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Effectiveness of haptic feedback coupled with the use of a head-mounted display for the evaluation of virtual mechanisms

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Signatures have been redacted for privacy

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Abstract

Adequate immersion in virtual environments is a key to having a successful virtual simulation experience. As people have more of a sense of "being there" (telepresence) when they experience a virtual simulation, their experience becomes more realistic and therefore they are able to make valid assessments of their environments. This thesis presents the results of a study focused on the evaluation of participants' perceptional and preferential differences between a haptic and non-haptic virtual experience coupled with the use and non-use of a head-mounted display (HMD). Several measurements were used in order to statistically compare the performance of participants from four groups, haptic with the HMD, non-haptic with the HMD, haptic without the HMD, and non-haptic without the HMD. The study found that the virtual environment (VE) display type, either HMD or desktop monitor, affected participants' ability to detect mechanism differences related to motion, arm length, and distances (mechanism length and location) as well as influenced the amount of time required to evaluate each mechanism design during trial one. The treatment type (haptic or non-haptic) affected participants' ability to estimate mechanism differences, influenced the detection of mechanism arm length differences, and resulted in differences in the amount of time needed to evaluate each mechanism design. Regardless of which treatment participants initially experienced, participants overwhelmingly preferred the haptic treatment to the non-haptic treatment. The results of this study will help scientists make more informed decisions related to haptic device utilization, as well as head-mounted display use, an the interaction of the two. Several recommendations for future human factor studies related to haptic sensation, HMD use, and virtual reality are also included.

CHAPTER 1. INTRODUCTION

Merriam-Webster's 10^{th} edition Collegiate Dictionary (1998) defines virtual reality as "an artificial environment, which is experienced through sensory stimuli (as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment". The goal of any virtual reality (VR) experience is to lead users to believe that they are interacting with real objects as opposed to computer generated ones. It is only natural to assume that as more of a person's five senses (sight, sound, touch, taste, and smell) become integrated into VR experiences, he/she will feel more of an illusion of presence in the virtual environments.

One of the greatest benefits of VR systems is that if virtual environments (VE) can be designed that are more similar to the real world, people will be able to apply their knowledge of everyday life skills to manipulating and experiencing the virtual objects. Consequently people will be able to learn to use computer software more rapidly and effectively. The majority of today's VR simulations use relatively realistic visual and auditory cues to help participants become immersed in the environment; but VR simulations that provide good touch information (haptic feedback) are just now starting to be used more frequently (Arsenault and Ware, 2000, Burdea, 2000, Dachille et al., 2001). Taste and smell information have not yet proven to be essential in most VR simulations (Burdea, 2000)

One of the common uses of VR is in product design, specifically virtual prototyping. Virtual prototyping is the process in which a new design is created and/or evaluated on a computer without the need to build a physical prototype. The benefits of virtual prototyping include: reduced cycle time, reduced cost, and the ability to create more interactive and efficient engineering design process (Chen, 1999). Although VR is being used frequently, industry is still concerned with answering the question – what product evaluations are valid to make in a virtual environment, and what VR tools are needed?

The research presented in this thesis evaluated the effectiveness of haptic feedback coupled with the use of a head-mounted display (HMD) for VE using several quantitative measurements. The results of this study will help scientists make more informed decisions related to haptic device utilization, as well as HMD use, and the interaction of the two.

OBJECTIVES

Adequate immersion in a VE is one of the keys to having a successful virtual simulation experience (Sheridan, 2000). As people have more of a sense of "being there" (telepresence) when they experience a virtual simulation, their experience becomes more realistic and therefore they are able to make valid assessments of their environments (Ruddle et al., 1999). Many research projects are now underway to determine the best possible way to effectively immerse participants in a virtual environment, and to evaluate the effect of doing so.

This thesis presents the results of a study focused on the evaluation of participants' perceptional and preferential differences between a haptic and non-haptic virtual experience coupled with the use and non-use of a HMD. Haptics is defined as the force feedback that is relayed back to the user during a VE simulation. The possibility of cross-modal sensory illusions is also discussed.

Organization of the Thesis

Chapter 2 gives a brief overview of VR technology, an introduction to haptic devices, and an introduction to HMDs. The experimental design as well as the organizational set-up of the study is discussed in Chapter 3. Chapter 4 presents the results of the data analyses, as well as observations made by the researcher during the study trials and their possible affect on the outcome of the experiment. Conclusions of the experiment and suggestions for future research are discussed in Chapter 5.

CHAPTER 2. IMMERSIVE VIRTUAL ENVIRONMENTS, HAPTIC DEVICES, AND HEAD-MOUNTED DISPLAYS

IMMERSIVE VIRTUAL ENVIRONMENTS

VR first appeared in the technological world in 1965 when Ivan Sutherland, then an associate professor of electrical engineering at Harvard University, proposed the Ultimate Display and built the first HMD using cathode ray tubes and a ceiling suspension system (Sutherland, 1965). Since that date, virtual reality has become a rapidly developing technology that involves many aspects of computer-augmented visualization (Cook et al., 1998).

The fundamental characteristic of VR technology is that it enables users to become immersed in the virtual environment (VE) presented to them. An immersive VE is a virtual world with which the user interacts, using devices that block out all elements of the real world that are not part of the virtual experience (Lindeman et al., 1999). Successfully becoming immersed in a VE requires the user to construct a mental model of how the world is perceived, based on the users' interaction with visual, aural, and tactile cues from the VE (Biocca, 2001). "To realize the full promise of VEs, haptic displays with force and/or tactile feedback are essential" (Srinivasan and Basdogan, 1997, page 393). Being able to touch, feel, and manipulate objects in a VE, in addition to seeing (and hearing) them, provides a sense of immersion to the user that is otherwise not possible (Srinivasan and Basdogan, 1997). Lindeman et al. (1999) determined that haptic feedback, coupled with a hand-held device, could greatly aid a participant's interaction in immersive VEs. Chen confirmed this notion by determining that the realism of virtual prototyping applications can be considerably improved by the addition of six degree-of-freedom force and torque feedback (Chen, 1999).

Today's VR technology prohibits complete user immersion due to the fact that the human eye is able to distinguish current computer-generated simulations from real experiences. Sound technology is closest to achieving simulated sounds that to the human ear are indistinguishable from the real thing (Sheridan, 2000). In the haptic realm, artificial touch and force feedback displays are not as highly developed and are currently unable to fully simulate the feelings of touch and force.

Salisbury and Srinivasan (1997) noted however, that to have a successful virtual experience, a VE does not have to be a perfect replication of reality; it only needs to match the abilities and limitations of the human sensory, motor, and cognitive system.

Humans' Sensory, Motor, and Cognitive Limitations

The information capacities for the fingertip, ear, and eye are $10^2 : 10^4 : 10^6$ bits/second respectively (Repperger et al., 1995). Although a human's sense of touch has the lowest information capacity, Repperger et al. (1995) determined that visual information gathered during a VR simulation could be supplemented with appropriate tactile and force information to improve the user's telepresence.

"Real-time" virtual graphical environments seek to achieve visual refresh rates of 30 to 60 Hz due to the fact that human's eyes generally cannot detect motion that occurs at higher frequencies. Although the nervous system of human beings can only perform tactile tasks at the order of 10-20 Hz, humans can sense small movements up to 1000 Hz (Dachille et al., 2001). To create convincing sensations of touch, the haptic loop must occur at an extremely high rate – typically, 300 to 1,000 Hz (Balasubramaniam et al., 2002, Burdea, 2000, Hasser and Massie, 1999). Time delays from distributed simulations disturb haptic feedback more than visual feedback (Hasser and Massie 1999).

Repperger et al. (1995) noted that the stimulus – response reaction times for force versus visual stimuli were approximately 70 ms versus 160 ms. Therefore, to find a target in the least amount of time, people using their sense of touch were more efficient than people who relied on their sense of vision.

Tactile sensory capabilities are most acute on the finger pad. Spatial location of a point is detectable to within 0.15 mm and the spatial resolution of two points is about a millimeter. Kinesthetic resolution is about 2 degrees for the fingers and wrist, and about 1 degree for the shoulder. Fingertip positional resolution is in the range of 0.5 to 2.5 mm during grasping objects of 1 to 80 mm length (Srinivasan and Basdogan, 1997).

The maximum exertable force for the human finger is on the order of 40 to 50 N, but during precise manipulation people rarely exert peak forces larger than 10N. In fact, the time-averaged force exerted during normal operation of the human finger is closer to 1 N (Hasser and Massie, 1999).

Haptic Devices

Haptics first immerged in a very crude form in the 1940s; remote manipulation systems were used for handling hazardous substances when the danger of working with nuclear materials necessitated developing remotely controlled devices (Salisbury and Srinivasan, 1997). Haptics includes both force feedback (simulating an object's hardness, weight, and inertia) and tactile feedback (simulating surface contact geometry, smoothness, slippage, and temperature) (Burdea, 2000). This thesis focuses on evaluating the use of the force feedback aspect of haptics in product evaluations.

Haptic interfaces increase the quality of human-computer interaction by integrating the sense of touch into the simulation. Of all the senses, only touch is bi-directional. Bi-directional refers to humans' ability to mentally and physically sense the location and geometry of an object and change the location and/or geometry of that object simultaneously (Massie, 1998). By using haptics in a virtual design environment, designers are able to feel and deform objects in a natural three-dimensional (3D) setting, rather than being restricted to 2D images for input and output. An ideal haptic interface should provide an easy way to control the position and orientation of a virtual object in 3D space. It should also provide the user with useful object contact information. A traditional computer interface with a mouse as an input device fails to provide an intuitive 3D interface for the user because the mouse is a 2D input device while a real object in free space has six degrees of freedom (x, y, z, roll, pitch, yaw) (Chen, 1999). Direct physical operations on virtual objects with a mouse are not as natural and intuitive as interaction using a 3D interface (Dachille et al., 2001).

The addition of force-feedback to a VE also reduces the user's dependence on visual feedback, which is beneficial if vision does not give the user sufficient information about the VE. With a haptic device, the user still is able to explore the simulation and gain additional information beyond just the visual feedback (Hasser and Massie, 1999).

Haptic information provides many benefits to users for interacting in both physical and digital 3D environments, including: "providing feedback to help position objects accurately in 3D space, resolving visual ambiguities by letting users feel the models, communicating physical properties of objects, and letting users naturally and continuously manipulate models" (Massie, 1998, page 65).

Haptic-based human-computer interactions that allow users to experience realistic tactile exploration and manipulation are also beneficial due to the fact that they are much more intuitive than traditional 2D input devices. By using intuitive force-feedback controls, designers, artists, as well as non-expert users, can feel the model representation and modify the object directly, thus enhancing the understanding of object properties and the overall design. Collaborative design processes involving artists, computer programmers, engineers, etc., can be accomplished more easily by using haptic interfaces (Dachille et al., 2001).

Haptic Device Requirements

Massie and Salisbury (1994), who together developed the PHANToM™ haptic device, determined that the generation of haptic cues to create virtual objects required the ability to

1) Track motion of the user
2) Detect collision between the user controlled probe (virtual finger tip) and the virtual object
3) Compute reaction forces in response to contact and motion
4) Exert forces on the user

By stressing design principles of low mass, low friction, low backlash, high stiffness, low back drive friction and inertia (which simulate free-space), Massie and Salisbury designed the PHANToM™ haptic device as a system capable of presenting convincing sensations of contact, constrained motion, surface compliance, surface friction, texture, and other mechanical attributes of virtual objects.

Hasser and Massie (1999) stated that haptic interfaces should be capable of peak forces 20 to 30 percent of the human maximum and continuous forces 3 - 15 % of the human maximum. Therefore, desktop interfaces with a maximum exertable force of 10 N, roughly 10 % of the maximum human fingertip force, can represent a realistic VE in which a conscious effort is required to drive through virtual obstacles.

The PHANToM™ arm (illustrated in Figure 2.1) has six degrees of freedom, and three electrical actuators. The PHANToM™ model shown in Figure 2.1 (Burdea, 2000) has a thimble finger attachment while the model used for this study used a stylus pen.

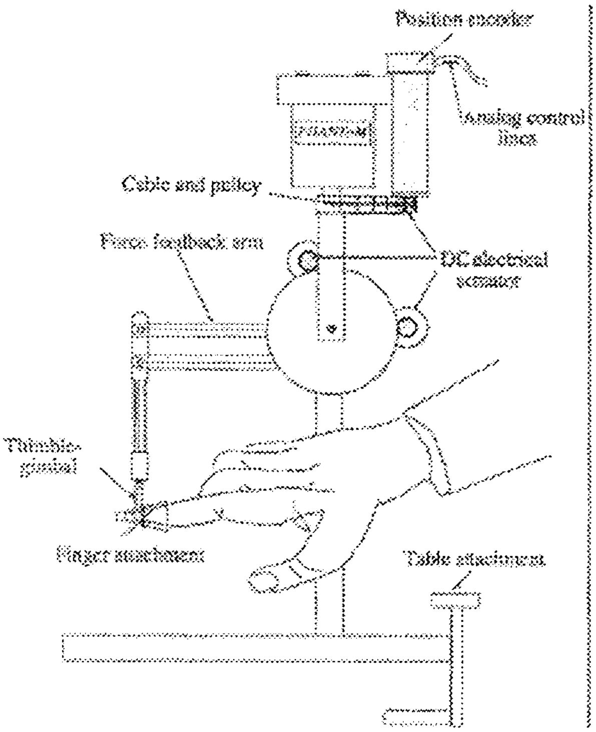

Figure 2.1. The PHANToM™ Arm (Burdea, 2000)

EXPERIMENTAL RESULTS WITH HAPTIC DEVICES

To date, there have been several studies performed by researchers to evaluate the effect of haptic sensation upon humans' performance in virtual simulations. The results are somewhat contradictory. Arsenault and Ware (2000) conducted a study in which participants underwent a Fitts tapping task (rapid tapping task whereby subjects tap back and forth between two targets). They found that participants who experienced force feedback committed fewer errors than participants who did not experience the force feedback. When force feedback was combined with head tracking, the performance in the Fitts tapping task improved by 20% and participants committed fewer errors. In an experiment designed to compare user performance with haptically enhanced buttons using four different haptic effects (texture, friction, recess, and gravity well) in a simple targeting task, Oakley et al. (2000) also found that participants who experienced the haptic effects made significantly fewer errors. In the same study, the results indicated that the haptic effects did not improve users performance in terms of task completion time. However, the lack of effect of the haptic treatment on task completion time found by Oakley et al. is contradicted by a study done by Lindeman et al. (1999) in which the addition of passive-haptic feedback (i.e., a physical work surface) to immersive VE interfaces was found to significantly decrease the time necessary to perform user interface tasks (subjects performed 44% faster on docking tasks, and 17% faster on selection tasks with haptic feedback present).

Hasser and Massie's work (1999) supported the finding that determined that force-feedback reduces task completion time. In addition they also found the following advantages to using haptics:

- Reduces training time.

- Reduces dependence on vision for some tasks.
- Reduces errors.
- Increases sense of immersion in VEs.

The research presented here follows from previous work of Volkov and Vance (2001) where it was found that the participants who experienced the haptic treatment took significantly less time to evaluate the virtual prototypes than the participants who experienced the non-haptic treatment. Volkov and Vance also found that the addition of haptics had no effect on the number of errors committed by the participants who experienced the haptic treatment compared to the non-haptic participants.

HEAD-MOUNTED DISPLAYS

Visual information can be delivered in a variety of ways. Desktop displays and HMDs are two common systems. One of the primary differences between HMDs and desktop displays lies in the device that users use to control their direction of view. Using a HMD, head and body movements control the view while a mouse or keyboard control the view when using a desktop display (Ruddle et al. 1999).

By using a HMD as opposed to a desktop monitor, participants become more fully immersed in the VE due to the fact that all outside visual distractions are blocked from their view (Ruddle et al., 1999). The user's sense of presence varies between "being inside" the immersive VE of the HMD and "looking into" the desktop monitor. Although HMDs completely block out the physical world that surrounds participants, it has been shown that this full immersion is not a large enough factor to completely create a sense of presence to the participants (Arns, 2002).

Experimental Results with Head-mounted Displays

Lathrop and Kaiser (2002) performed an experiment that examined perceived spatial orientation of participants in a small environment as a function of experiencing that environment under three different conditions: in the real world, through a desktop display (DD), or through a HMD. Their results indicated that participants who performed the task in the real world or by using a HMD were significantly more consistent in relaying the remembered direction of a previously seen target than participants who performed the task by using the DD. In the same study, the results showed a significant difference in exhaustive search times of the participants, favoring body and head rotations for controlling viewpoint over keyboard or mouse inputs (Lathrop and Kaiser 2002).

Ruddle et al. (1999) asked participants to use a HMD or DD to learn the layouts of two large-scale VEs through repeated, direct navigational experience. They determined that the participants who used the HMD navigated the buildings significantly more quickly and developed a significantly more accurate sense of relative straight-line distance than the DD participants. In the same study, it was also found that participants who used the HMD explored their VE significantly more than the participants who used the DD. The most likely explanation for the behavioral difference may be that the HMD provided a more intuitive interface (head and body movements) for participants to change viewing directions, as opposed to the desktop interface (holding down a mouse button).

Although HMD use can prove to be more consistent and time effective than traditional desktop displays, drawbacks of HMD use have also been found. For example, Howarth and Costello (1996) found that the use of immersive virtual reality equipment (such as HMDs) for around twenty minutes in an interactive situation can cause physiological changes in the visual system and can bring about the onset of symptoms such as nausea, disorientation, dizziness and drowsiness, similar to those experienced during motion sickness. The field of view (FOV) in most HMDs is no more than 60° wide – far narrower than humans' normal FOV (about 200° wide). Restricting a person's FOV to 50° or less in an HMD has been shown to degrade participants' task performance (Arthur, 2000), as well as yield apparent motion of the participants' viewpoint in eccentric paths that is sometimes quite disturbing to HMD users (Psotka et al., 1998). Restricted FOVs of HMDs also increases the angle to which (and the number of times) users must rotate their head in order to notice what they are walking past when navigating in VEs (Ruddle et al., 1999).

MULTIMODAL VIRTUAL ENVIRONMENTS

Multimodal VEs that combine the visual, haptic, and auditory sensory information are essential for designing immersive virtual worlds (Srinivasan and Basdogan, 1997). However, merely adding more sensory information does not necessarily improve participants' performance in virtual simulations. The use of multiple sensory modalities may improve, disrupt, or not affect performance depending on whether the sensory modalities interact synergistically. Both perception and performance may suffer if the sensory modalities do not have the appropriate compatibility (Repperger et al., 1995).

Vision is not treated as substitutable for touch; the two modalities are useful for learning different aspects of objects (Klatzky et al., 1993). A haptic display by itself, can give users a realistic feel of the virtual objects presented in the simulation. Combining haptics with visual and auditory feedback allows users to take advantage of the human ability to synergistically integrate sensory information into a more convincing virtual experience (Salisbury and Srinivasan, 1997). Information from one modality, such as visual, can interact with information from other modalities, such haptic, to enhance the properties of the virtual illusion in an interacting modality, thereby "filling in" information or clarifying information in another modality (Biocca et al., 2001).

It is intuitive to believe that a participant's virtual experience would be enhanced if more of his or her senses were utilized in the simulation. However, if the user experiences discrepancies in information from his or her different senses, his or her perception can be altered. In VEs, it is not uncommon for the visual location of the hand and the feeling of the hand location to be misaligned and discrepant. When visual and proprioceptive (sensory information about the state of the body, i.e. kinesthetic) cues of the location of the hand are discrepant, the participant's visual sense of their perceived hand location or a haptic stimulus to their hand location will dominate over kinesthetic senses (Biocca et al. 2001, Klatzky et al. 1993, Srinivasan and Basdogan 1997).

