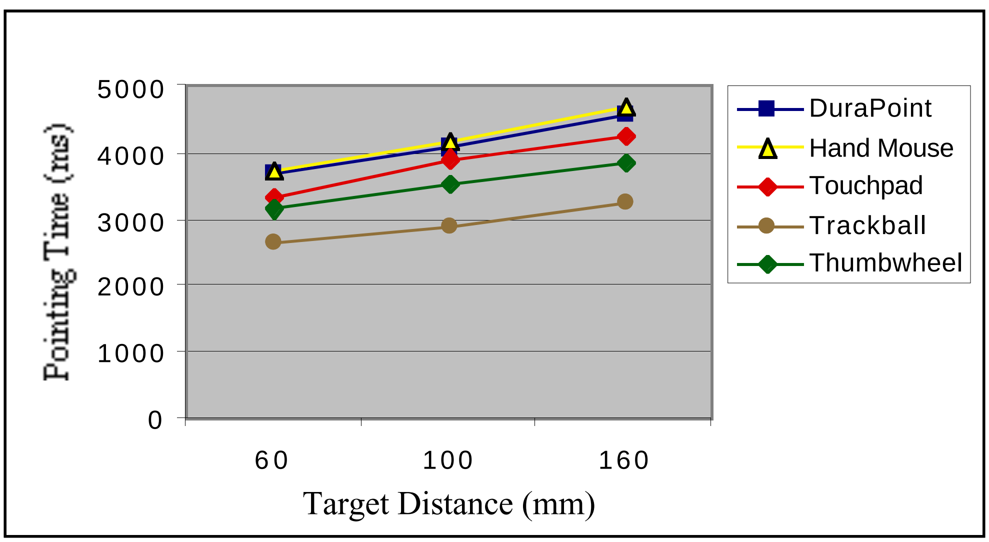

Figure 6.11. Effect of target distance on pointing time, n=20.

Using MacKenzie s formula (equation 2), the targets distance and width were combined in order to calculate the ID. Figure 6.12 plots the mean trail times for the last two blocks using the ID.

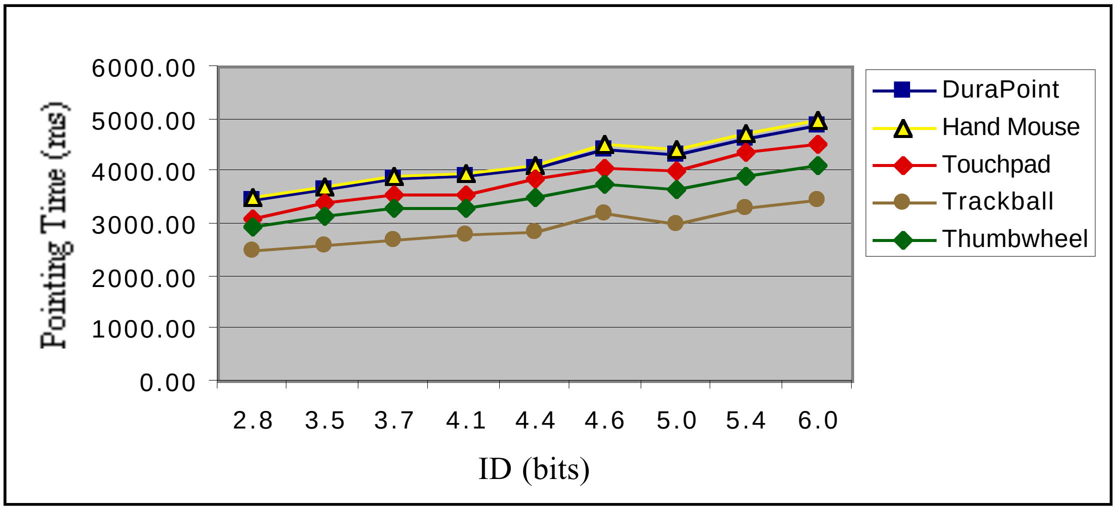

Figure 6.12. Mean pointing time using the MacKenzie ID, n=20.