Cross-modal Transfer

When building a spatial mental model of the VE, users of immersive virtual reality systems sometimes experience a form of cross-modal transfer or synesthesia. A cross-modal transfer is defined as "a perceptual illusion in which stimulation to a sensory modality connected to the interface, such as the visual modality, is accompanied by perceived stimulation to an unconnected sensory modality that receives no apparent stimulation from the VE, such as the haptic modality" (Biocca et al., 2001, page 247). Participants in VEs sometimes experience visual-to-haptic cross-modal transfers when manipulating objects. As users experience higher levels of presence, they are more likely to report cross-modal illusions in the VEs they experience (Biocca et al., 2001). Massie and Salisbury (1994) found that many users of the PHANToM™ claim that they can "see a sphere" after touching a virtual sphere with the PHANToM™ stylus even without visual feedback.

The goal of this study was to evaluate how a haptic device, coupled with a HMD, affects the ability of a person to make design decisions based on the virtual mechanisms presented to them. The study evaluated how the participants' design evaluation time was affected, as well as the participants' accuracy in determining design differences between two different virtual mechanisms. The study also took into consideration participants' treatment preference (haptic or non-haptic) for the different tasks that were presented to them. Chapter 3 gives the description of the experiment that was conducted.

Chapter 3. Description of the Study

The goal of the experiment was to evaluate how haptic force feedback and the use of a HMD affect human ability to evaluate designs, and human ability to detect and estimate differences between alternative mechanism designs. Four separate groups of people performed similar mechanism design evaluation tasks under four different treatments. The first treatment group worked with the haptic treatment without the use of the HMD. The second treatment group worked with the non-haptic treatment, also without the use of the HMD. The third treatment group experienced the haptic treatment, with the use of the HMD. Finally, the fourth treatment group did not experience the haptic treatment, but did use the HMD. Both the haptic and non-haptic participants used the PHANToM™ haptic device, however the forces were not activated for the non-haptic participants. The first two treatment groups, the participants who did not use the HMD, participated in the experiment in 2000 as part of Sergei Volkov's master's thesis research (Volkov, 2000). The analysis of results from this current research will include a comparison using Mr. Volkov's experimental results as well as results from this research. The data from the four groups were analyzed in order to determine if the haptic treatment or the use of the HMD affected participants' performance, and also if there was any interaction between the haptic/non-haptic treatment and the HMD/non-HMD use.

Participants

Sixty-five students and employees of Iowa State University (ISU) volunteered to participate in the recent study. Ninety-two students and employees of ISU participated in the earlier experiment. Participants were recruited through personal invitations and presentations given in beginning mechanical engineering courses. The participants were not paid for their participation. Data from three participants in the current study were disregarded due to incomplete pilot study sessions (one participant reported the onset of nausea caused by the simulation); data from 16 participants in the previous study were disregarded due to incomplete reports or incomplete pilot study sessions. Therefore, study conclusions were based on a total of 62 participants with the use of the HMD, and 76 participants without the use of the HMD; combining for 138 participants overall. There were 31 participants in each of the HMD groups (haptic and non-haptic) and 38 participants in each of the non-HMD groups. To ensure that each group had a similar representation of participants, groups were compared in terms of age, gender representation, vision quality, level of education, experience with computers, and how comfortable each participant was with learning new applications. The average age of the current study's participants was found to be 25.8 years while the previous study had an average participant age of 24.2 years, combining for an average age of 24.9 years overall. The participants were 78.1% male and 21.9% female in the previous study, while there were 82.3% male and 17.7% female participants in the recent study. Overall, there were 78.3% male and 19.7% female volunteers. All participants had normal, or corrected-to-normal vision; the participants who had corrected-to-normal vision were asked to wear their normal vision correction for the experiment. No participants had anything more than trivial previous exposure to the PHANToM™. All other comparison factors were relatively similar.

Task Overview

In both experiments, the current and previous, each participant went through an introductory session, four trials, and an alternative treatment experience, either haptic or non-haptic. In each trial, the participant was asked to detect and estimate differences between two alternative designs of a parking brake mechanism.

The parking brake mechanism consisted of a virtual parking brake placed in a specific location of a virtually simulated car interior (Figure 3.1). Participants were able to move the parking brake through its normal range of motion (rotation) using the PHANToM™ stylus pen and were asked to mentally determine the location and motion of the parking brake.

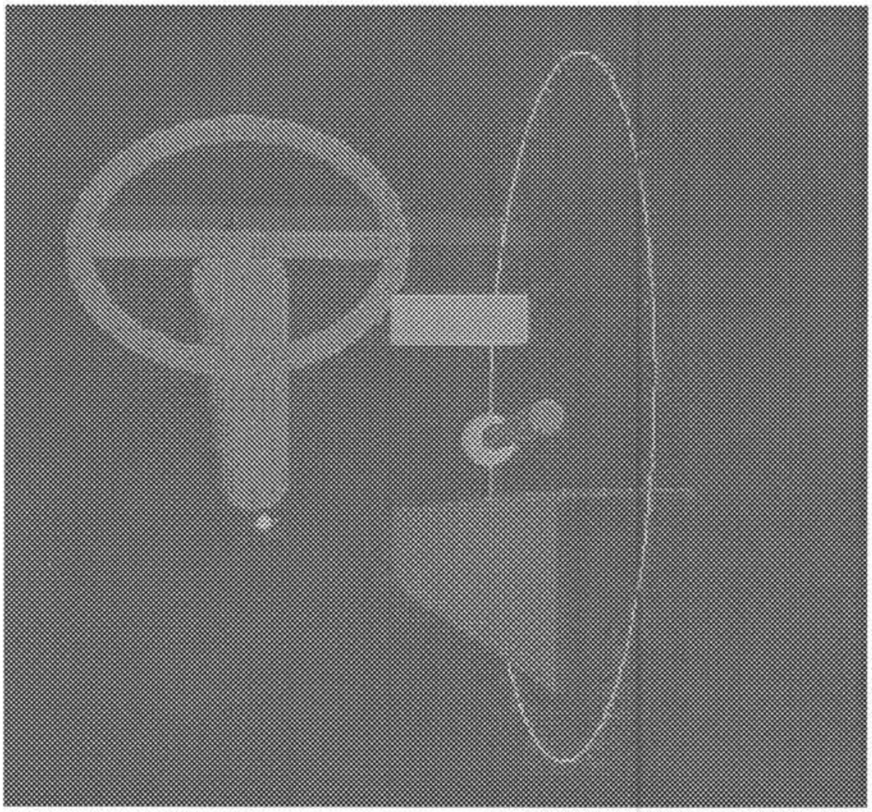

Figure 3.1. VE shown to participants who used the HMD

Each trial had a unique set of differences between mechanism one and mechanism two, in terms of parking brake location and parking brake arm angle of motion and length. Following the four trials, each participant was allowed to experience the alternative treatment (haptic or non-haptic) in order for the participant to develop a treatment preference for performing a variety of design evaluation tasks.

Before each experiment began, participants filled out a survey form concerning general background information (Appendix A). During the study, participants completed a questionnaire form (Appendix B) immediately after each trial. The researcher kept track of the amount of time that each participant required to evaluate each mechanism on a separate form (Appendix C). Table 3.1 shows the type of design differences that existed between the alternative designs of a parking brake for each trial, as well as a numerical value with a sign defining the direction of the design differences. The first parking brake design in each trial was identified as mechanism one (the base design). Participants were asked to evaluate changes in mechanism two as compared to mechanism one. Table 3.1 shows the differences between mechanisms one and two for each trial.

Table 3.1. Design differences between mechanisms one and two (linear values are in inches; angular values are in degrees)

SURVEY	TRIAL 1		TRIAL 2		TRIAL 3		TRIAL 4	
Question # / type	Direction	Value	Direction	Value	Direction	Value	Direction	Value
1) Left-right location	Left	-0.875	Right	0.875	Same	0	Same	0
2) Up-down location	Up	0.875	Up	0.875	Same	0	Same	0
3) Forward-rearward location	Rearward	0.875	Forward	-0.875	Same	0	Same	0
4) Arm length	Same	0	Same	0	Longer	0.875	Longer	0.875
5) Angle of motion	Same	0	Same	0	Smaller	-8.59	Larger	8.59

DATA COLLECTION

The data collected in each experiment were analyzed in four different categories to help determine the effect of experiencing the haptic and non-haptic treatments, and the effect of the use of the HMD.

During each of the four trials, each participant was asked the same five questions regarding possible location and/or motion changes between mechanisms one and two (Appendix B). There were three possible parking brake arm location differences between the two design mechanisms: the parking brake arm could have moved either to the left or to the right from mechanism one to two, or it could have stayed in the same location; it could have moved either higher or lower from mechanism one to two, or remained in the same location; or the parking brake arm could have moved further towards the front of the simulated car interior or the rear from mechanism one to two, or remained in the same place. There were two possible parking brake arm angle of motion differences between the two design mechanisms: the parking brake arm could have a longer or shorter radius of motion in mechanism one than in mechanism two, or the radius of motion could remain the same; and finally, the parking brake arm could have a smaller or larger angle of motion in mechanism one than in mechanism two, or the angle of motion could remain constant. The information gathered allowed an evaluation of whether or not using the haptic or non-haptic treatment and/or the HMD or non-HMD had an influence on how successful participants were in detecting differences between the alternative designs.

If a participant determined that he/she detected a difference between mechanisms one and two, the participant was asked to estimate the amount of his/her perceived design difference. The participants' estimated values were compared against the actual values to calculate the error of each participant's estimation. This was the second set of data that were collected. The estimations were evaluated to determine if there was any effect of the use of the HMD or non-HMD, as well as the haptic treatment or the non-haptic treatment on the precision of people's estimations.

The third set of data collected was the time that each participant required to evaluate both mechanism one and mechanism two in each of the four trials. Participants were allowed to take as much time to examine each mechanism as they felt was necessary, but they were informed that the time they used would be recorded. The time required for each participant to understand each mechanism was recorded to determine if there was any effect of either of the variables (presence of haptics or display type) on the time required for design evaluation.

The fourth set of data collected evaluated the participants' treatment preference. After each participant completed each of his/her four trials, he/she was allowed to try the alternative treatment (either haptics or non-haptics). Participants were asked to record their treatment preference for performing a variety of design evaluation tasks (Appendix B). This information was collected to determine the overall preference of participants for either the haptic treatment or the non-haptic treatment in different design evaluation situations.

Experiment Session

The researcher and each study participant decided on a mutually agreeable time to schedule an individual experiment session, which on average required 45 minutes. At the beginning of each session, the participant flipped a coin to determine which of the two treatments he/she would experience (heads = haptics, tails = non-haptics). While each participant filled out the first two pages of general survey information on the questionnaire (Appendix A), the researcher set up the appropriate treatment and prepared the PHANToM™ and application for the procedure.

After the participant had filled out the survey, he/she sat in a chair with the haptic pen located on his/her right in approximately in the same location an actual parking brake would be located in a real car interior. In each of the studies (previous and recent), the researcher explained how the equipment worked and discussed the goals of the study. Due to the fact that two different study populations were combined into one data set, it was extremely important that all participants had the same information about the study presented to them in the same manner. The participants in the most current study were read the following instructions before each experimental session by the researcher. The information was taken directly from Mr. Volkov's research notes.

"A haptic device is any device that provides force information in a realistic physical form. The PHANToM™ is the device used in this study. The PHANToM™ is designed with a pen that is attached to a mechanism with connected levers. The pen has a clicking button that may allow you to perform different functions defined by an application in the same manner as a computer mouse button. The haptic pen is represented in virtual form on the screen of the computer as a small pink ball. The tip of the virtual pen is located in the VE in correlation with the location of the actual pen tip in the real world. This arrangement allows you to touch and feel objects in the VE.

The application used for this study involves virtual prototypes of a car interior design and the task is to investigate alternative designs using the haptic device. You are to assume that you are sitting in an actual car seat and that you are reaching and moving parts of the car interior design in a way as if these parts were not virtual, but real and located around you.

In order to hold the virtual part, you should position the tip of the virtual pen inside a red area located on the part. At this time, you can click the pen button and keep it pressed. When the pen is properly located, the part will change color from blue to green (in the case of the parking brake shaft and from red to green in the case of the cup holder) indicating a correct pen location. As long as the button is pressed, the pen controls the location of the virtual device. If you are using the active haptic treatment, the PHANToM™ generates forces that keep the haptic pen location and motion on track defined by the location and motion of the virtual part. If you are using the non-haptic treatment, you operate the pen in the same manner, but the PHANToM™ will not produce any force to keep you on the correct path.

The goal of the study is to determine how the haptic treatment affects the ability to detect differences between two alternative designs of a virtual mechanism and if the haptic treatment helps to estimate linear and angular values of detected differences.

It may be very challenging to distinguish differences between designs because the differences can be very small. There are several questions (on the questionnaire form) where the correct answer could be 'no difference between designs' on a particular aspect. The actual differences have irregular numerical values and are difficult to report precisely. You are only expected to write down an approximate estimation of the sensation that you experience comparing the two virtual mechanisms. Take as much time as you feel is necessary to examine each design."

Up until this point in the experimental session, there were no changes from the experience of the participants who were a part of the first study and the experience of the participants who were a part of the most recent study.

The major difference between the current study and Mr. Volkov's study was the use of the HMD. The participants in Mr. Volkov's study viewed each design mechanism directly from a computer monitor in front of them. The participants in the current study placed the HMD on their heads and viewed each design through the HMD that was also position tracked so the view changed as the user moved his/her head (Figure 3.2).

Figure 3.2. Participant using the HMD and the PHANToM™ device

The participants in each study were allowed to become familiar with the PHANToM™ device by manipulating a cup holder in the VE as an example. Each participant was given as much time as he/she needed to interact with the cup holder to feel that he/she was ready to move on to the first of the four study trials.

During each experiment session, the participant went through four trials, each consisting of a comparison of two alternative designs of a virtual parking brake. Each trial had the same mechanism one (the base case) and a mechanism two that varied from one trial to the next (Table 3.1). In each trial, the researcher began the experiment by activating the first design mechanism and starting the timing device. The participant would then operate the virtual mechanism by moving the PHANToM™ stylus until he/she verbally indicated he/she was done examining mechanism one. The researcher would stop the timing device and note the time that had elapsed (Appendix C). The researcher then activated the second design mechanism and again, began the timing device. Once the participant was done examining mechanism two, mentally noting if there were any location or motion changes from mechanism one to two, the participant verbally indicated that he/she was finished. The researcher again recorded the participant's design evaluation time. The participants were asked to complete the multiple-choice questionnaire, which is found in Appendix B, about the differences between the two mechanisms after each trial. This procedure was repeated for all four trials.

The questionnaire in Appendix B consists of five questions that ask the participant to respond with his/her perceived design mechanism differences. The location of each mechanism was defined by the location of the red active point of the mechanism. The first question asked the participant whether the second mechanism was located to the right, in the same place, or to the left of where it was located in mechanism one. The second question asked if the participant thought the second mechanism was located higher, in the same location, or lower than mechanism one. The third question asked if mechanism two was located more towards the front of the car interior, remained in the same place, or was located more towards the rear of the car interior than mechanism one. The fourth question asked if the participant believed that the parking brake arm length was longer, the same length, or shorter in mechanism two than it was in mechanism one. Finally, the fifth question asked about the angle of motion of the parking brake; if the participant believed that the angle of rotation was smaller, the same, or larger in mechanism two than it was in mechanism one. If the participant determined that there were differences between mechanism one and two on any of the five questions, he/she was asked to estimate the value of the detected difference.

After all four trials were completed, the researcher gave each participant the opportunity to experience the alternative treatment (haptic or non-haptic). This opportunity involved the participant viewing all of the trials for as long as the participant wished to get an idea of what the alternative treatment was like. No mechanism difference detections were required of the participant. After the participant experienced the alternative treatment, he/she was asked to state which treatment was preferred to perform tasks related to design evaluation (Appendix B). If the participant could not give preference to either treatment, he/she could indicate it by writing "no preference" or "NP".

Once all trials had been completed, each participant was asked to write down any comments he/she had about any aspects of the experiment. The form that the participants were given is found in Appendix B.

STIMULI AND APPARATUS

HARDWARE

Both studies (previous and current) were arranged in a computer laboratory in the Virtual Reality Applications Center at Iowa State University. A Silicon Graphics (SGI) Octane computer with two R10000 processors at 295 MHz and 384 MB memory provided computational power for both of the studies. Two SGI color display monitors model

CM2187ME were used for mono visual display of the 3D VEs. In the previous study, participants used one monitor while the researcher used the other monitor to manage study trials. In the current study, both monitors were used by the researcher to manage the study. The head position of the participant was not tracked in the previous study, while in the current study, an Ascension Flock of Birds magnetic tracker was used. The V8 Head Mount Display, from Virtual Research Systems, uses two 1.3 inch diagonal Active Matrix Liquid Crystal Displays, which give a resolution per eye of (640 × 480). The HMD has a field of view of 60° diagonal. The HMD had a weight of 34 ounces (1.0 kg). The HMD graphics were run using an SGI Onyx2 computer equipped with 24 R12000 processors at 400 MHz and 12GB memory. In both studies, the PHANToM™ 1.5 three degree-of-freedom haptic device, product of SensAble Technologies, was used to provide haptic feedback with the VE. The PHANToM™ 1.5 has a 7.5 × 10.5 × 15 in (19.5 × 27 × 37.5 cm) workspace, 860 dpi (0.03 mm) nominal position resolution, three degrees of freedom (x, y, z) force feedback, and 1.9 lbf (8.5 N) maximum exertable force.

SOFTWARE

The software used in the previous study was the proprietary product of the Ford Corporation. The software allowed presentation of a simplified 3D car interior design to be shown on the DD. Different parts of the car interior design could be modified, relocated, and tested for motion functionality. The view of the main window simulated the point of view of a driver for each participant. Because on a 2D screen it is difficult to judge depth, a second side view of the car interior was shown in the small window in the upper right corner of the screen. The view taken from the computer monitor is shown in Figure 3.2.

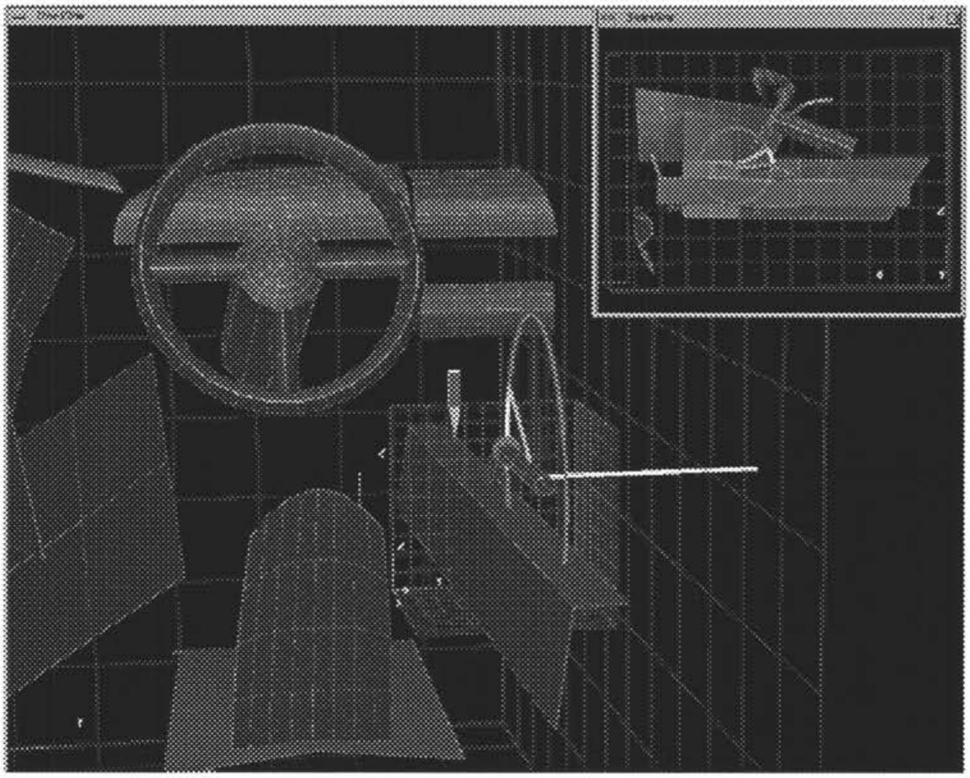

Figure 3.3. VE shown to non-HMD study participants

Another ISU graduate student, Tom Duncan, wrote the software for the current study because the Ford software did not support display in a HMD. The new software allowed for a somewhat more simplified 3D car interior design. Similar to the previous study, the only maneuverable parts of the car interior design were the cup holder and the parking brake. There was only one graphics window that was utilized by the researcher to manage study trials and the participants viewed the VE directly through the HMD. The worldview seen by the HMD users is shown in Figure 3.4. In this view, the user has already selected the parking brake, which is indicated by the color of the handle turning from blue to green. The cup holder remained red throughout the study. A view showing the world as viewed from the side is shown in Figure 3.5.

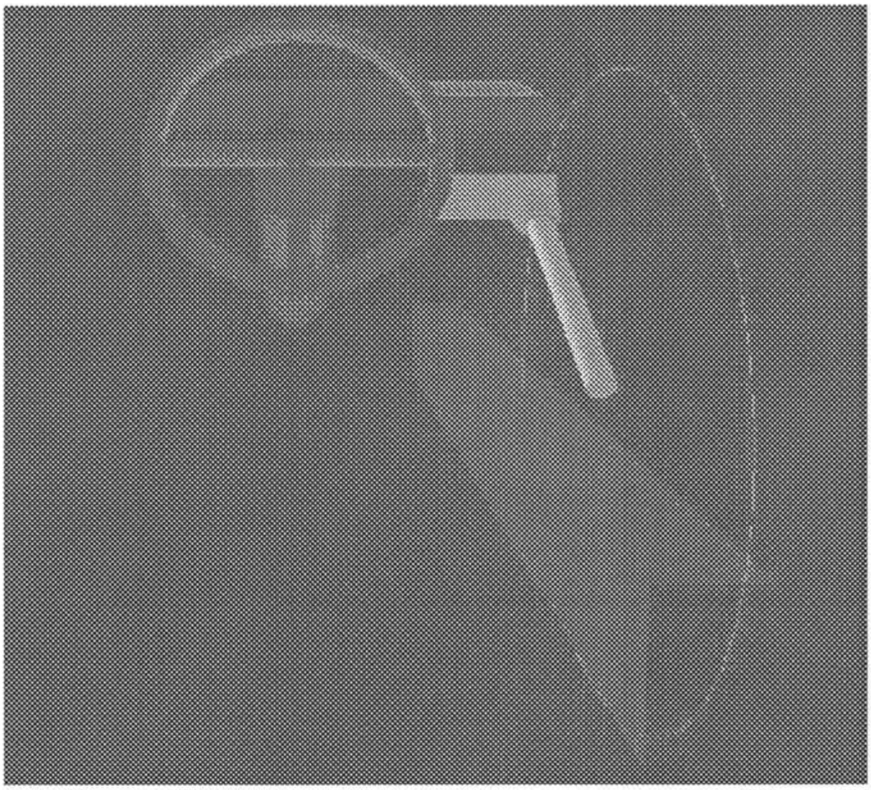

Figure 3.4. Front view of HMD participants with the parking brake selected

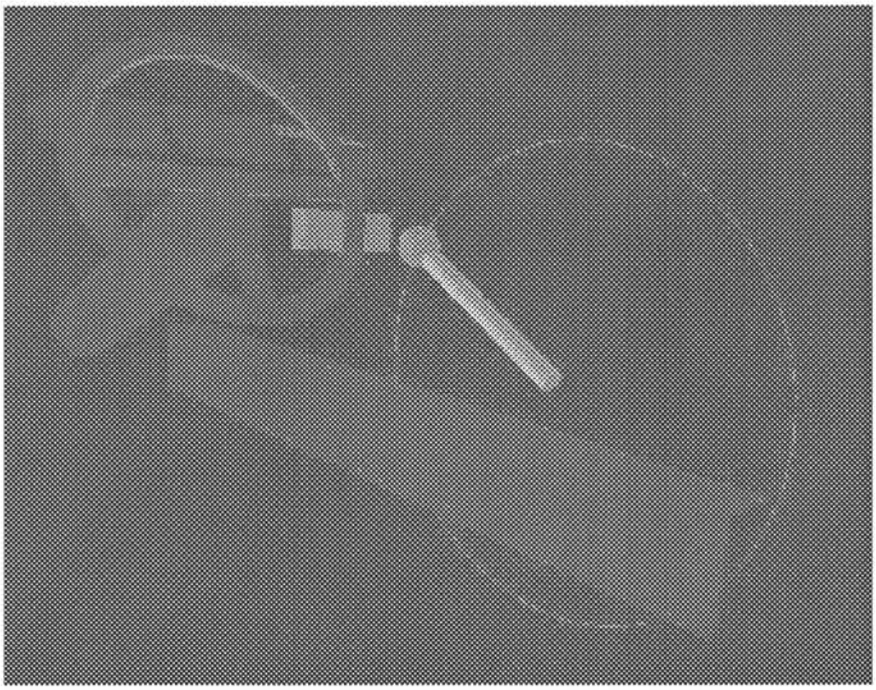

Figure 3.5. Side view of HMD participants with the parking brake selected

Although the intent was to exactly replicate the world of the first study for the resent study, there were some differences. The geometry in the HMD simulation is a much more simplified version of the DD car interior, however, in both simulations, only the parking brake and cup holder were maneuverable. Also, in the DD simulation, the car interior included a grid around the parking brake, which as not included in the HMD VE. Although the lighting and resolution of the images shown to the participants look different from the figures shown in this thesis, the actual images seen by the participants were very similar in quality.

DATA ANALYSIS

The data were analyzed using analysis of variance tests (ANOVA). ANOVA tests determine if the differences in sample means of two or more samples are statistically significant or not by comparing them to the variation within the samples. For this study, the samples are considered to be statistically different if the tail probability value (p-value) associated with the F-value equals 0.05 or less.

The participants were separated into four different groups (Table 3.2); HMD users with the haptic treatment, HMD users with the non-haptic treatment, non-HMD users with the haptic treatment, and non-HMD users with the non-haptic treatment. The data from all four groups was analyzed together to determine if there was any effect of using the HMD versus not using the HMD, experiencing the haptic treatment or the non-haptic treatment, or any interaction between the variables. Thus, a 2×2 factorial experiment was created.

Table 3.2. 2 × 2 factorial experiment

		Haptic Status	
		Haptic	Non-Haptic
Display Method	HMD	Haptic HMD	Non-Haptic HMD
	No HMD	Haptic No HMD	Non-Haptic No HMD

The data from each treatment group were analyzed in the following four categories:

PERCENTAGE OF CORRECT ANSWERS ON QUESTIONS REGARDING ALTERNATIVE MECHANISM DESIGN DIFFERENCES

The data were analyzed using ANOVA to test for differences in the mean percentage of correct answers among the four treatment groups. The data used for the analysis were grouped as follows:

- All questions in each trial
- All questions combined
- All questions related to length
- All questions related to location differences between the two mechanisms
- All questions related to motion differences between the two mechanisms
- All questions about left – right location differences between the two mechanisms
- All questions about high – low location differences between the two mechanisms

- All questions about forward – rearward location differences between the two mechanisms
- All questions about arm length differences between the two mechanisms
- All questions about angle of motion differences between the two mechanisms

Accuracy and Precision of Participants' Estimations for Differences Between the Two Alternative Mechanism Designs

ANOVA was used to evaluate the accuracy of estimations between all treatment groups. The data were presented in terms of estimation errors for individual questions and participants. The data used for the analysis were grouped as follows:

- All questions related to location differences between the two mechanisms
- All questions about left – right location differences between the two mechanisms
- All questions about high – low location differences between the two mechanisms
- All questions about forward – rearward location differences between the two mechanisms
- All questions about arm length differences between the two mechanisms
- All questions about angle of motion differences between the two mechanisms

Time Required by Participants to Evaluate Each Mechanism Design

The time required for every participant to evaluate each alternative mechanism design was analyzed using ANOVA to test for differences of the mean between the treatment groups. The data used for the analysis were grouped as follows:

- Time to evaluate mechanism one in each trial

- Average time to evaluate mechanism one, all 4 trials combined
- Time to evaluate mechanism two in each trial
- Average time to evaluate mechanism two, all 4 trials combined
- Average time to evaluate a design in each trial, mechanisms one and two combined
- Average time to evaluate a design, mechanisms one and two combined, all 4 trials combined

PARTICIPANTS' TREATMENT PREFERENCE

After each participant completed all four trials and tried the alternative treatment, the participant was asked eight preference questions about the treatments. The questions can be found in the questionnaire form that is presented in Appendix B. The preferences of all treatment groups were gathered to determine which treatment (haptic or non-haptic) the participants would prefer in different design evaluation situations.

CHAPTER 4. RESULTS AND DISCUSSION

DATA ANALYSIS RESULTS

The following section presents the results of the statistical analyses for the four different treatment groups in each of the four data collection segments: percentage of correctly detected mechanism differences, accuracy and precision of estimations of mechanism differences, mechanism design evaluation time, and treatment preference. The data from two of the treatment groups, haptic without HMD and non-haptic without HMD, came from Mr. Volkov's previous research (Volkov, 2000).

PERCENTAGE OF CORRECT ANSWERS ON QUESTIONS REGARDING ALTERNATIVE MECHANISM DESIGN DIFFERENCES

There are several different question combinations that have a statistically significant difference in means as shown by the ANOVA. The average percentage of questions that all treatment groups answered correctly for each question by trial number is shown in Table 4.1. The last row in each trial, labeled "All Combined" is the average percentage of questions that each group answered correctly for each trial combined. This information is also displayed as a graph in Figure 4.1. Table 4.2 shows the average percentage of questions each group answered correctly by question category.

Table 4.1. Percentage of correct answers on individual questions

Percentage of correct answers of all questions for each trial								
	Trial 1				Trial 2			
Question	Haptic HMD	Haptic No HMD	Non-Haptic HMD	Non-Haptic No HMD	Haptic HMD	Haptic No HMD	Non-Haptic HMD	Non-Haptic No HMD
1	3.2	76.3	19.4	63.2	6.5	76.3	19.4	63.2
2	38.7	57.9	54.8	57.9	22.6	57.9	41.9	57.9
3	32.3	57.9	12.9	68.4	16.1	57.9	35.5	68.4
4	32.3	34.2	45.2	42.1	61.3	34.2	61.3	42.1
5	51.6	60.5	45.2	42.1	61.3	60.5	61.3	42.1
All Combined	31.6	57.4	35.5	54.7	33.5	57.4	44.5	54.7
	Trial 3				Trial 4			
Question	Haptic HMD	Haptic No HMD	Non-Haptic HMD	Non-Haptic No HMD	Haptic HMD	Haptic No HMD	Non-Haptic HMD	Non-Haptic No HMD
1	80.6	73.7	64.5	63.2	64.5	84.2	74.2	68.4
2	61.3	55.3	48.4	60.5	54.8	57.9	51.6	57.9
3	61.3	65.8	58.1	65.8	61.3	63.2	41.9	55.3
4	29.0	31.6	45.2	28.9	41.9	57.9	54.8	47.4
5	64.5	63.2	74.2	63.2	90.3	100.0	93.5	94.7
All Combined	59.4	57.9	58.1	56.3	62.6	72.6	63.2	64.7

Table 4.2. Percentage of correct answers for question category

Percentage of correct answers for question combinations				
Question Category	Haptic HMD	Haptic No HMD	Non-Haptic HMD	Non-Haptic No HMD
	Average	Average	Average	Average
a) All questions combined	46.8	56.1	50.3	54.2
b) All questions related to length	41.7	53.5	45.8	53.1
c) All questions related to location differences	41.9	60.3	43.5	57.7
d) All questions related to motion differences	54.0	49.7	60.5	49.0
e) Four trials combined:				
left - right location differences	38.7	65.8	44.4	55.3
high - low location differences	44.4	53.3	49.2	62.5
forward - rearward location differences	42.7	61.8	37.1	55.3
arm length differences	41.1	32.9	52.4	39.5
angle of motion differences	66.9	66.4	68.5	58.6

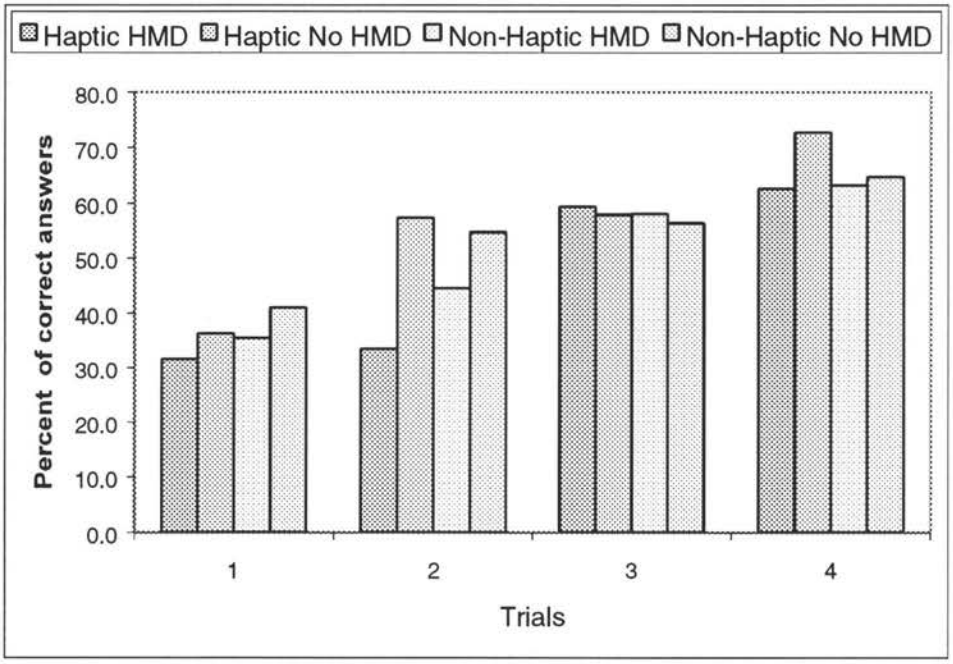

Figure 4.1. Percentage of correct answers of all questions for each trial

As can be seen from Figure 4.1, each of the treatment groups increased the average percentage of questions answered correctly from trial one through trial four. The ANOVA determined that there was a statistically significant main effect of type of display on the mean percentage of questions answered correctly in the second trial $F(1,138) = 21.53, p < 0.0001$. Participants who used the HMD performed less well (39.0% of the questions answered correctly) than the participants who did not experience the HMD (56.1% of the questions answered correctly). The mean percentage values for each trial, grouped by display type, are shown in Figure 4.2. The ANOVA did not find any meaningful differences between the effects of variables in any of the other treatment groups throughout any of the other trials. Interaction between variables was insignificant.

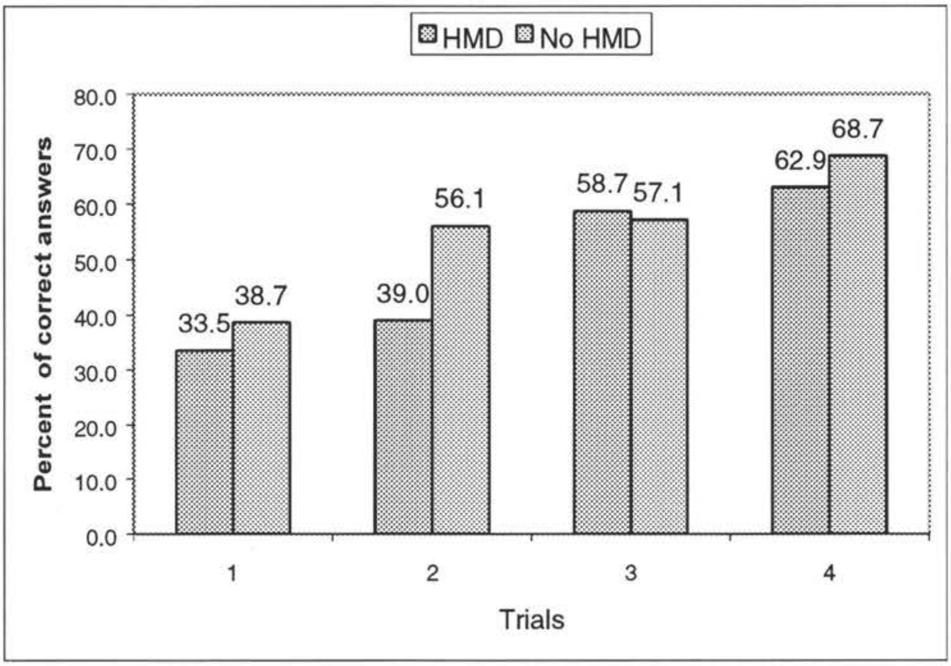

Figure 4.2. Average percentage of questions answered correctly in each of the four trials, HMD versus non-HMD users

Figure 4.3 presents the average percentage of questions answered correctly for all questions combined (first row of Table 4.2). The ANOVA indicated that there was a statistically significant main effect of type of display on the mean values obtained $F(1,138) = 11.90$, $p = 0.0008$. Participants who used the HMD (48.55% of the questions answered correctly) performed less well than the participants who did not use the HMD (55.13% of the questions answered correctly). There was no statistical difference found between the means of the participants who experienced the haptic treatment versus the participants who experienced the non-haptic treatment. There was no interaction found between the variables.

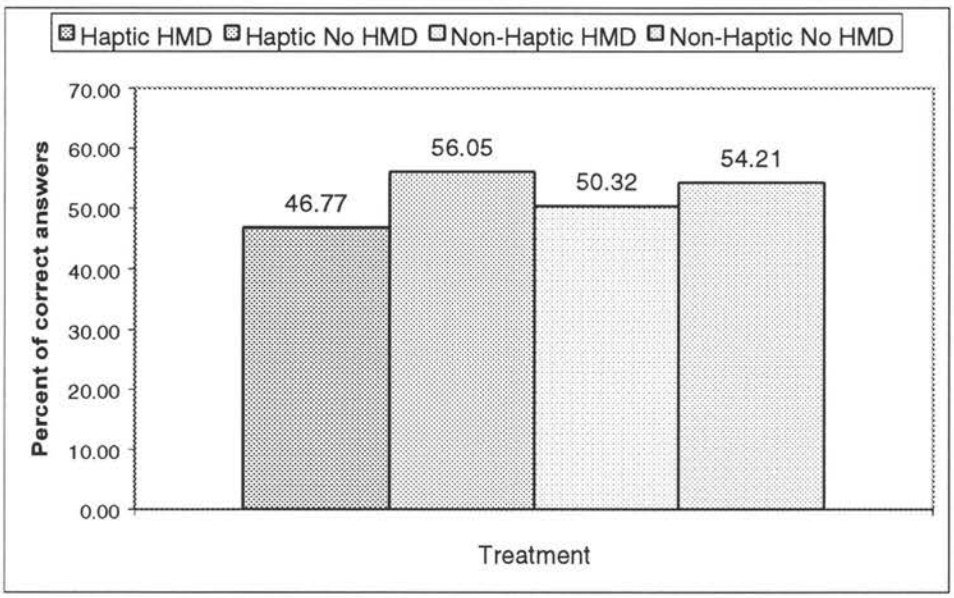

Figure 4.3. Average percentage of correct answers on all questions combined

Figure 4.4 shows the average percentage of questions regarding length, questions 1, 2, 3, and 4 in Appendix B, that each treatment group answered correctly. Again, the ANOVA determined that there is a statistically significant main effect of display on the means of the percent of questions answered correctly for the participants who used the HMD (43.75% of the questions answered correctly) and those who did not (53.29% percent of the questions answered correctly) $F(1,138) = 19.16, p < 0.0001$. The ANOVA showed no statistical significance in the difference in the mean values of the participants who experienced the haptic treatment versus those who experienced the non-haptic treatment. Again, there was no interaction found between the variables.