An regression equation was derived based on the pointing times and ID using Microsoft Excel. The equations for each of the devices follow:

DuraPoint	MT=2221+437ID	r^2=.957	$p \leq .0001$	(4)
Hand Mouse	MT=2177+465ID	r^2=.964	$p \leq .0001$	(5)
Thumbwheel	MT=1972+354ID	r^2=.955	$p \leq .0001$	(6)
Touchpad	MT=1898+441ID	r^2=.959	$p \leq .0001$	(7)
Trackball	MT=1601+305ID	r^2=.920	$p \leq .0001$	(8)

These regression equations (r^2 and p-values) support the view that human performance with each of the pointing devices is predictable by Fitts law. Using the formula IP=ID/MT (Douglas and Mithal, 1997) the IP for each device was calculated. This calculation is the same as taking the reciprocal of the slope (1/b) in the regression equation. The resulting calculation is the IP, and it is given for each of the pointing devices that follow:

Trackball	=	3.28 bits/sec.
Thumbwheel	=	2.82 bits/sec.
Touchpad	=	2.27 bits/sec.
DuraPoint	=	2.26 bits/sec.
Hand Mouse	=	2.15 bits/sec.

The results clearly show that the trackball and thumbwheel devices out perform the other devices for pointing tasks. The hand mouse proved to be the slowest device for the pointing task.

Pointing Device Assessment Questionnaires.

Immediately after completing the pointing and homing tasks with each pointing device, the participants were asked to complete a usability questionnaire (Appendix D). The questionnaire used a 5-point Likert-type scale consisting of eleven questions covering issues of effort, speed, accuracy, comfort and overall usability. Questions 1-4 address the effort required to use the pointing devices. Questions 5 and 6 address the accuracy of the cursor movement for the pointing device. Question 7 addresses the speed in which the cursor moves. Questions 8 and 9 address the hand and finger fatigue when using the device. Question 10 addresses the comfort of using the pointing device, and question 11 deals with the overall usability of the pointing device.

Upon completing all the pointing and homing tasks, the participants were asked to complete a final questionnaire (Appendix D). Similar to the questionnaire for assessing pointing devices, this questionnaire is a 5-point Likert-type scale and was used to assess the visual displays. Questions 1 & 6 related to the ease at which targets could be seen using the visual display. Questions 2-5 related to the comfort of the visual display. Question 7 dealt with the ease at which the pointing devices could be used with the visual display. Question 8 asked the participants to rank order the pointing devices using the number 1 as the most preferred device and number 5 to represent the least preferred device. The final question solicits the participants opinion about their comfort of having tactical information presented to them on the visual display.

To test whether the responses to the pointing device questionnaire differ between the groups wearing the HMD and those wearing the FPD, the Wilcoxon-Mann-Whitney test was used. The results show a significant difference between the groups in response to several questions. As a result, the questionnaire responses from the participants wearing the HMD were assessed separately from those wearing the FPD. The means and standard deviation of the responses by the participants wearing the HMD and FPD are shown in Table 6.5.

Table 6.5.

Results of the Pointing Device Questionnaire by Visual Display.

Question	HMD									
	DuraPoint		**Hand Mouse**		**Trackball**		**Touchpad**		**Thumbwheel**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Q1	3.700	1.059	2.900	0.316	2.800	0.422	3.300	1.059	2.800	0.422
Q2	2.700	0.675	2.400	0.966	2.700	0.675	2.700	1.252	2.400	0.843
Q3	3.400	0.699	3.100	0.568	2.800	0.632	2.900	0.568	3.000	0.000
Q4	3.500	0.972	3.100	0.316	3.000	0.000	3.500	0.850	2.900	0.994
Q5	3.400	1.075	2.700	1.703	1.800	0.789	3.300	1.160	1.800	1.033
Q6	3.300	1.160	3.300	1.703	2.200	1.229	4.100	0.876	2.800	1.476
Q7	2.800	0.632	3.600	0.843	3.300	0.823	3.300	0.675	3.300	0.675
Q8	2.100	1.287	1.900	1.101	1.400	0.699	1.900	1.370	1.900	1.101
Q9	1.800	1.229	2.000	1.491	1.800	0.919	1.400	0.843	1.700	1.337
Q10	2.700	1.160	3.000	1.333	3.100	1.197	2.500	0.972	2.600	1.350
Q11	3.000	1.247	2.200	1.135	1.600	0.843	3.300	1.160	1.900	1.370