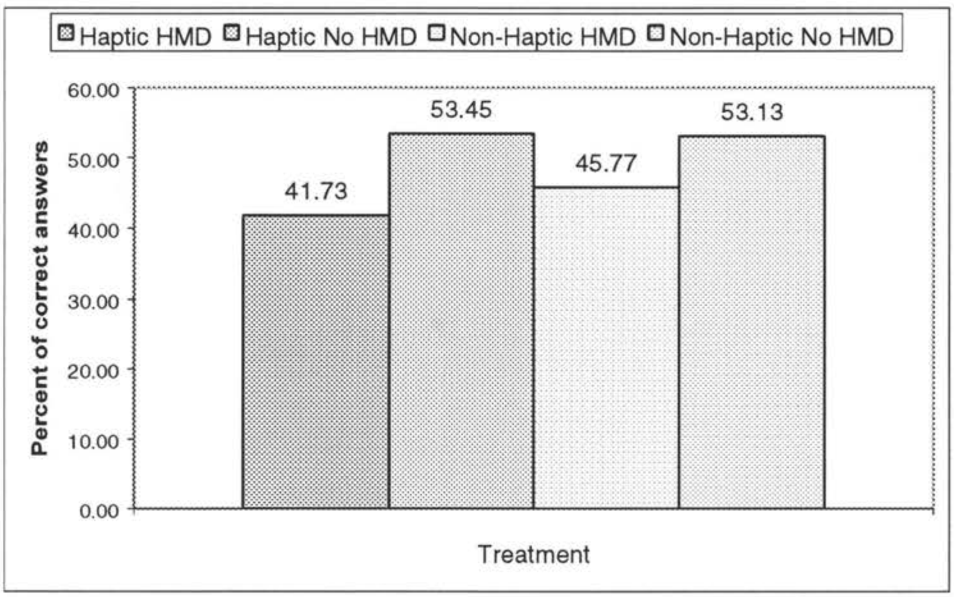

Figure 4.4. Average percentage of correct answers on questions regarding length

Figure 4.5 displays the average percentage of questions regarding parking brake location (questions 1, 2, and 3 in Appendix B) answered correctly for each of the treatment groups. The ANOVA indicated that there was a main effect of type of display on the mean values of the average percentage of questions regarding location answered correctly. The participants that experienced the HMD performed less well (42.74% of the questions answered correctly) than those who did not use the HMD (58.99% of the questions answered correctly). The ANOVA resulted in F (1,138) = 36.24, $p < 0.0001$. Again, the ANOVA showed no significance of the difference in the mean values of the haptic participants' percentage of correct answers versus the non-haptic participants' percentage of correct answers, nor was any interaction found between the variables.

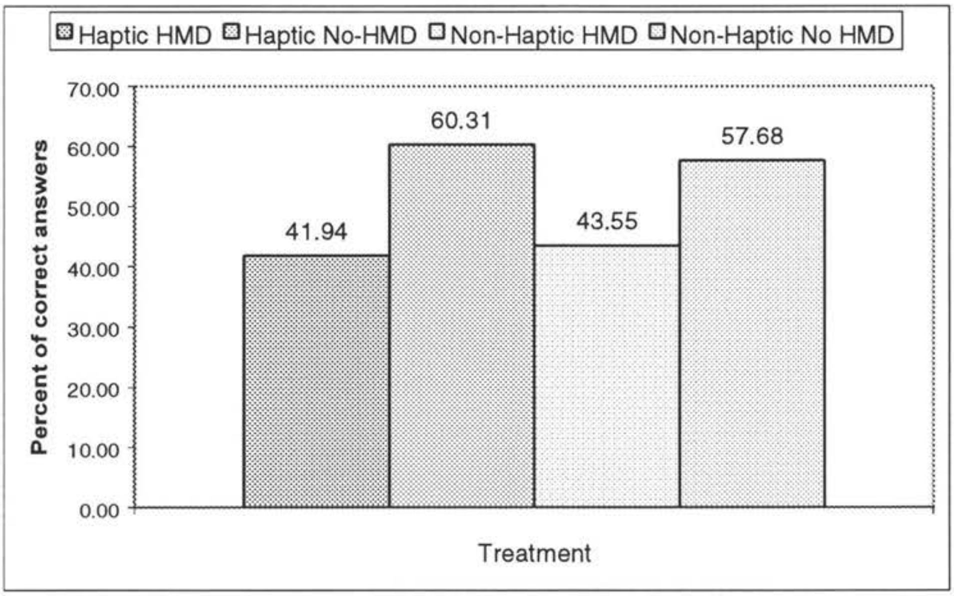

Figure 4.5. Average percentage of questions regarding location answered correctly

Figure 4.6 displays the average percentage of questions regarding parking brake motion (questions 4 and 5 in Appendix B) answered correctly for all treatment groups. Again, the ANOVA determined that there was a statistically significant main effect of type of display on the means of the percentage of parking brake motion questions answered correctly. The participants who used the HMD performed better (57.26%of the questions answered correctly) than those who did not use the HMD (49.34% of the questions answered correctly). The ANOVA for this comparison resulted in $F(1,138) = 7.25, p = 0.0080$. The ANOVA showed no meaningful difference in the means of the percentage of questions regarding parking brake motion answered correctly by the haptic participants versus the non-haptic participants. There was also no indication of any interaction between the variables.

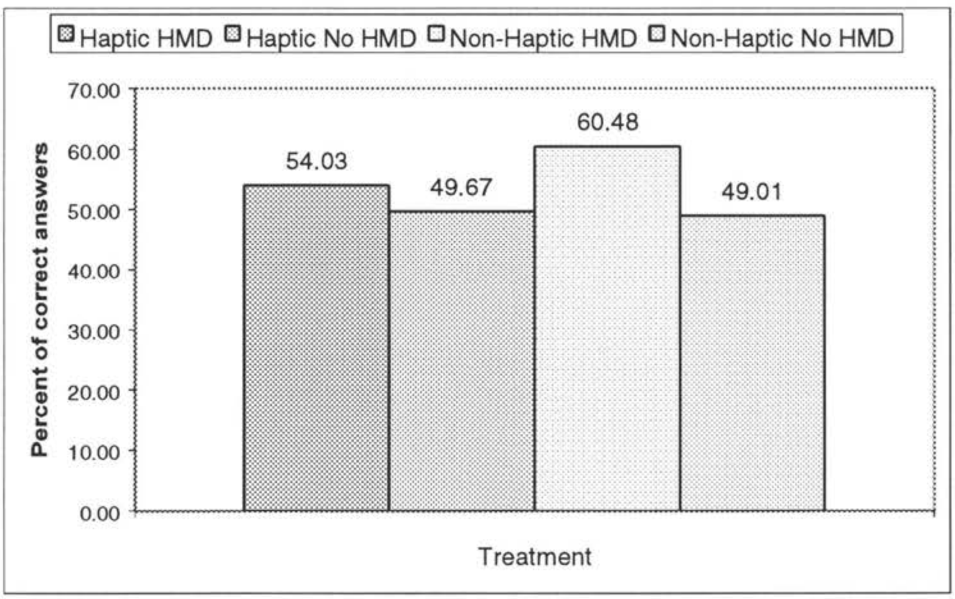

Figure 4.6. Average percentage of questions regarding parking brake motion answered correctly

Figure 4.7 displays a graph of the average percentage of questions regarding left – right location differences between mechanisms one and two (question 1 in Appendix B) that each of the treatment groups answered correctly. The ANOVA showed that there was a statistically significant main effect of type of display on the means of the percentage of left – right questions answered correctly. The participants who experienced the HMD performed less well (41.53%) than those who did not use the HMD (60.53%) $F(1,138) = 23.95$, $p < 0.0001$. The ANOVA also showed that there is a statistically significant interaction between the factors. This interaction is displayed in Figure 4.7 by the fact that the percentage of correct answers for the HMD users increased from haptic to non-haptic, while the participants who did not use the HMD answered more questions correctly when they experienced the haptic treatment than if they experienced the non-haptic treatment.

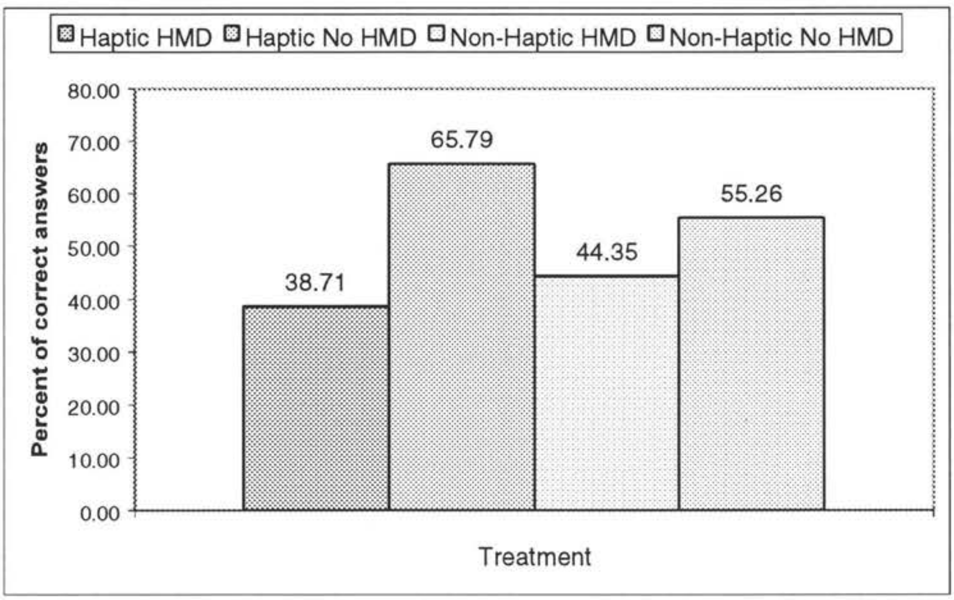

Figure 4.7. Average percentage of questions regarding left – right location differences answered correctly

Figure 4.8 displays a graph of the average percentage of correct answers all treatment groups gave on questions regarding high – low parking brake arm differences in mechanisms one and two (question 2 in Appendix B). The ANOVA determined that there was a statistically significant main effect of type of display on the means of the percentage of correct answers given. The participants who used the HMD performed less well (46.77% of the questions answered correctly) than those who did not use the HMD (57.89% of the questions answered correctly) $F(1,138) = 6.11$, $p = 0.0147$. Again, the ANOVA did not find any statistical significance in the means of the percentage of correct answers between the participants who experienced the haptic treatment and those who experienced the non-haptic treatment, nor was there any indication of interaction between the variables.

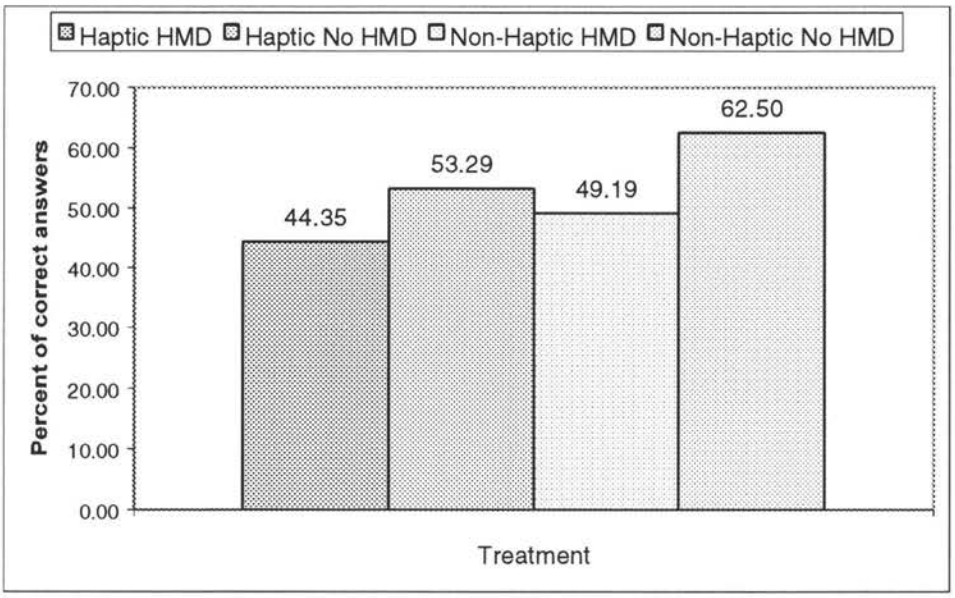

Figure 4.8. Average percentage of correct answers on questions regarding high – low parking brake differences

Figure 4.9 shows the average percentage of correct answers each treatment group gave on questions regarding forward – rearward parking brake differences between mechanisms one and two (question 3 in Appendix B). The ANOVA determined that there was a main effect of type of display on the means of the percentage of correct answers given. The participants who used the HMD performed less well (39.92% of the questions answered correctly) than the participants who did not use the HMD (58.55% of the questions answered correctly) $F(1,138) = 21.93$, $p < 0.0001$. The ANOVA did not find any significance in the differences in the means between the haptic participants and the non-haptic participants. Again, no interaction between the variables was found.

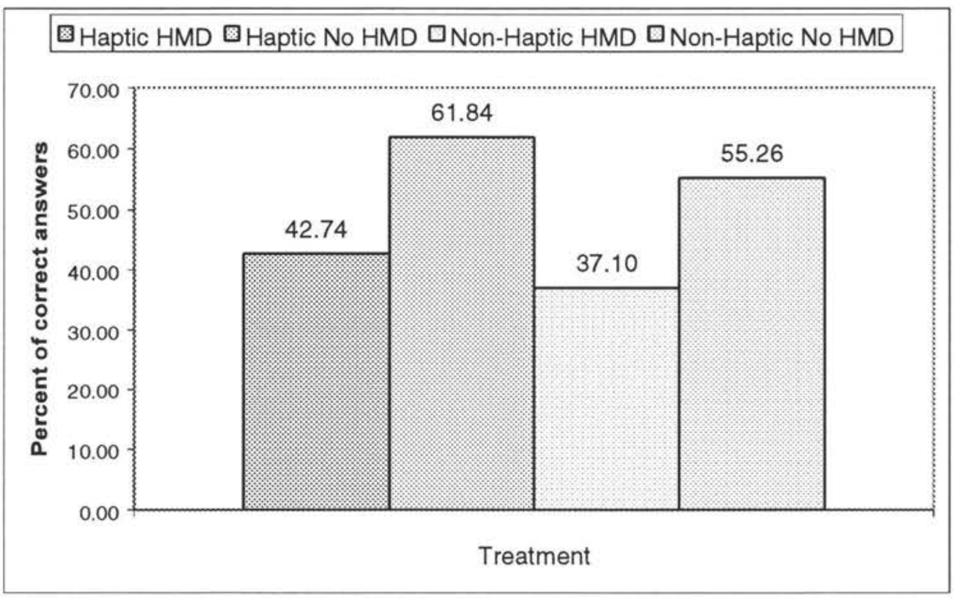

Figure 4.9. Average percentage of correct answers on questions regarding forward – rearward parking brake differences

The average percentage of questions regarding parking brake arm length differences between mechanisms one and two (question 4 in Appendix B) answered correctly for each of the treatment groups is shown as a graph in Figure 4.10. The ANOVA determined that there was a statistically significant main effect of type of display on the means of the percent of questions answered correctly. The participants who experienced the HMD performed better (46.77% of the questions answered correctly) than those who did not use the HMD (36.18% of the questions answered correctly) F (1,138) = 7.38, $p = 0.0075$. The ANOVA also determined that there was a main effect of treatment type on the means of correct answers given. The participants who used the haptic treatment performed less well (36.59%) than those who did not (45.29%) F (1,138) = 5.25, $p = 0.0235$. The interaction found was not significant.

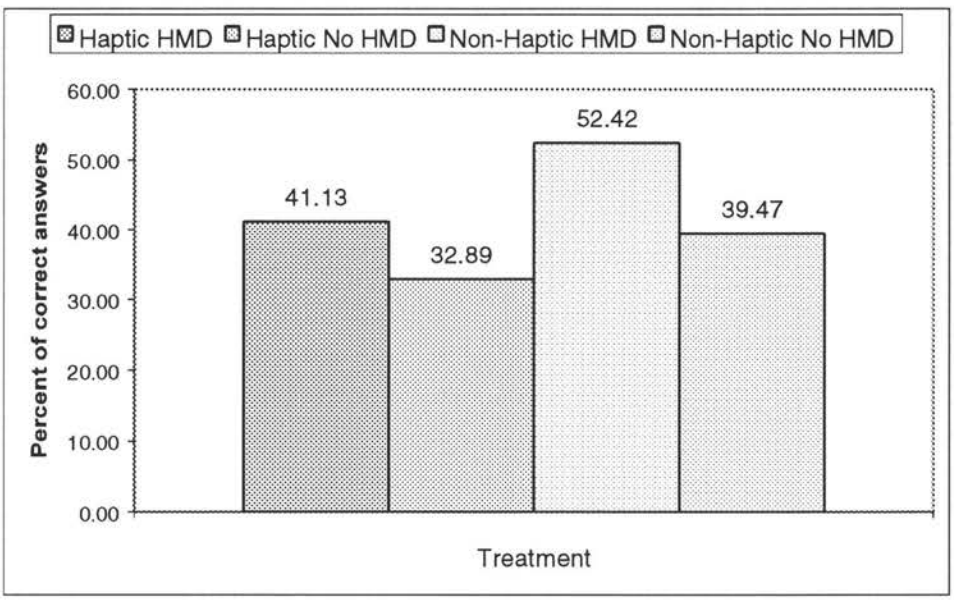

Figure 4.10. Average percentage of questions regarding parking brake arm length differences answered correctly

The ANOVA determined that there was no statistical significance between the means of any of the treatment groups regarding the percentage of correct answers on questions about parking brake arm angle of motion differences between mechanisms one and two (question 5 in Appendix B). A plot of the percentage of correct answers for each of the treatment groups is shown in Figure 4.11.

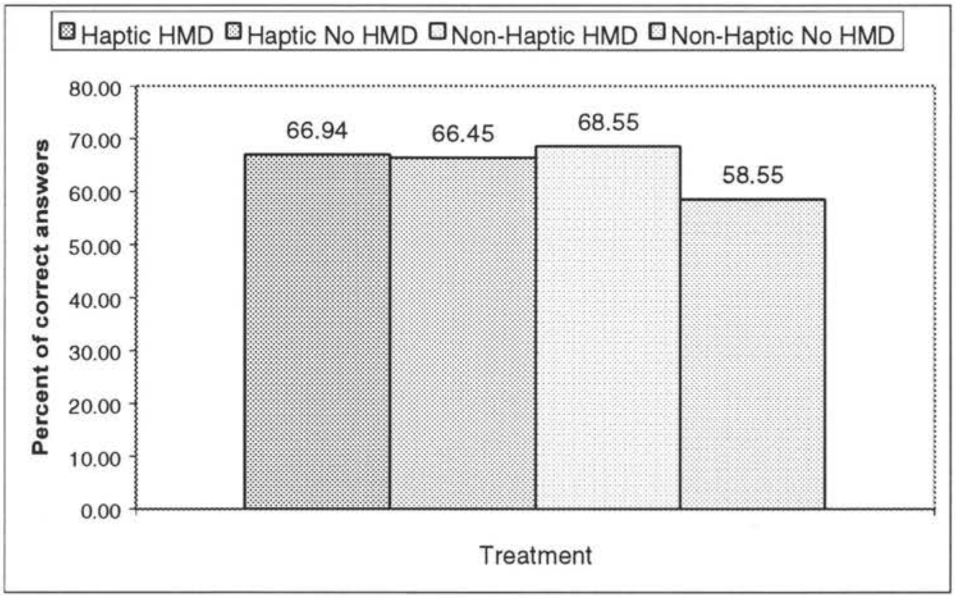

Figure 4.11. Average percentage of questions regarding parking brake arm angle of motion differences answered correctly

DISCUSSION

Generally, participants who did not use the HMD answered more questions regarding parking brake arm location (questions 1, 2, and 3) correctly than did the participants who did use the HMD. However, participants who used the HMD answered (on average) more questions about parking brake arm motion (questions 4 and 5) correctly than did the non-HMD participants. Due to the fact that each participant went through the same sequence of trials, it is difficult to determine if the absence of an HMD is more useful in locating virtual devices and the presence of an HMD is better for motion detection, or if the participants who used the HMD just took longer (more trials) to become accustomed to the hardware. The fact that the percentage of correct answers on questions regarding parking brake angle of motion were higher for all treatment groups brings up the same question: Is the success of angle of motion differences due to the fact that they are easier to detect than other mechanism differences (i.e. location differences), or is it due to the fact that the later trials (trials 3 and 4) were the trials with angle of motion differences between mechanisms one and two? Varying the trial order from participant to participant would enable the resolution of this question. The effect of the treatment could be examined along with the participant's learning (becoming more familiar with what is expected of them) by counterbalancing (varying the trial order systematically) the trial sequence.

Participants who used the HMD and DD were members of different samples selected by different researchers (O'Leary and Volkov) at different times. It is unlikely that the different research periods and/or researchers would have an impact on the results of this study, but it is another variable that needs to be taken into account.

ACCURACY AND PRECISION OF PARTICIPANTS' ESTIMATIONS FOR DIFFERENCES BETWEEN THE TWO ALTERNATIVE MECHANISM DESIGNS

Once a participant indicated he/she detected a location or motion difference between mechanisms and two, they were asked to estimate the difference that was detected. Figure 4.12 displays the boxplots of combined parking brake location difference estimations (questions 1, 2, and 3 in Appendix B) for each of the four treatment combinations. A boxplot shows the minimum, maximum, and median values in each sample group, as well as the 25th and 75th percentile values. The 25th percentile value is the value within the sample group that has at most 25% of the values below it and at most 75% above it. Similarly, the 75th percentile value represents the point where at most 75% of the values fall below and at most 25% fall above. The boxplots are useful because they graphically show the distribution, the range of values, and where the values are concentrated.

Each of the four treatments has a similar looking boxplot, which indicates that there is no statistical difference in their distribution. This is confirmed by the ANOVA, which did not find any significant effects on parking brake errors.

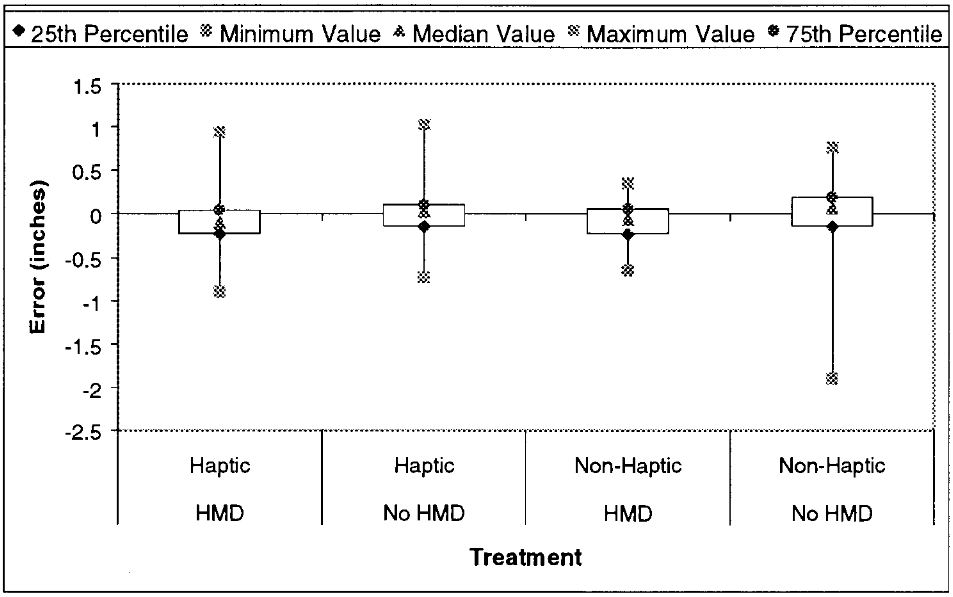

Figure 4.12. Combined parking brake location errors for all treatment groups

Figure 4.13 displays the four boxplots for the participants' estimation errors on left – right location differences between mechanisms one and two (question 1 in Appendix B). Again, the boxplots are all similar, indicating that there is little statistical difference between the four samples. This is confirmed by the ANOVA, which again did not find any significant effects.

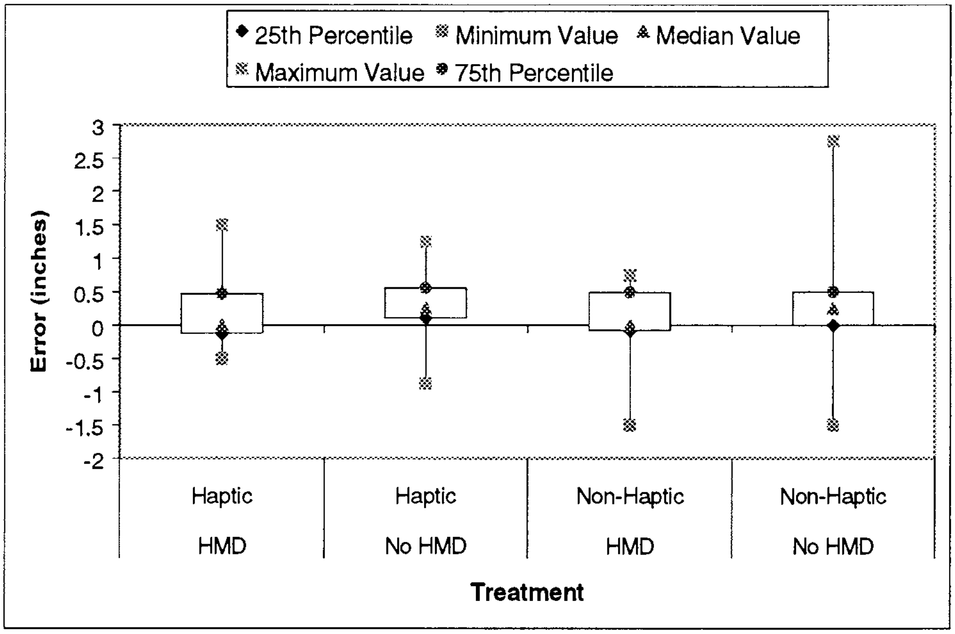

Figure 4.13. Participants' estimation errors on left – right parking brake location questions

The distribution of participants' estimation errors for questions regarding high – low parking brake location differences between mechanisms one and two (question 2 in Appendix B) are displayed in Figure 4.14. The ANOVA indicated that there was a significant main effect of the treatment type on the mean error values $F(1,138) = 3.98$ $p = 0.0482$. The participants who experienced the haptic treatment averaged an estimation error of -0.21 inches while the participants who experienced the non-haptic treatment averaged an estimation error of -0.04 inches. The non-haptic participants' average estimation error value of –0.04 inches is much closer to zero (no error) than the haptic participants' average estimation error value of –0.21 inches; this indicates that the non-haptic participants were better able to estimate high – low location differences in the parking brake mechanisms.

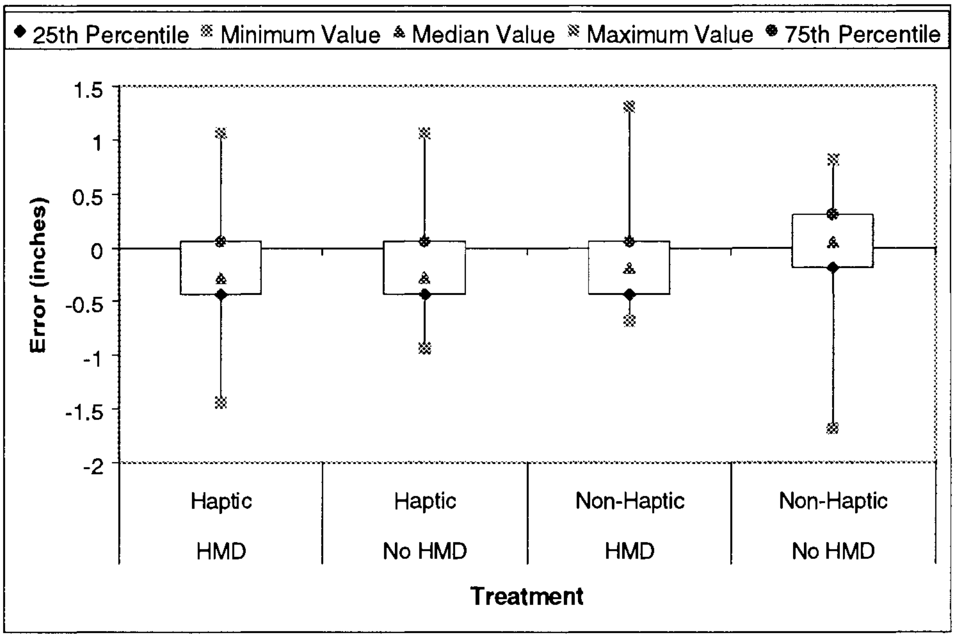

Figure 4.14. Participants' estimation errors on high – low parking brake location questions

Figure 4.15 shows the boxplots of all treatment group participants' estimation errors on forward – rearward parking brake location differences between mechanisms one and two (question 3 in Appendix B). The ANOVA determined that there was a statistically significant main effect of the treatment type on the mean estimation error values $F(1,138) = 4.81, p = 0.0300$. The haptic participants average estimation error was -0.08 inches while the mean estimation error value of the non-haptic participants was -0.34 inches. The haptic participants' average error value of –0.08 inches is much closer to zero (no error) than the non-haptic participants' value of –0.34 inches; this indicates that the haptic participants were better able to estimate forward – rearward parking brake location differences between mechanisms.

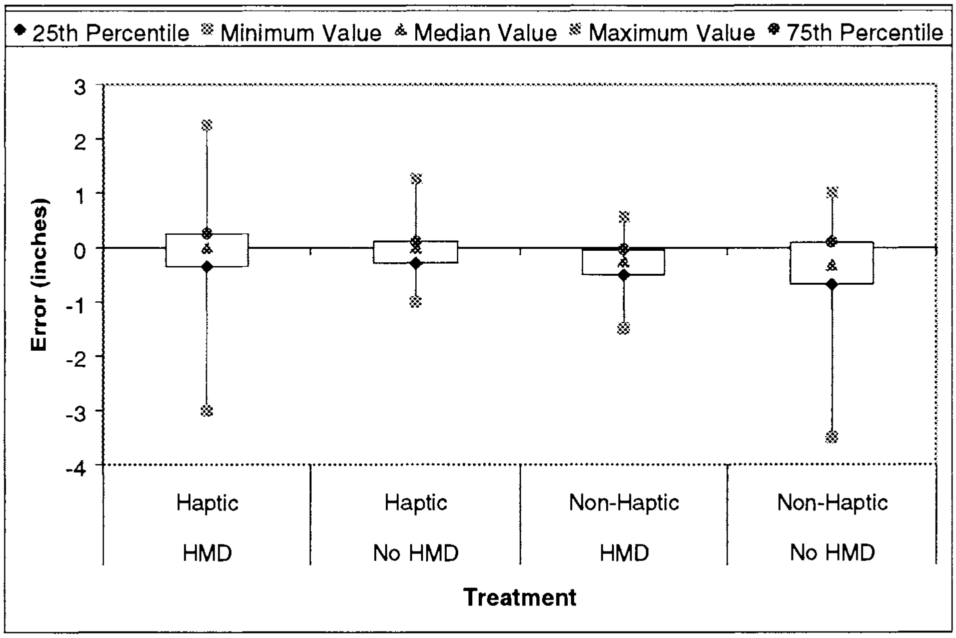

Figure 4.15. Participants' estimation errors on forward – rearward parking brake location difference questions

The ANOVA did not find any significance in the difference of the means of any of the treatment groups when the participants' errors of parking brake arm length questions (question 4 in Appendix B) and angle of motion questions (question 5 in Appendix B) were compared. The boxplots for those two question categories follow as Figures 4.16 and 4.17 respectively.

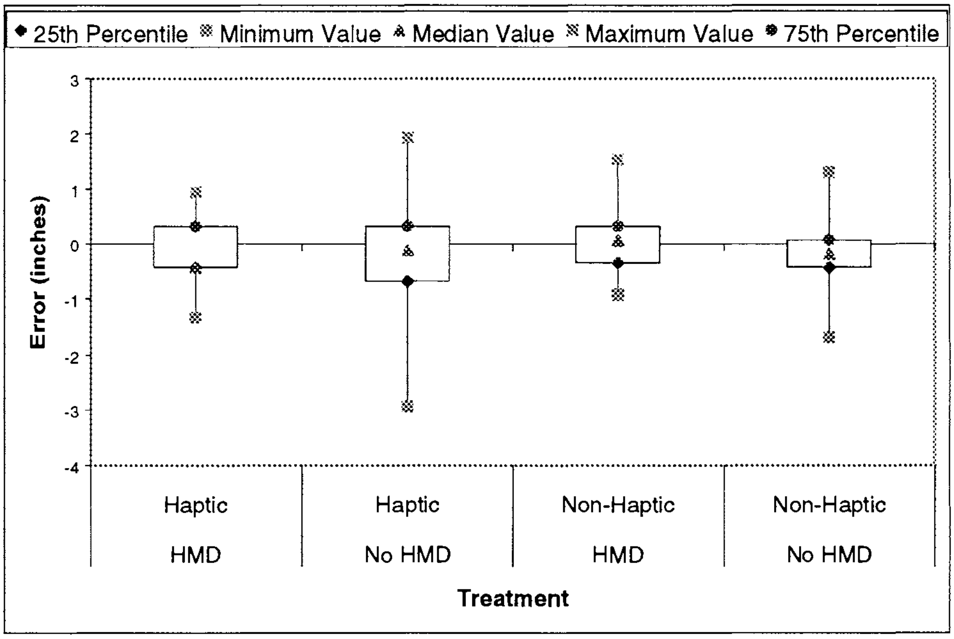

Figure 4.16. Participants' estimation errors on questions regarding parking brake arm length differences

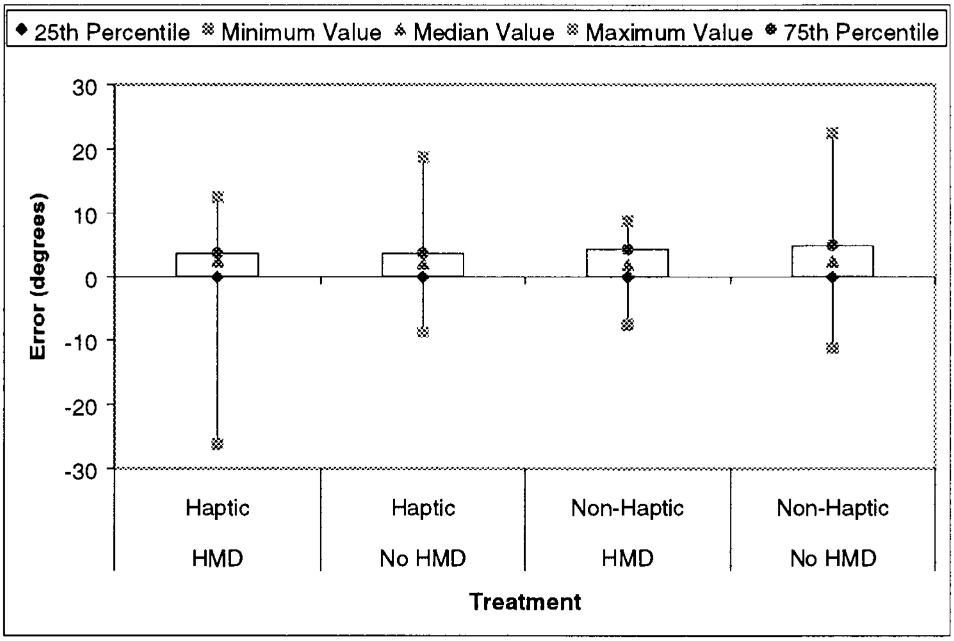

Figure 4.17. Participants' estimation errors on questions regarding parking brake arm angle of motion differences

DISCUSSION

Only two of the ANOVAs found instances where there was a statistically significant effect when the accuracy and precision of estimations of the participants were compared. One such instance was in the comparison of estimations of high – low parking brake location differences between mechanisms one and two. The other was in the comparison of estimations of forward – rearward parking brake location differences between mechanisms one and two. The following figures are boxplots of each of the question combinations compared for each of the treatment groups.

The lack of statistically significant differences in mean error values of participants who used the HMD compared to the participants who did not use the HMD indicates that there is no affect of display type on participants' ability to estimate mechanism differences. The use of the haptic treatment allowed for more accurate estimations of forward – rearward parking brake arm location differences, while the non-haptic treatment enabled participants to be more successful with high – low parking brake location differences.

TIME REQUIRED BY PARTICIPANTS TO EVALUATE EACH MECHANISM DESIGN

The time each participant took to evaluate mechanism design was also a factor for comparison. Figure 4.18 shows the average time for all treatment groups to evaluate mechanism one for all four trials. The pattern in the graph suggests that there was a major discrepancy in times from group to group. The ANOVA confirmed that there were differences. For trial one, the ANOVA determined that there was a statistically significant main effect of display type on the trial one – mechanism one mean evaluation times $F(1,138) = 7.57, p = 0.0067$. The participants who experienced the HMD had an average trial one – mechanism one evaluation time of 46.77 seconds while those who did not use the HMD had an average trial one – mechanism one evaluation time of 58.97 seconds. The ANOVA also determined that there was a statistically significant main effect of treatment type on the trial one – mechanism one mean evaluation times $F(1,138) = 21.67, p < 0.0001$. The participants who experienced the haptic treatment had an average trial one – mechanism one evaluation time of 42.49 seconds while those who experienced the non-haptic treatment had an average trial one – mechanism one evaluation time of 64.49 seconds. The ANOVA also indicated that there was an interaction between the display type (HMD or non-HMD) and the treatment type (haptic or non-haptic) $F(1,138) = 9.15, p = 0.0030$. This interaction indicated that participants had shorter trial one – mechanism one evaluation times when using either haptics or the HMD, but it was not additive; a participants' evaluation time would not be shorter by using the haptic treatment and the HMD at the same time.