Question	FPD									
	DuraPoint		**Hand Mouse**		**Trackball**		**Touchpad**		**Thumbwheel**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Q1	3.300	0.675	2.800	0.632	2.500	0.707	3.200	1.033	2.900	0.738
Q2	3.000	0.000	2.900	0.738	3.200	0.789	3.000	1.491	2.100	0.994
Q3	2.800	0.632	3.100	0.876	3.000	0.000	3.100	0.994	3.000	1.054
Q4	3.300	0.675	2.700	0.675	2.900	0.316	3.000	1.054	2.700	0.675
Q5	1.900	1.370	2.700	1.337	1.700	0.949	3.800	1.033	2.900	1.370
Q6	1.900	1.524	2.900	1.370	1.700	1.059	4.200	1.135	3.300	1.567
Q7	2.700	0.675	3.200	0.632	3.500	0.707	2.800	0.789	3.300	0.675
Q8	1.400	0.699	1.600	0.966	1.400	0.699	2.100	1.287	1.900	1.101
Q9	1.400	0.516	1.600	0.966	1.300	0.483	1.900	1.101	1.700	0.823
Q10	2.900	1.370	3.200	1.135	3.500	1.269	2.600	0.699	3.000	1.247
Q11	1.600	0.699	2.000	1.155	1.500	0.850	3.500	0.972	2.300	1.567

A Friedman two-way ANOVA by ranks test was performed on the individual questions to determine if there are significant differences among the responses to each question across the five pointing devices. Questions 1, 5, 6 and 11 are the only questions where there was a significant difference among devices.

Question 1 asked about the force required to use a specific pointing device, and the result is presented in the following table. For this question, the participants claim that the force required to operate the durapoint device is high followed by the touchpad. The participants also indicate that the force for the hand mouse, trackball and thumbwheel was close to optimum.

Table 6.6

Friedman Test for Question #1 for participants wearing the HMD.

Device	N	Est. Median	Sum of RANKS
Hand Mouse	10	2.95	26.5
DuraPoint	10	3.75	37.0
Thumbwheel	10	3.05	26.0
Trackball	10	2.95	24.5
Touchpad	10	3.55	36.0

S = 9.73 d.f. = 4 p = 0.046

Question 5 asked about the ease at which the cursor could be moved from the home position to the target. The responses to this question was also significant among devices, and the results are shown in Table 6.7. to move a specific pointing device, and the result is presented in the following table. The results show that moving the cursor from the home position to the target was easiest with the trackball followed by the thumbwheel. The participants also reported that the cursor movement was most difficult with the durapoint device.

Table 6.7.

Friedman Test for Question #5 for participants wearing the HMD.

Device	N	Est. Median	Sum of RANKS
Hand Mouse	10	2.50	31.0
DuraPoint	10	3.40	37.0
Thumbwheel	10	2.10	22.5
Trackball	10	1.90	21.5
Touchpad	10	3.10	38.0

S = 9.70 d.f. = 4 p = 0.047

Not surprisingly, the participants responses to Question 6 also proved significant among devices. The question asked about the ease of centering the cursor, which was presented as cross-hairs, on the target. Again the trackball and thumbwheel proved to be the most preferred devices for the task. However, the touchpad was reported as the most difficult device to use for this task with a mean score of 4.1. Both the durapoint and hand mouse were recorded as neither easy nor hard for this task.

Table 6.8.

Friedman Test for Question #6 for participants wearing the HMD.