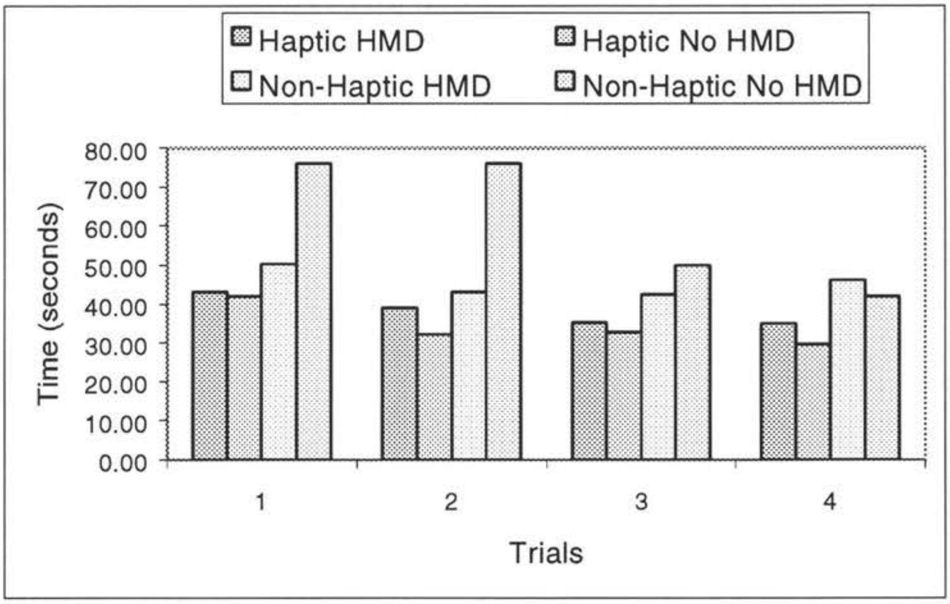

Figure 4.18. Average time for all groups to evaluate mechanism one, all four trials

Each of the remaining three trials were also found to have statistically significant main effect of the treatment type, haptic or non-haptic, on the average evaluation times of mechanism one. The average time the haptic participants took to evaluate mechanism one in trial two was 35.29 seconds while the non-haptic participants took an average of 46.97 seconds. The ANOVA for this comparison resulted in $F(1,138) = 8.90$, $p = 0.0034$).

The average time the haptic participants took to evaluate mechanism one in trial three was 37.36 seconds; the non-haptic participants took an average of 42.22 seconds. The ANOVA for trial three resulted in $F(1,138) = 5.64$, $p = 0.0189$.

The haptic users took an average of 32.06 seconds to evaluate mechanism one during trial four, while the non-haptic users took an average of 43.08 seconds. The ANOVA for trial four resulted in $F(1,138) = 8.20$, $p = 0.0049$.

When the times for each participant to evaluate mechanism one were added together to get an average over all trials combined (Figure 4.19), the ANOVA found a statistically significant main effect of the treatment type on the means mechanism one design evaluation times F (1,138) = 17.06, $p = 0.0001$. The participants who experienced the haptic treatment took an average of 35.92 seconds to evaluate mechanism one over all four trials versus the non-haptic participants who required an average of 49.19 seconds to evaluate mechanism one over all four trials.

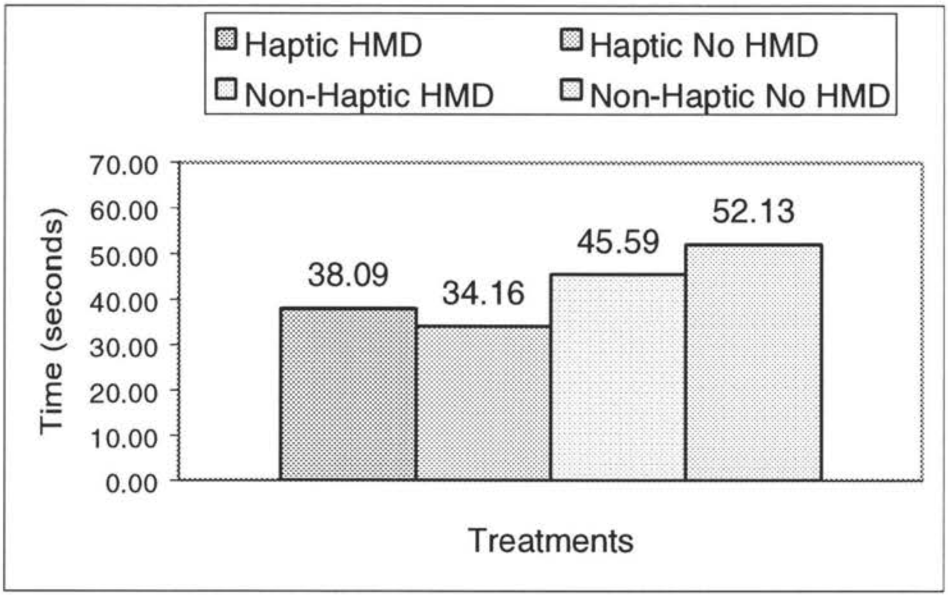

Figure 4.19. Average time to evaluate mechanism one, all four trials combined

Similar results were found when the evaluation times for mechanism two were compared using the ANOVA. The average evaluation times for all treatment groups over all trials are shown in Figure 4.20. The ANOVA showed a main effect of the display type on the mean design evaluation time for trial one – mechanism two F (1,138) = 5.23, $p = 0.0238$. The average design evaluation time for the participants who used the HMD to evaluate trial one - mechanism two was 40.98 seconds while the average design evaluation time for the participants who did not use the HMD was 51.88 seconds.

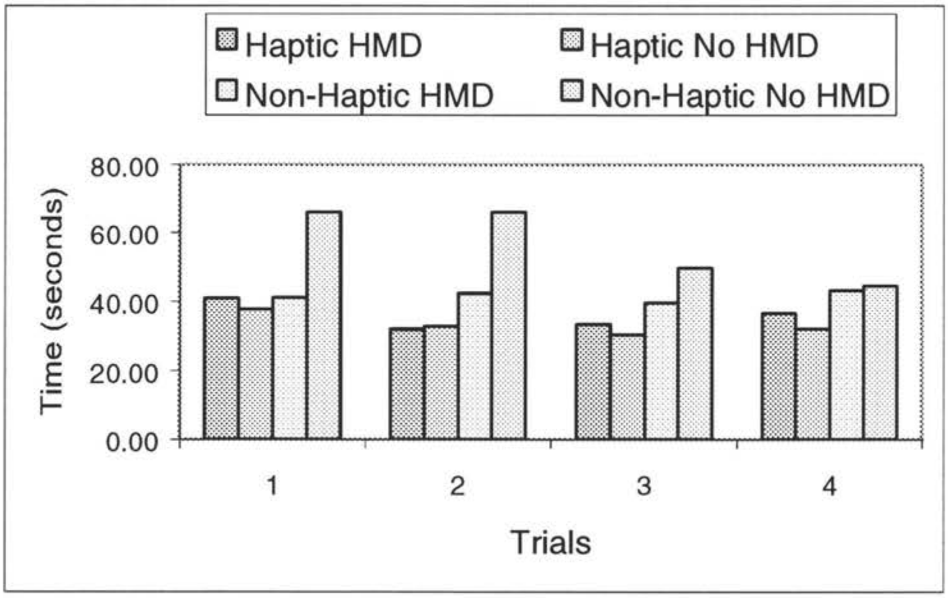

Figure 4.20. Average time for all groups to evaluate mechanism two, all four trials

The ANOVA also indicated that there was a statistical main effect of the treatment type on the average design evaluation time for trial one – mechanism two F (1,138) = 8.82, p = 0.0035. The participants who experienced the haptic treatment took an average of 39.19 seconds to evaluate trial one – mechanism two versus the non-haptic users average trial one – mechanism two design evaluation time of 54.77 seconds. Again, there was also an interaction between the display type (HMD or non-HMD) and the treatment type (haptic or non-haptic) found during the ANOVA. The ANOVA resulted in F (1,138) = 8.65, p = 0.0039 for the interaction. The interaction again indicated that participants had shorter trial one – mechanism two evaluation times when using either haptics or the HMD, but it was not additive; a participants' evaluation time would not be shorter by using the haptic treatment and the HMD at the same time.

Again, the ANOVA indicated that there was a statically significant main effect of the treatment type on the mean evaluation times of mechanism two for the three remaining trials. The haptic participants took an average of 32.37 seconds to perform the design evaluation for trial two – mechanism two while the non-haptic participants took an average of 46.28 seconds to perform the design evaluation for trial two – mechanism two. The ANOVA resulted in $F(1,138) = 13.09$, $p = 0.0004$.

The ANOVA for the main effect of treatment type on the mean design evaluation times of trial three – mechanism two resulted in $F(1,138) = 6.61$ $p = 0.0112$. The participants who experienced the haptic treatment had a shorter trial three – mechanism two average design evaluation time of 31.72 seconds, while the non-haptic participants took an average of 42.24 seconds to evaluate trial three – mechanism two.

The ANOVA for the main effect of the treatment type on the mean design evaluation times of trial four – mechanism two resulted in $F(1,138) = 8.44$, $p = 0.0043$. The participants who experienced the haptic treatment had a mean trial four – mechanism two design evaluation time of 34.12 seconds, while the non-haptic treatment participants averaged 45.41 seconds to evaluate trial four – mechanism two.

Figure 4.21 displays the average time for each treatment group to evaluate mechanism two when all four trials are combined. The ANOVA signified a statistically significant main effect of the treatment type on the mean design evaluation times for mechanism two over all four trials F (1,138) = 13.78, $p = 0.0003$. The participants who experienced the haptic treatment took an average of 34.39 seconds to evaluate mechanism two over all four trials, while the non-haptic participants required an average of 47.18 seconds to evaluate mechanism two over all four trials.

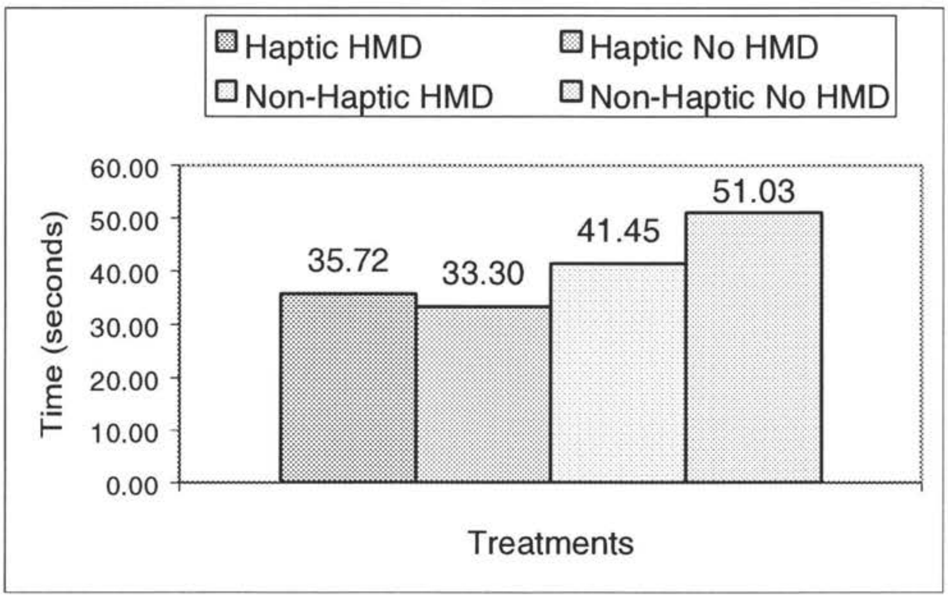

Figure 4.21. Average time to evaluate mechanism two, all four trials combined

Discussion

The time that each participant required to evaluate each design was greatly affected by which treatment they experienced (haptic or non-haptic) and was often affected by their method of display (HMD or non-HMD). Throughout each trial and each mechanism, the haptic participants consistently took less time to evaluate the design mechanism than the participants who did not experience the haptic treatment. HMD users were also shown to take less time evaluating both mechanisms one and two during trial one than non-HMD users. This implies that HMD users were either more confident of their first design evaluation than non-HMD users and thus took less time, or that it was easier for HMD users to comprehend what was expected of them during trial one (therefore it took HMD users less time to evaluate both mechanisms in trial one) than it was for non-HMD users. Again, there was an interaction found between the treatment type, haptic or non-haptic, and display type, HMD or DD for trial one with both mechanisms one and two regarding design evaluation times. However, the effect of treatment and display type are not additive, meaning that using the haptic treatment coupled with the HMD did not decrease a participants' design evaluation time for mechanisms one and two during trial one.

It can be noted also, that during the experimental session, participants (regardless of their treatment group) consistently took less time to evaluate each pair of mechanisms in each successive trial. The final two trials had parking brake arm length and angle of motion differences between mechanisms while the first two trials had arm location differences. The fact that participants (regardless of their treatment group) consistently answered a higher percentage of questions about parking brake angle of motion questions correctly than other types of questions leads to the assumption that differences in angle of motion between mechanisms were easier for participants to detect, and therefore took them less time to evaluate. As one participant who experienced the haptic treatment with the HMD commented:

> "The easiest change to detect is change in rotation angle or length of shaft. Position changes were hard to detect."

With this experiment design, it is impossible to determine if the participants could more easily detect differences between mechanisms in the later trials than they could in the earlier trials, if the participants were becoming more comfortable about what was expected of them, and thus took less time, or if the problems presented in the later trials are simply easier than the problems presented in the earlier trials. If the order in which each trial is presented were switched from participant to participant, the effect of learning of the participant (becoming more familiar with what is expected of them) could be tested.

Participants' treatment preference

By gathering the data from each of participants' responses to the questions presented in Appendix B, the treatment preferences from each of the treatment groups could be tabulated. Each question was analyzed individually with each of the treatment groups in its own column. The data are presented in tabular form in Table 4.3.

Table 4.3. Participants' treatment preferences by percentage of participants

Question	Preference	Haptic HMD	Haptic No HMD	Non-Haptic HMD	Non-Haptic No HMD
Q1	Haptic	93.55	94.74	77.42	92.11
	Non-Haptic	6.45	0.00	3.23	7.89
	No Preference	0.00	5.26	19.35	0.00
Q2	Haptic	93.55	86.84	83.87	86.84
	Non-Haptic	3.23	0.00	0.00	10.53
	No Preference	3.23	13.16	16.13	2.63
Q3	Haptic	93.55	92.11	70.97	78.95
	Non-Haptic	0.00	5.26	12.90	5.26
	No Preference	6.45	2.63	16.13	15.79
Q4	Haptic	61.29	65.79	58.06	63.16
	Non-Haptic	16.13	7.89	6.45	5.26
	No Preference	22.58	26.32	35.48	31.58
Q5	Haptic	74.19	89.47	87.10	76.32
	Non-Haptic	9.68	0.00	6.45	10.53
	No Preference	16.13	10.53	6.45	13.16
Q6	Haptic	87.10	92.11	90.32	89.47
	Non-Haptic	6.45	0.00	3.23	2.63
	No Preference	6.45	7.89	6.45	7.89
Q7	Haptic	83.87	97.37	87.10	86.84
	Non-Haptic	9.68	0.00	9.68	7.89
	No Preference	6.45	2.63	3.23	5.26
Q8	Haptic	83.87	100.00	80.65	92.11
	Non-Haptic	6.45	0.00	6.45	7.89
	No Preference	9.68	0.00	12.90	0.00

It is readily apparent from the preference figures that regardless of which treatment a participant experienced throughout the experimental session, they (as a whole) preferred the haptic treatment to the non-haptic treatment in each of the questions asked of them. As one participant who experienced the non-haptic treatment with the HMD commented:

> "I preferred the haptics on when I was testing because it made it much easier to determine depth of items in the car. It also gave me a better sense of where I was and what was going on around me."

The preference figures follow.

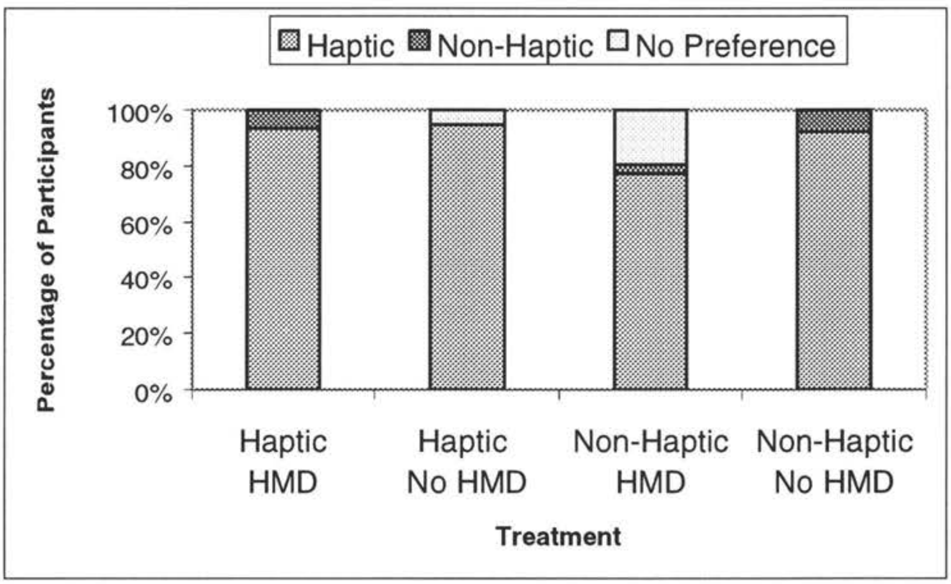

Figure 4.22. Participants' treatment preference on question 1 (which method participants would choose to use while comparing mechanisms), by percentage of particpants

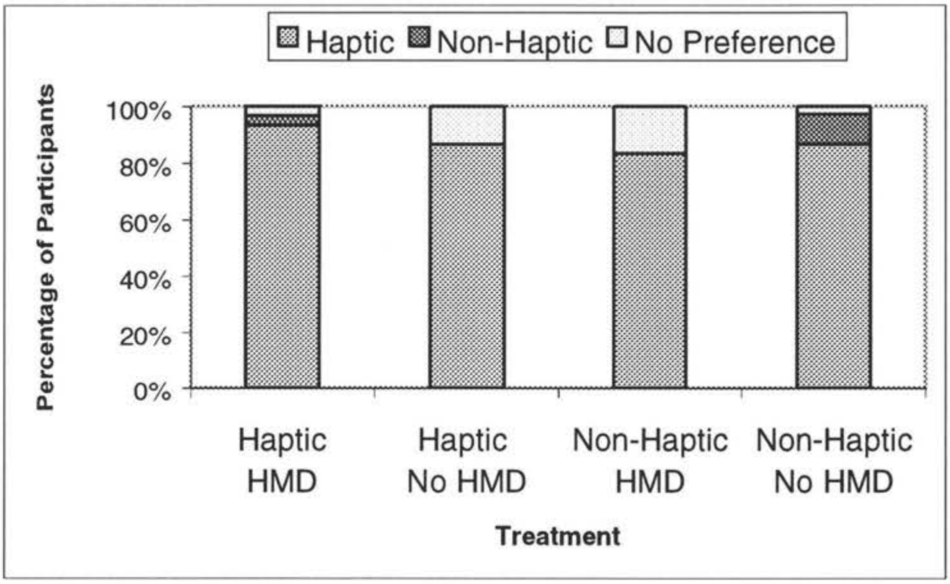

Figure 4.23. Participants' treatment preference on question 2 (which method provides the most information about a mechanism), by percentage of participants

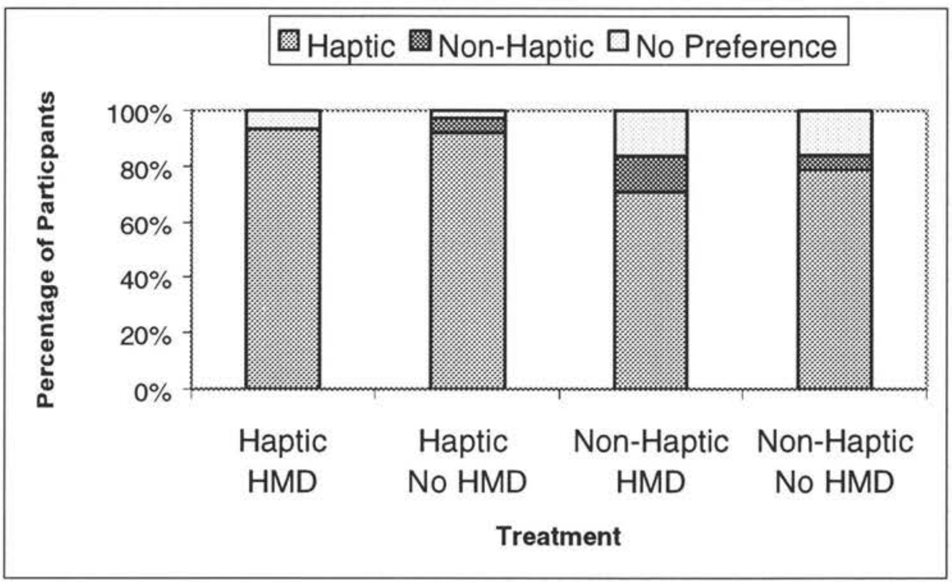

Figure 4.24. Participants' treatment preference on question 3 (method participants felt most comfortable using), by percentage of participants

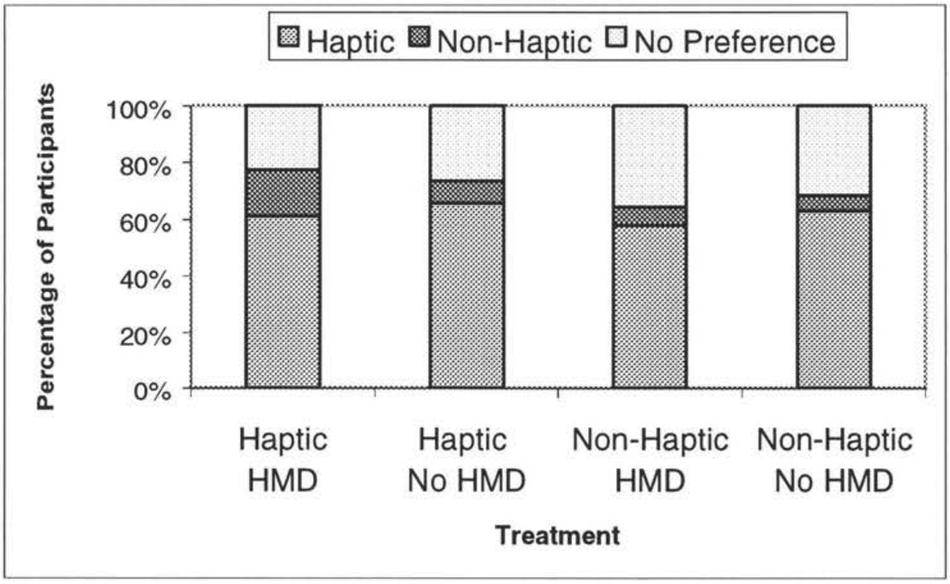

Figure 4.25. Participants' treatment preference on question 4 (method that made it easiest to intersect the pen with a mechanism's active point), by percentage of participants

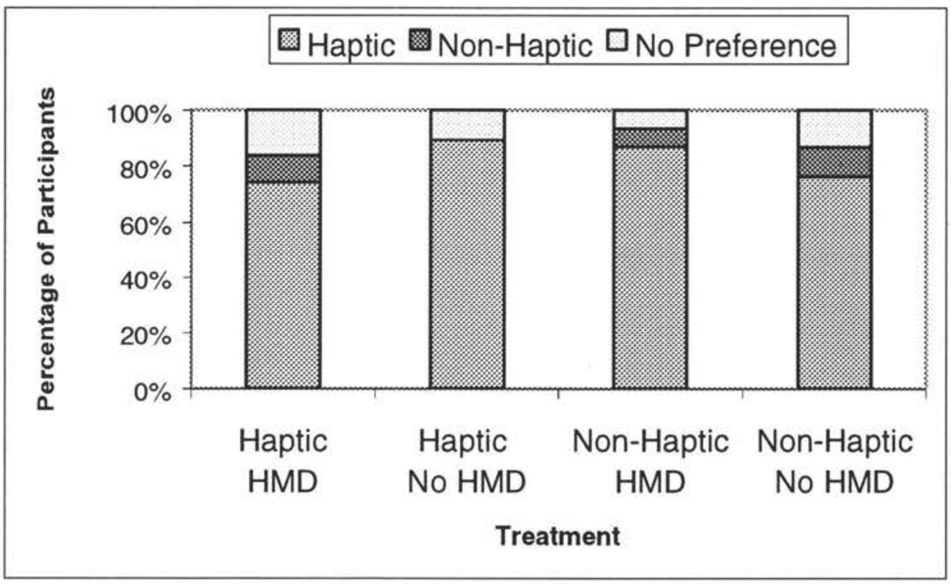

Figure 4.26. Participants' treatment preference on question 5 (method that made it easiest to understand the position of a mechanism), by percentage of participants

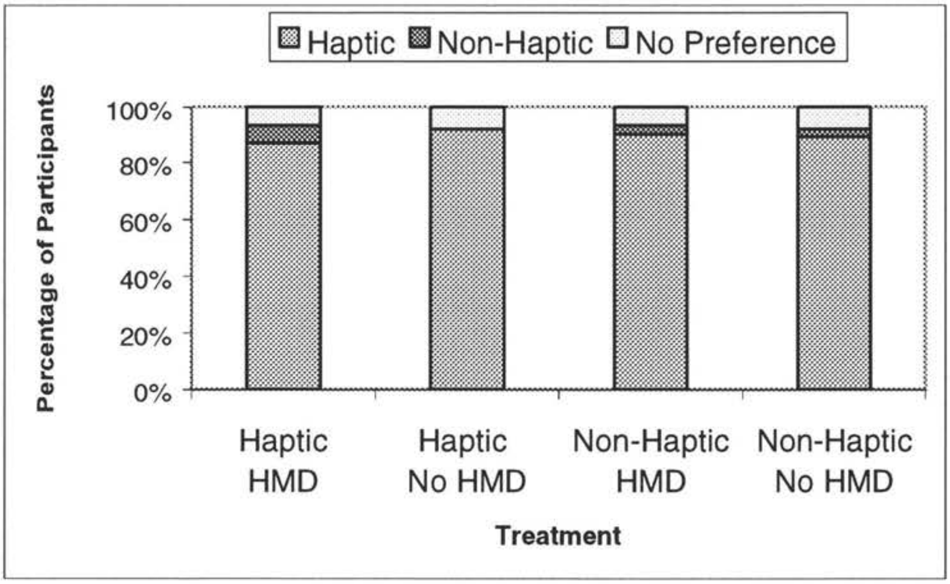

Figure 4.27. Participants' treatment preference on question 6 (method that made it easiest to understand the motion of a mechanism), by percentage of participants

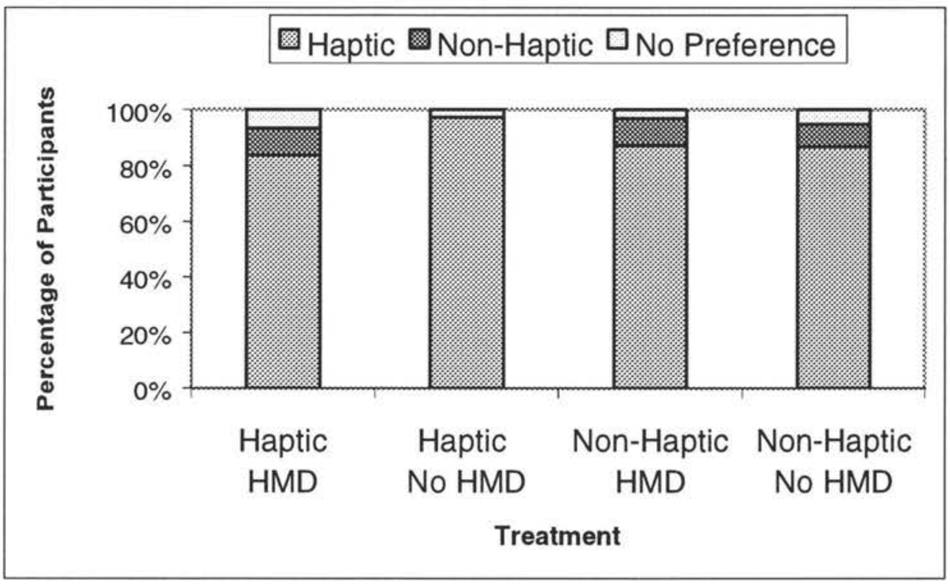

Figure 4.28. Participants' treatment preference on question 7 (method that would be the fastest for evaluating mechanisms), by percentage of participants

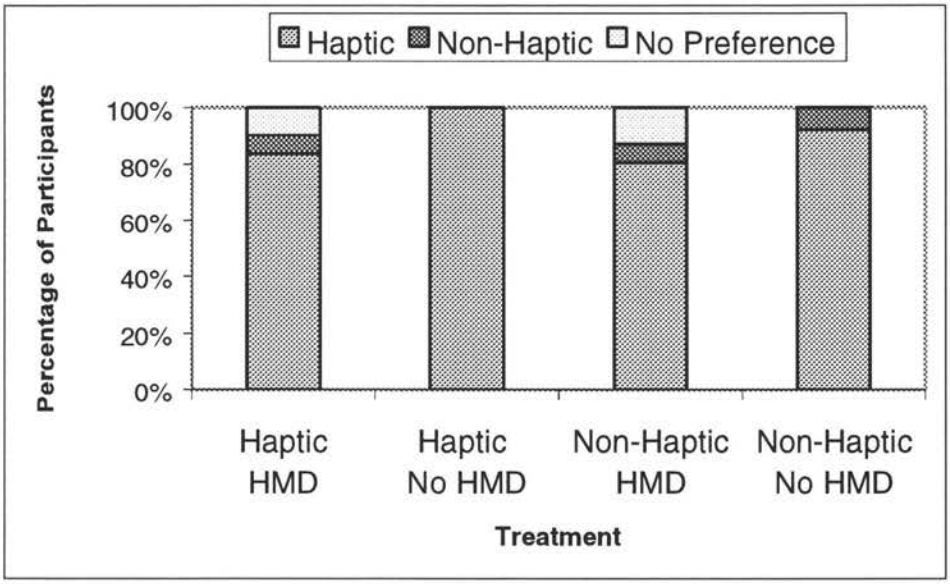

Figure 4.29. Participants' treatment preference on question 8 (method that is most effective for comparing mechanisms), by percentage of participants

The participants' treatment preference data were also analyzed by creating an overall treatment preference for each treatment group for each question. This was done by summing the preferences of each participant in each treatment group for each question; a value of one (1) was given to a participant who preferred the haptic treatment, a value of negative one (-1) was given to a participant who preferred the non-haptic treatment, and a zero value (0) to a participant who indicated that they did not have a preference between the two treatments. When the data were compared this way, the ANOVA indicated that there was a statistically significant main effect of the treatment type on the participants' preferences on question three $F(1,138) = 7.29$, $p = 0.0078$. The participants who experienced the haptic treatment initially, preferred haptics on question three (which method the participant felt most comfortable using) to a greater extent (92.8% of the participants) than did the participants who initially experienced the non-haptic treatment (75.4% of the participants). The percentage data for the haptic and non-haptic participants preferences on question three are shown in Figure 4.30.

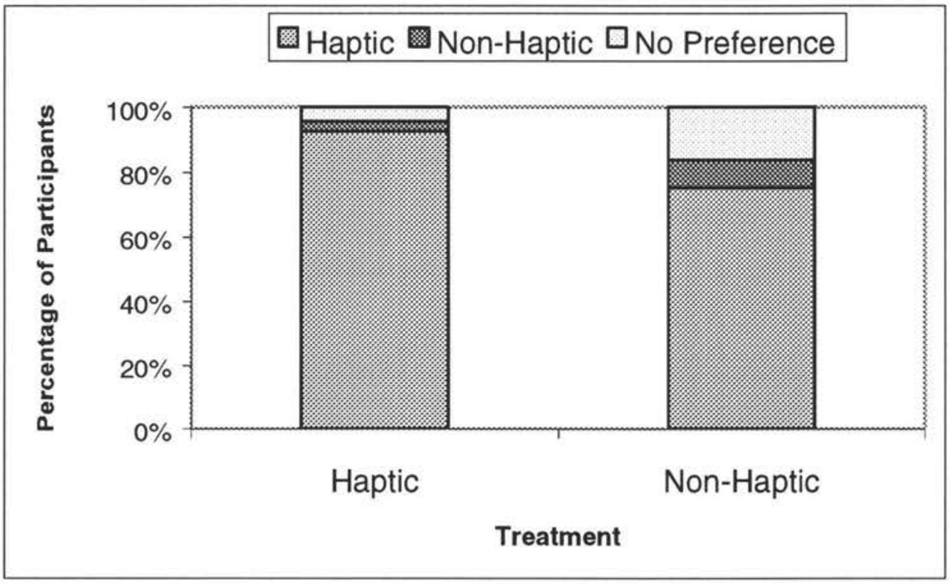

Figure 4.30. Participants' treatment preference on question 3 (method the participant felt most comfortable using), by percentage of participants, haptic versus non-haptic users

The ANOVA also indicated that question 8 in Appendix B (method that is most effective for comparing mechanisms) had a statistically significant main effect of display type on the participants' preferences $F(1,138) = 4.31$, $p = 0.0398$. The participants who used the HMD preferred the haptic treatment to a lesser extent (82.3% of the participants) than the participants who did not use the HMD (96.1% of the participants). The participants' preference percentages are shown in Figure 4.31.

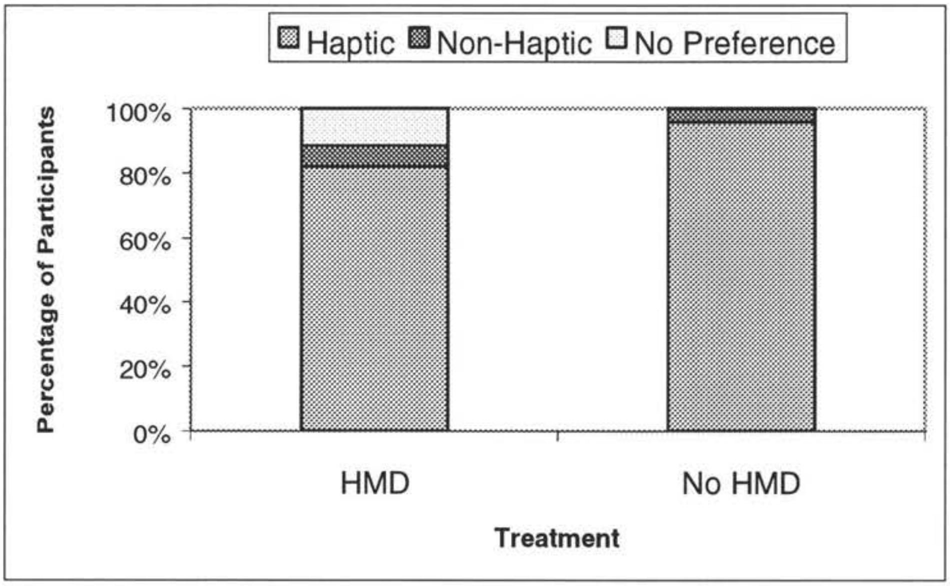

Figure 4.31. Participants' treatment preference on question 8 (method that is most effective for comparing mechainsms), by percentage of participants, HMD versus non-HMD users

Observations and Discussion

This study found that the VE display type, either HMD or DD, affected participants' ability to detect mechanism differences related to motion, arm length, and distances (mechanism length and location) as well as influenced the amount of time required to evaluate each mechanism design during trial one. The treatment type, haptic or non-haptic, affected participants' ability to estimate mechanism differences, influenced the detection of mechanism arm length differences, and resulted in differences in the amount of time needed to evaluate each mechanism design. Regardless of which treatment participants initially experienced, participants overwhelmingly preferred the haptic treatment to the non-haptic treatment.

Due to the fact that this study was essentially made up of two different experiments joined together as one, it was imperative that differences between the participants and the experimental sessions were kept to a minimum. However, because the study involved human subjects, some variations are inevitable. The most obvious (to the researcher) variation between participants was their physical differences while performing the experiment, and upon what each participant was trying to base their perceived location differences.

The chair that each participant sat in was at a fixed location in relation to the haptic device, but there were many different ways that participants either sat in the chair, or placed their right arm while completing the study. Some participants chose to keep their arm free from their body and to try to judge location differences solely based on what it visually looked like. Others kept their right elbow close to their body enabling them to determine location differences based on the change in either the pressure their elbow put on their torso, or the movement that their arm made as it followed the mechanisms. Still others tried to plant their entire right arm on their right leg to give them a more stable base to judge location differences. There were of course, a number of participants who tried one or more of the above methods throughout their simulation experience as well. As one participant who experienced the haptic treatment and the HMD commented:

> "It was difficult to determine how much movement took place from mechanism to mechanism, so I had to think hard. If my elbow had been stabilized (like on a 'virtual armrest') it might have been easier to judge if the angle of rotation had changed."

Participant's arm location was not recorded as part of the study, and since many participants changed their position from trial to trial, it is difficult to classify a participant as having any defined arm position at all. Thus, it cannot be determined by this study which arm position approach (if any) resulted in the most accurate detection of mechanism differences.

Many participants varied as to what they were basing their detection of mechanism differences upon as well. Some tried to rely solely on their visual acuity and indicated a difference between mechanisms if things "looked different" to them; others had a more systematic approach and tried to measure the length of the parking brake shaft and/or the distance between the parking brake shaft and stationary objects (steering wheel, dashboard, etc) using the pink ball which simulated the cursor of the haptic device, as one participant who experienced the haptic device and the HMD commented:

"While doing this experiment, I tried to locate the parking brake in relation to the steering wheel and the cup holder. It proved to be difficult because it was hard to remember exactly what the first looked like in relation to the second. I knew something was different, but I couldn't always tell what."

Still other participants would repeatedly move the pink ball of the virtual pen back and forth from the virtual parking brake to other virtual objects in order to memorize the approximate distance that their arm/hand moved. Some of the participants who used the HMD also tried to incorporate their head movements as a gauge to determine mechanism differences; participants would try to keep their eyes pointed directly at mechanism one, and when it switched to mechanism two, the participant would move their eyes and head accordingly.

Another way in which participants differed from one another was their ability to attribute spatial differences between the mechanisms to specific X, Y, Z (right – left, forward – rearward, high – low) planes. Each mechanism difference was a combination of three location changes or two motion changes of the parking brake, which some participants were able to distinguish more successfully than others.

In the case of the location differences (trials 1 and 2), the mechanism differences occurred in all three directions (X, Y, and Z planes). The three location differences, each of 0.875 inches, created an overall mechanism difference of 1.5 inches between mechanisms one and two. Many participants were able to detect the 1.5-inch difference, but were unable to determine its specific directional components. As the experimental session was conducted, participants were given one opportunity to examine mechanism one, and then the simulation was switched to mechanism two. By allowing repeated viewings of mechanisms one and two (possibly one viewing for each X, Y, and Z plane), participants would most likely be able to determine directional components more successfully.