Device	N	Est. Median	Sum of RANKS
Hand Mouse	10	3.20	31.5
DuraPoint	10	3.30	31.0
Thumbwheel	10	3.00	27.5
Trackball	10	2.00	20.0
Touchpad	10	4.00	40.0

S = 10.41 d.f. = 4 p = 0.035

Finally, Question 11 also proved significant among devices. The question asked about the overall usability of the pointing devices for the target acquisition task. The trackball and thumbwheel was rated as the easiest devices to use while the touchpad was rated the most difficult to use.

Table 6.9.

Friedman Test for Question #11 for participants wearing the HMD.

Device	N	Est. Median	Sum of RANKS
Hand Mouse	10	1.55	28.5
DuraPoint	10	1.45	24.5
Thumbwheel	10	1.65	31.5
Trackball	10	1.55	21.5
Touchpad	10	3.55	44.0

S = 12.12 d.f. = 4 p = 0.017

Next, a Friedman two-way ANOVA test was performed on the individual questions for those participants wearing the FPD. Only questions 5, 6 and 11 showed a significant difference among devices. Again, question 5 & 6 related to the easy of moving the cursor for the home position to the target, and positioning the cursor in the center of the target. Question 11 asked about the overall easy of using the various pointing devices (Tables 6.10, 6.11, 6.12). For question 5 & 6, the durapoint and trackball were identified as the easiest device to move the cursor to and engage the target. For both these questions, the touchpad was the most difficult device to use for these tasks. Likewise for question 11, the trackball and durapoint were rated the easiest to use while the touchpad was rated the most difficult.

Table 6.10.

Friedman Test for Question #5 for participants wearing the FPD.

Device	N	Est. Median	Sum of RANKS
Hand Mouse	10	2.50	31.0
DuraPoint	10	3.40	37.0
Thumbwheel	10	2.10	22.5
Trackball	10	1.90	21.5
Touchpad	10	3.10	38.0

S = 9.70 d.f. = 4 p = 0.047

Table 6.11.

Friedman Test for Question #6 for participants wearing the FPD.

Device	N	Est. Median	Sum of RANKS
Hand Mouse	10	3.20	31.5
DuraPoint	10	3.30	31.0
Thumbwheel	10	3.00	27.5
Trackball	10	2.00	20.0
Touchpad	10	4.00	40.0

S = 9.70 d.f. = 4 p = 0.047

Table 6.12.

Freidman Test for Question #11 for participants wearing the FPD.

Device	N	Est. Median	Sum of RANKS
Hand Mouse	10	1.20	28.5
DuraPoint	10	2.00	35.5
Thumbwheel	10	1.00	23.0
Trackball	10	1.10	22.0
Touchpad	10	2.20	41.0

S = 10.66 d.f. = 4 p = 0.031

Summary of Pointing Devices Questionnaire.

For both groups, questions 5, 6 and 11 were significantly different. For each of these questions, the group wearing the HMD responded consistently; reporting that the speed and accuracy was best with the trackball, followed by the thumbwheel, hand mouse, durapoint and touchpad. This group also responded to question 11, which related to the usability of the device, with the same results.

Similar to the group wearing the HMD, the group wearing the FPD responded to the three questions favoring the trackball and reporting the touchpad as being the most difficult to use. The hand mouse was also reported as neither easy nor difficult to use for all three questions. For question 5, however, the group reported the durapoint as easier than the thumbwheel for moving the cursor, but the thumbwheel was rated better for centering the cursor on the target. The durapoint was rated easier to use overall than the thumbwheel.

Rank Order of Pointing Devices.

The participants were also asked to rank order the pointing devices based on their overall preference with the number one being the most preferred and five being the least preferred. A Friedman two-way ANOVA by ranks was performed. Again, the data were separated by the two groups (HMD and FPD), and the results are presented in Tables 6.13 and 6.14. For the participants wearing the HMD, there was a significance for rank by device with the trackball being the most preferred followed by the hand mouse, thumbwheel, durapoint, and the touchpad.

Table 6.13.

Friedman two-way ANOVA test of rank by device for participants wearing the HMD.

Device	N	Est. Median	Sum of RANKS
DuraPoint	10	3.500	34.0
Hand Mouse	10	2.000	24.0
Trackball	10	2.000	22.0
Touchpad	10	4.100	40.0
Thumbwheel	10	3.400	30.0

S = 8.64 d.f. = 4 p = 0.072

The participants wearing the FPD also showed a significance for rank by device with the trackball being the most preferred followed by the durapoint, hand mouse, thumbwheel and touchpad.

Table 6.14.

Friedman two-way ANOVA test of rank by device for participants wearing the FPD.

Device	N	Est. Median	Sum of RANKS
DuraPoint	10	2.400	24.0
Hand Mouse	10	3.200	33.0
Trackball	10	1.900	17.0
Touchpad	10	4.300	41.0
Thumbwheel	10	3.700	35.0

S = 14.40 d.f. = 4 p = 0.006

Summary of Rank Order.

Both groups of participants (HMD and FPD) rated the trackball as the most preferred pointing device for the target acquisition task. However, the group wearing the HMD ranked the hand mouse as the second preferred device while the group wearing the FPD ranked the durapoint as the second preferred device. Although the group wearing the FPD ranked the hand mouse as their third most preferred device, the HMD group ranked the thumbwheel device has their third most preferred. Both groups, on the other hand, rated the touchpad as the least preferred devices.

Visual Display Assessment Questionnaire.

To test whether the responses to the visual display questionnaire differ between the groups wearing the HMD and those wearing the FPD, the Wilcoxon-Mann-Whitney test was used. The results show no significant difference between the groups in response any of the questions. The means and standard deviation of the responses for both groups are shown in Table 6.15.

Table 6.15.

Results of the Visual Display Assessment Questionnaire.

Question	HMD	FPD
	Mean (SD)	Mean (SD)
1	1.7 (1.06)	1.6 (0.52)
2	2.3 (0.95)	2.6 (1.35)
3	3.1 (1.66)	3.5 (1.43)
4	2.6 (1.26)	3.4 (1.17)
5	4.0 (0.67)	3.7 (1.16)
6	1.7 (0.67)	1.9 (0.74)
7	1.9 (0.99)	1.9 (0.74)

Summary of Visual Display Assessment Questionnaire.

The participants response to the questionnaire show that both the HMD and FPD were comfortable to wear. However, the HMD users did slightly agree that the display caused eye fatigue. The participants also reported that the targets and cursor were easy to locate on both visual displays. Finally, the participants did agree that the pointing devices were easy to operated with both displays.

CHAPTER VII

DISCUSSION

As mentioned at the beginning of the thesis, the main objective of this research was to enhance wearable computer capabilities for users by ensuring that pointing device design characteristics were compatible with the uses of wearable computers. In order to achieve this goal, specific questions were investigated. These questions are presented below in more detail followed by the findings based on the results of the various analyses.

The first question of this thesis was whether there are differences in speed and accuracy between the index finger and thumb for target acquisition tasks when operating a pointing device for wearable computers? Since surface space is either limited or non-existent to a soldier wearing a computer in the field, he must rely on using one hand to operate a pointing device. This is especially true since his weapon occupies the soldier s opposite hand. The five pointing devices were specifically chosen because their operational characters could be used to answer these questions. The hand mouse and thumbwheel were both thumb-operated devices, and the durapoint, trackball and touchpad were operated with the index finger. Moreover, the hand mouse and durapoint are operated in very similar ways (applied force) but use different hand digits. The durapoint is controlled by the index finger while the thumb operates the hand mouse. Likewise, the trackball and thumbwheel are similarly operated. As the name suggests, the thumbwheel is thumb-operated and the trackball is operated by the index finger. Initial review of the results (Figure 6.4) implies that there is a difference in pointing speed between the index finger and thumb when controlling a pointing device. The mean pointing speed with the trackball was significantly faster than the mean pointing speed with the thumbwheel. Additionally, the mean pointing speed with the durapoint was slightly faster than the mean pointing speed with the hand mouse. However, the difference in pointing speed between these devices was not statistically significant. These results then indicate that if the pointing device had the same characteristics (i.e. rotating ball, forced applied button or stick, etc.), the devices involving the index finger would be faster than those involving the thumb. These findings were similar to those of (Mehr, 1973). That is, when similar devices were operated with the finger and thumb, the fastest pointing times were made when controlled by the finger. This suggests that the finger s speed over the thumb, as reported by Nieble and Freivalds (1999), has an effect on pointing speed.