The motion changes (trials 3 and 4) also caused difficulty with some participants as several combinations of parking brake shaft length changes and angle of motion changes could result in the same overall mechanism difference. Although most participants could detect a difference between mechanisms one and two, they were unable to attribute that difference to the length of the shaft being different, the angle of rotation changing, or a combination of both.

It is difficult to foresee possible ways in which human subjects will find to make their experimental session slightly different from the next participant. Any way in which an experiment can be designed to minimize variation between participants is a benefit to the overall results of the study. Future human factor studies could provide an armrest or some sort of arm position stabilization device for the participants to give a more consistent participant arm position from experimental session to session. Future studies could also suggest possible ways in which the participant could try to detect and measure differences between mechanisms when the experimental process is being described.

The simulation presented to participants in this study was rather simplistic (basic location and motion difference detections); it is possible that as more complex VEs that require more thought and concentration from the participant are developed, the use of a

HMD (increased immersion level in the virtual simulation) would have more of an effect on users' performance. The same experiment, run with a more complex VR simulation, could be conducted as a future study in order to better determine the affect of HMD use. The future study also could monitor participants' level of head movement with the HMD as opposed to the desktop monitor to determine if HMD users "look around" more in the VE. Participants' level of disorientation and dizziness could be a measurable factor as well by making the simulation time substantially longer than the time involved in this study (approximately 15 minutes total) thus enabling researchers to evaluate participants' performance with prolonged exposure to a VE.

CHAPTER 5. CONCLUSIONS AND FUTURE WORK

CONCLUSIONS

This study was designed to evaluate how haptic force feedback and the use of a HMD (HMD) affects human ability to evaluate designs, and human ability to detect differences between alternative mechanism designs. One hundred thirty-eight volunteers participated in the study and were asked to determine location and motion differences between two sets of virtual parking brake designs.

Participants using a HMD in comparison to a desktop monitor display were found to:

- Answer more questions about mechanism motion correctly.
- Answer more questions related to mechanism arm length differences correctly.
- Answer fewer questions about distances (mechanism length and location) correctly.
- Take less time to evaluate both mechanisms one and two in trial one.
- Show a somewhat lower preference for haptics as “the method that is most effective for comparing mechanisms”.

Participants who experienced the haptic treatment in comparison to the non-haptic treatment were found to:

- Answer fewer questions related to mechanism arm length differences correctly.
- Be more accurate in estimating forward – rearward parking brake location differences.
- Be less successful in estimating high – low parking brake location differences.

- Take less time to evaluate each mechanism design.
- Show a somewhat higher preference for haptics as "the method you felt most comfortable using".

Regardless of which treatment participants initially experienced, participants overwhelmingly preferred the haptic treatment to the non-haptic treatment.

It was expected that by having an increased sense of immersion (use of the HMD) participants would increase their performance in detecting mechanism differences between the virtual parking brakes. This was not found to be the case.

Several studies have found that haptics reduces task completion time (Hasser and Massie, 1999, Lindeman et al., 1999, Volkov and Vance, 2000). The work presented here further supports this finding. This study did not support the findings of Hasser and Massie (1999) that haptic reduced errors. This study found that the use of haptics enabled participants to be more successful in estimating forward – rearward mechanism differences, but less successful in estimating high – low mechanism differences. This study also determined that the presence of haptics actually increased the number of errors participants made in detecting mechanism arm length differences. It was difficult to determine if haptic reduced dependence on vision

RECOMMENDATIONS FOR FUTURE WORK

This study pinpointed several effects of haptic force-feedback and the use of a HMD on the ability of humans to evaluate virtual mechanisms. For continuous research in this area, it would be beneficial to minimize or eliminate the areas of potential variation between participants as well as to isolate the variables within the mechanism differences. This could be done by the following:

- Provide a more physically constrictive seating arrangement for participants so their position is more uniform.
- Suggest mechanism difference detection methods to participants before session begins.
- Vary directional design differences one at a time.
- Randomly switch the sequence of trial presentation to participants.
- Allow repeated viewings of mechanisms one and two during each trial.
- Increase the level of complexity of the VE.
- Measure the HMD participants' head movement.
- Increase the amount of time participants are immersed in the VE.

APPENDIX A. SURVEY FORM

INTRODUCTORY SURVEY

Basic Information

Subject ID # : __________ Age : _______

Date : ________________ Current Time : _________ AM / PM

Gender : Male Female

Country Born : __________ if not US, how long have you lived in the US : ________

Vision Information

Are you? _____ Near Sighted (Can see things that are close)

_____ Far Sighted (Can see things that are far)

_____ Normal Vision

Will you be wearing today?

_____ Glasses

_____ Contacts

Is this your normal means of vision correction? YES NO

Dominant Hand

Are you? _____ Right Handed

_____ Left Handed

Occupational Information

Please check / fill in all that apply:

_____ Student at ______________________________

_____ Employee at ____________________________

If you are a student:

Major / Minors : __________________ Year / Classification : __________________

Subject ID # : _________

PREVIOUS EXPERIENCES

Indicate (roughly) the number of days / months / years experience that you have with:

IBM or compatible :	____________	days months years
Apple / Macintosh :	____________	days months years
SGI / SUN / UNIX :	____________	days months years
Other : _________________	____________	days months years

Please mark on the scale below to indicate how comfortable you feel learning new computer applications.

|________________|__________________|__________________|__________________|

Extremely	Very	Moderately	Minimally	Not at all

Indicate (roughly) the number of days / months / years experience that you have with:

Automobile Interior Evaluation :	____________	days months years
Virtual Mock-ups :	____________	days months years
Virtual Automobile Interior Evaluations :	____________	days months years
Virtual Reality :	____________	days months years
Haptic devices :	____________	days months years

How long ago was your most recent experience with a haptic device : _________________

Please list all the haptic devices you have used. (If you do not remember the names, the administrator can provide assistance)

____________________________ ____________________________

____________________________ ____________________________

____________________________ ____________________________

Appendix B. Questionnaire Form

Subject ID # : _________ Trial # : _____

With haptics : _________ Without haptics : ________

Participant's Response About Differences Between Hand Brake Designs

Please circle the response that fits best. Enter your best estimate for the offset (if any), indicating the units of your choice.

LOCATION : These questions refer to the location of the active point of the virtual mechanism when it is in the full down position.

1. The 2nd mechanism in the relation to the 1st mechanism is located :

   TO THE RIGHT / IN THE SAME PLACE / TO THE LEFT

   Please estimate the distance of offset (if any) _______ inch cm

2. The 2nd mechanism in relation to the 1st mechanism is located :

   HIGHER / IN THE SAME PLACE / LOWER

   Please estimate the distance of offset (if any) _______ inch cm

3. The 2nd mechanism in relation to the 1st mechanism is located (along the long axis if the car) :

   FORWARD / IN THE SAME PLACE / REARWARD

   Please estimate the distance of offset (if any) _______ inch cm

MOTION : These questions refer to the motion of the virtual mechanism.

4. The 2nd mechanism in relation to the 1st mechanism has an arm length (distance from active point to pivot) that is :

   SHORTER / THE SAME / LONGER

   Please estimate the distance of offset (if any) _______ inch cm

5. The 2nd mechanism in relation to the 1st mechanism has a total rotation (degrees of rotation about its pivot) that is :

   SMALLER / THE SAME / LARGER

Please estimate the difference (if any) _______ degrees

Subject ID # : _________

With haptics : _________ Without haptics : ________

PARTICIPANT'S TREATMENT PREFERENCE

1. Circle the method you would choose to use while comparing mechanisms :

   HAPTICS NOT ACTIVE HAPTICS ACTIVE

2. Circle the method that provides you with the most information about a mechanism :

   HAPTICS NOT ACTIVE HAPTICS ACTIVE

3. Circle the method you felt most comfortable using :

   HAPTICS NOT ACTIVE HAPTICS ACTIVE

4. Circle the method that made it easiest for you to intersect the pen with a mechanism's active point :

   HAPTICS NOT ACTIVE HAPTICS ACTIVE

5. Circle the method that made it easiest for you to understand the position of a mechanism :

   HAPTICS NOT ACTIVE HAPTICS ACTIVE

6. Circle the method that made it easiest for you to understand the motion of a mechanism :

   HAPTICS NOT ACTIVE HAPTICS ACTIVE

7. Circle the method that would be the fastest for evaluating the mechanisms :

   HAPTICS NOT ACTIVE HAPTICS ACTIVE

8. Circle the method that is most effective for comparing mechanisms :

   HAPTICS NOT ACTIVE HAPTICS ACTIVE

Subject ID # : _________

With haptics : _________ Without haptics : ________

PARTICIPANT'S COMMENTS

APPENDIX C. TIME RECORD FORM

Subject ID # : _________

With haptics : _________ Without haptics : ________

PARTICIPANT'S DESIGN EVALUATION TIMES

Trial 1

Time on 1st mechanism : ________________

Time on 2nd mechanism : ________________

Trial 2

Time on 1st mechanism : ________________

Time on 2nd mechanism : ________________

Trial 3

Time on 1st mechanism : ________________

Time on 2nd mechanism : ________________

Trial 4

Time on 1st mechanism : ________________

Time on 2nd mechanism : ________________

BIBLIOGRAPHY

Ansar, Adnan, Rodrigues, Denilson, Desai, Jaydev P., Daniilidis, Kostas, Kuman, Vijay, Campos, Mario F.M., 2001, "Visual and Haptic Collaborative Tele-presence," *Computers & Graphics,* No. 25, pp. 789-798.

Arns, Laura L, 2002, "A new taxonomy for locomotion in virtual environments," *Ph.D. Dissertation*, Iowa State University.

Arsenault, R., Ware, C., 2000, "Eye-Hand Co-ordination with Force Feedback," *Proceedings of the CHI 2000 Conference on Human Factors in Computing Systems,* Vol. 2, No. 1, pp. 408-414.

Aukstakalnis, S., Blathner, D., 1992, "Silicon Mirage, the Art and Science of Virtual Reality," *Peachpit Press, Inc.,* pp. 70-99.

Arthur, Kevin W., 2000, "Effects of Field of View on Performance with Head-Mounted Displays," *Ph.D. Dissertation*, UNC Department of Computer Science.

Balasubramaniam, Mahadevan, Ho, Stephen, Sarma, Sanjay, Adachi, Yoshitaka, 2002, "Generation of collision-free 5-axis tool paths using a haptic surface," *Computer-Aided Design,* No. 34, pp. 267-279.

Biocca, Frank, Kim, Jin, Yung, Choi, 2001, "Visual Touch in Virtual Environments: An Exploratory Study of Presence, Multimodal Interfaces, and Cross-Modal Sensory Illusions," *Presence,* Vol. 10, No. 3, pp. 247-265.

Burdea, G., 2000, "Haptic Feedback for Virtual Reality," *International Journal of Design and Innovation Research,* Vol. 2, No. 1, pp. 17-29.

Burdea, G., 2000, "Haptic Issues in Virtual Environments," *Proceedings of Computer Graphics International 2000,* Geneva, Switzerland, pp. 295-302.

Chen, E., 1999, "Six Degree-of-Freedom Haptic System for Desktop Virtual Prototyping Applications," *Proceedings of the First International Workshop on Virtual Reality and Prototyping,* Lavel, France, pp. 97-196.

Cohen, A., Chen, E., 1999, "Six Degree-of-Freedom Haptic System for Desktop Virtual Prototyping Applications," *Proceedings of the ASME Winter Annual Meeting, Dynamics Systems and Control,* Nashville, Tennessee, DSC-vol. 76, pp. 401-402.

Cook, D., Cruz-Neira, C., Kohlmeyer, B., Lechner, U., Lewin, N., Nelson, L., Olsen, A., Pierson, S., Symanzik, J., 1998, "Exploring Environmental Data in a Highly Immersive Virtual Reality Environment," *Environmental Monitoring and Assessment,* Vol. 51, pp. 441-450.

Dachille IX, F., Qin, H., Kaufman, A., 2001, "A Novel Haptics-Based Interface and Sculpting System for Physics-Based Geometric Design," Computer-Aided Design, No. 33, pp. 403-420.

Fasse, Ernest D., Hogan, Neville, 1994, "Quantitative Measurement of Haptic Perception," *IEEE Conference on Robotics and Automation,* Vol. 4, pp. 3199-3204.

Hannaford, B., Wood, L., McAffee, D., and Zak, H., 1991, "Performance Evaluation of a Six-axis Generalized Force-reflecting Tele-operator," *IEEE Transactions on Systems, Man, and Cybernetics,* Vol. 21, No. 3, pp.620-633.

Hasser, C. J., and Massie, T. H., 1999, "The Haptic Illusion," *in Digital Illusion, Entertaining the future with High Technology,* pp. 287-310.

Hogan, N., Kay, B.A., Fasse, E. D., Mussa-Ivaldi, F.A., 1990, "Haptic Illusions: Experiments on Human Manipulation and Perception of 'Virtual Objects'," G*old Spring Harbor Symposia on Quantitative Biology,* Vol. LV, pp. 925-931.

Howarth, P.A., Costello, P.J., 1996, "The Nauseogenicity of Using a Head-Mounted Display, Configured as a Personal Viewing System, for an Hour," *Proceedings of the Second FIVE International Conference Palazzo dei Congressi,* Pisa, Italy.

Johnson, E., Thompson II, T. V., Kaplan, M., Nelson, D., Cohen, E., 1999, "Painting Textures with a Haptic Interface," *Proceedings of IEEE Virtual Reality,* pp. 282-285.

Kessler, G., Bowman, D., and Hodges, L., 2000, "The Simple Virtual Reality Library: An Extensible Framework for Building VE Applications," *Presence: Teleoperators and Virtual Environments,* Vol. 9, No. 2, pp. 187-208.

Klatzky, R. L., Lederman, S. J., and Matula, E. E., 1993, "Haptic Exploration in the Presence of Vision," *Journal of Experimental Psychology: Human Perception and Performance,* Vol. 19, No. 4, pp. 726-743.

Lathrop, William B., Kaiser, Mary K., 2002, "Perceived Orientation in Physical and Virtual Environments: Changes in Perceived Orientation as a Function of Idiothetic Information Available," *Presence,* Vol. 11, No. 1, pp. 19-32.

Lindeman, R., Sibert, J., Hahn, J., 1999, "Towards Usable VR: An Empirical Study of User Interfaces for Immersive Virtual Environments," *Proceedings of the CHI '99 Conference on Human Factors in Computing Systems,* pp. 64-71.

Massie, T. H., 1998, "A Tangible Goal for 3D Modeling," *IEEE Computer Graphics and Applications,* Vol. 28, pp. 62-65.

Massie, T., Salisbury, J., 1994, "The PHANToM Haptic Interface: A Device for Probing Virtual Objects," *Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems,* Chicago, Illinois.

Merriam, Webster, 1998, "Merriam-Webster's Collegiate Dictionary Tenth Edition," *Merriam-Webster, Inc.*

Oakley, I., McGee, M., Brewster, S., Gray, P., 2000, "Putting the Feel in 'Look and Feel'," *Proceedings of the CHI 2000 Conference on Human Factors in Computing Systems,* pp. 415-422.

Ott, R. Lyman, Longnecker, Michael, 2001, "An Introduction to Statistical Methods and Data Analysis, 5th Edition," *Duxbury/Thomson Learning.*

Pierce, Jeffrey S., Pausch, Randy, Sturgill, Christopher B., Christiansen, Kevin D., 1999, "Designing A Successful HMD-Based Experience," *Presence,* Vol. 8, No. 4, pp. 469-473.

Popescu, V., Burdea, G., Bouzit, M., 1999, "Virtual Reality Simulation Modeling for a Haptic Glove," *Computer Animation '99 Conference,* Geneva, Switzerland, pp. 185-200.

Popescu, V., Burdea, G., Bouzit, M., Hentz, V., 2000, "A Virtual-Reality-Based Telerehabilitation System with Force Feedback," *IEEE Transactions on Information Technology in Biomedicine,* Vol. 4, No. 1, pp. 45-51.

Psotka, Joseph, Lewis, Sonya A., King, Donald, 1998, "Effects of Field of View on Judgments of Self-Location: Distortions in Distance Estimations Even When the Image Geometry Exactly Fits the Field of View," *Presence,* Vol. 7, No. 4, pp. 352-369.

Repperger, D. W., Phillips, C. A., and Chelette, T. L., 1995, "A Study on Spatially Induced Virtual Force with an Information Theoretic Investigation of Human Performance," *IEEE Transactions on Systems, Man, and Cybernetics,* Vol. 25, No. 10, pp. 1392-1404.

Ruddle, Roy A., Payne, Stephen J., Jones, Dylan M., 1999, "Navigating Large-Scale Virtual Environments: What Differences Occur Between Helmet-Mounted and Desk-Top Displays?," *Presence,* Vol. 8, No. 2, pp. 157-168.

Salisbury, K., 1995,"Haptics: The Technology of Touch" *HPCwire Special. Van Dam, Andries. "Post-Wimp User Interfaces: The Human Connection."*

Salisbury, K., Brock, D., Massie, T., Swarup, N., Zilles, C., 1995, "Haptic Rendering: Programming Touch Interaction with Virtual Objects," *Proceedings of the 1995 Symposium on Interactive 3D Graphics,* Monterey, California, pp. 123-130.

Salisbury, K., Srinivasan, M. A., 1997, "PHANToM Based Haptic Interaction with Virtual Objects," *IEEE Computer Graphics and Applications,* Vol. 17, No. 5, pp.6-10.

Sheridan, T., 2000, "Interaction, Imagination and Immersion Some Research Needs," *Proceedings of the Symposium on Proceedings of the ACM Symposium on Virtual Reality Software and Technology,* pp. 1-7.

Snibbe, S., MacLean, K., Shaw, R., Roderick, J., Verplank, W., Scheeff, M., 2001, "Tactile User Interface: Haptic Techniques for Media Control," *Proceedings of the 14th Symposium on Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology,* pp. 199-208.

Song, C.G., Kwak, N.J., Jeong, D.H., 2000, "Developing an Efficient Technique of Selection and Manipulation in Immersive V.E.," *Proceedings of the Symposium on Proceedings of the ACM Symposium on Virtual Reality Software and Technology,* pp. 142-146.

Srinivasan, Mandayam A., Basdogan, Cagaty, 1997, "Haptics in Virtual Environments: Taxonomy, Research Status, and Challenges," *Computers & Graphics,* Vol. 21, No. 4, pp. 393-404.

Sutherland, Ivan E., 1965, "The Ultimate Display," *Proceedings of the IFIP Congress,* pp. 506-508.

Swing, E., 2000, "Adding Immersion to Collaborative Tools," *Proceedings of the Web3D-VRML 2000 Fifth Symposium on Virtual Reality Modeling Language,* pp. 63-68.

Volkov, Sergei, 2000, "Effectiveness of Haptic Sensation for the Evaluation of Virtual Prototypes," *Master's Thesis,* Iowa State University.

Volkov, Sergei, Vance, Judy M., 2001, "Effectiveness of Haptic Sensation for the Evaluation of Virtual Prototypes," *Journal of Computing and Information Science in Engineering,* Vol. 1, pp. 123-128.

Ware, C., Balakrishnan. R., 1994, "Reaching for Objects in VR Displays: Lag and Frame Rate," *ACM Transactions on Computer-Human Interaction,* Vol. 1, No. 4., pp. 331-356.

Yoshikawa, Tsuneo, Nagura, Akihiro, 2001, "A Touch/Force Display System for Haptic Interface," *Presence,* Vol. 10, No. 2, pp. 225-235.