Device switching (homing speed) may also effect pointing speed, and must be considered when assessing device characteristics on pointing speed. Surprisingly, the thumbwheel and trackball resulted in the best homing speed. This is surprising because it was hypothesized that the hand-held devices would solicit the fastest homing speed. If this hypothesis proved true, the thumbwheel and hand mouse would have produced the fastest performance times. The results of the questionnaire indicated that the soldiers felt comfortable using the trackball and this reason, as well as the size of the ball, could explain the trackball having the second fastest homing time. Just as surprising is the fact that the touchpad produced the slowest homing time. This was true even though the touchpad had the largest surface space to reposition the index finger to initiate cursor movement.

The soldiers response to the questionnaire also show that the touchpad was the most difficult device to use, and this probably contributed to the slow homing time. The results show that the thumbwheel produced a significantly faster homing speed over all other devices. The next fastest time was the trackball followed by the hand mouse, durapoint and touchpad. As shown in this research, there is no indication that the difference between hand digits support faster homing speeds. However, the data does suggest that overall hand-held devices do contribute to faster homing speeds. The difference between homing time for the hand-held devices and devices that were positioned on a desktop are not hard to explain. The hand-held device only required the repositioning of the hand-digit to initiate movement of the cursor. Thus resulting in a faster homing time. The lack of a hand-held device operated by the index finger, however, confounded the results as to whether the finger or thumb is quicker for homing.

Differences in accuracy among pointing devices controlled by the same hand digit. Again, the trackball, which is controlled by the index finger proved to be the most accurate device, and it was significantly more accurate than the thumbwheel device, which is operated in a similar manner with the thumb. Likewise, the durapoint proved to be significantly more accurate than the hand mouse. Applying force with the index finger controls the durapoint, whereas applying force with the thumb controls the hand mouse. The results indicate that using the index finger to control pointing devices is more accurate than the using the thumb. This result is not surprising because the index finger is controlled by smaller muscles, and thus is more accurate for finer control movement than the thumb (Oborne, 995). However, Sanders and McCormick (1993) reported that the thumb is better suited for repetitive use because the thumb makes use of stronger muscles. They noted that as a rule, frequent use of the index finger should be avoided, and thumb-operated control should be used.

As expected, similar results were found for errors. Significantly less errors were committed with the trackball than the thumbwheel. There were also more errors with the hand mouse than the durapoint. However, the difference between the hand mouse and durapoint were not statistically significant. Overall less errors were committed with the trackball and durapoint devices than the thumbwheel and hand mouse. This suggests that devices operated with the index finger are more accurate than those operated with the thumb. The reasons for this are similar to those given for accuracy.

An interesting result is that the two devices that were operated by rotating a ball proved to have the fastest pointing times, the fastest homing times, the first and third best for accuracy performance, and made the first and third least number of errors. Additionally, the soldiers rated the trackball and thumbwheel as the most usable devices. These findings suggest that the designers of pointing devices for wearable computers should include a rotating ball as an operational characteristic for target acquisition tasks.

The second question this thesis set out to answer was to determine whether pointing devices for wearable computers follow Fitts Law. The results demonstrated that target size and distance have an effect on pointing time. Fitts Law predicts that as target sizes decrease, pointing time should increase. Furthermore, as target distance increases, so should pointing time. The results of this study indicated that pointing devices for wearable computers do follow Fitts Law. Combining pointing time for the various target sizes and distances lead to the calculation of the Fitts Law ID. These results were then used to calculate the IP for each pointing device. The

IP, which Douglas et al (1997) notes as being analogous to the channel capacity, has as units, bits per second. Thus, the higher the IP the faster the device. The result reported here show that the trackball has the highest IP of 3.28 bits/sec, followed by the thumbwheel (2.82 bits/sec), touchpad (2.27 bits/sec), durapoint (2.26 bits/sec) and hand mouse (2.15 bits/sec). This finding is important for the future assessment of pointing devices. As wearable technology progresses, so will interfaces to this technology. By applying the methodology described in this thesis, novel devices can be tested and the calculated IP can be compared with the IP s of this and other research that follow the same procedures.

The third and final question of this thesis was to determine if there was a significant performance differences between the visual displays when operating the devices. The results show that there was no significant difference between displays. Again, this was an important finding because up to this point only the HMD was considered with wearable computers for soldiers. Reducing the field-of-view of SOF soldiers, who are assigned special missions and usually operate in small teams, could be detrimental to accomplishing the mission. The results of this research have shown that an alternative arm-mounted display is equally effective for target acquisition tasks. This allows mission planners to choose between displays based on tactical demands.

CHAPTER VIII

CONCLUSIONS

Developers are quickly designing wearable computers that can be used various environments. These wearable computers are expected to allow users to quickly transmit and receive information to assist them in performing their work. The software interface on these computers should allow users to manipulate the various menus and information through a series of point and selection type tasks. As a result, the design of the pointing device will contribute significantly to the overall usability of the system. The following findings and recommendations are provided to support the designers, researcher and engineers of wearable computer technology that could eventually be used by soldiers.

Design Guidelines

The following guidelines are based on the findings of this study:

¥ A rotating ball should be incorporated into the design of a pointing device.

¥ The thumb should be used as the primary digit to operate the cursor device.

¥ If the pointing device is a hand-held device, it should be designed in such a way that it can be easily controlled by the thumb. If the rotating ball is going to be embedded onto the weapon, it should be design so that it can be easily controlled with the index finger.

¥ A touchpad device should be avoided as a design consideration for wearable computers because the participants reported the touchpad as being the most difficult and frustrating device to use, they also were less accurate with the touchpad, and they made significantly more errors with this device.

Although the pointing device design, which includes a rotating ball, is recommended, there are several other issues relating to pointing devices that remain unanswered and must be researched before an agreement is made on the final design. These issues are discussed in the next section.

Further Research.

The gap in the literature that served as the motivation for this research has been partially filled by this thesis. However, future research implications resulted from these findings. The first implication is the task that was performed for this research. For this thesis, pointing and homing time were two important considerations for the design of pointing devices. A third task, dragging objects, is another important consideration. Dragging objects to various positions on the screen is much like pointing and selecting objects. However, there is an additional difficulty involved with this task. With desktop pointing devices, a button is usually held down while a dragging action is performed. With a hand-held device, the operator will likely on have one digit of the hand available for manipulating the pointing device. As a result, the operator will not be able to hold down a device button and simultaneously manipulate the cursor movement. An additional design consideration must be employed to allow the button to be held down during a dragging action.

The effects of the environmental factors must also be considered in the design of pointing devices for the soldiers. This research took place in a controlled laboratory environment. The effects of dirt, water, heat, cold, noise and vibration on the performance of the pointing devices was not tested. These are important considerations when designing devices for outdoor use because it is highly likely that they will be exposed to different environmental conditions. In this study, we have recommended the design of device that includes a rotating ball. Thus, the design includes moving parts. These moving parts are likely to be effected by environmental factors unless these concerns are engineered in a way to protect them from these factors. For instance, advances in trackball development now allow them to be operated in sealed servo mounts, which protect them from dirt and other debris. Further research on how environmental factors effect user performance while operating pointing devices is necessary.

Finally, the workload placed on the user while performing the pointing tasks was minimum. Many users, like soldiers, are likely to travel several miles while carrying loads that weigh several pounds. This obviously will effect the fatigue level of the soldiers, which may also effect their performance with the pointing devices. Thus, the design of pointing devices must also consider the physiological state of the soldier using the device.

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