EFFECTS OF DISPLAY TYPE AND STEERING FORCE FEEDBACK ON PERFORMANCE IN A MEDIUM-FIDELITY DRIVING SIMULATOR

by

Chuck H. Perala

Thesis submitted to the faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Industrial and Systems Engineering
(Human Factors Engineering Option)

Approved:

Dr. John G. Casali, Chair

Dr. Gary S. Robinson

Dr. Tonya L. Smith-Jackson

May 2003
Blacksburg, Virginia

EFFECTS OF DISPLAY TYPE AND STEERING FORCE FEEDBACK ON PERFORMANCE IN A MEDIUM-FIDELITY DRIVING SIMULATOR

Chuck H. Perala

(ABSTRACT)

Research has shown that head-mounted displays (HMD) can produce greater presence in a virtual environment than direct-view displays (D-V). It has also been shown that after vision, haptic response is one of the most important inputs for humans in a simulated environment. This research was designed primarily to determine the performance differences associated with different display types, levels of steering force feedback, and the interaction between these two factors in a low-to-medium fidelity, PC-based driving simulator. Participants drove on a simulated driving course during which both objective driving performance data were collected (lane deviation, speed control, steering wheel angle variance, and time to the complete course) as well as subjective self-report measures including questionnaires designed to tap immersive tendencies and perceived levels of presence.

Results of the research show that the use of a head-mounted display can significantly impact driving performance in terms of speed control and lane deviation. Speed control was significantly improved (increased) and lane deviation was significantly improved (decreased) in three of the four roadway segments with the use of an HMD. Results for active steering force feedback, however, showed a significantly negative effect on driving performance with an increase in average lane deviation. Descriptive statistics showed that participants preferred the HMD and D-V equally and all but one participant preferred active steering force feedback.

“nam et ipsa scientia potestas est”

-Sir Francis Bacon

DEDICATION

This thesis is dedicated to my mother, Mrs. Iris Jane Perala, and my late father, Mr. Charles Harold Perala. You have always encouraged me to be the best that I could be in whatever I chose to do in life. Your love and support has never wavered and has empowered me to set and achieve goals far beyond my wildest dreams. Thank you.

ACKNOWLEDGEMENTS

I would like to express my gratitude to a few special people without whose support this thesis would not be possible. First, I would like to thank Theresa - my wife, my best friend, and truly the reason my life is so wonderful. Without her love, support, and tolerance, I would not be at such a point in life as this. I would also like to thank Dr. Robin Keesee, Director of the U.S. Army Research Laboratory's Human Research and Engineering Directorate for allowing me the privilege of better serving this great nation by providing the means with which to advance my knowledge and capabilities. As a former soldier, I am honored by his commitment to providing the best possible support for our armed forces. To Mr. Richard Haddox and Mr. Ronald Spencer, I thank for their steadfast friendship and support for so many years. They have been my leaders, mentors, colleagues, and true friends. Without their wisdom, patience, and willingness to assist me in my personal and professional growth, I would not have been in a position to have this opportunity.

To my one and only sibling, Ellie Krueger and her family, along with my wife's family, the Molnars, I extend very special thanks. For more than six years, during my undergraduate work at NCA&T, and my graduate work at Virginia Tech, they have all provided Theresa and me with much needed and much appreciated love, support and encouragement. This journey would have been truly difficult were it not for them.

To William Penhallegon, I also extend special thanks. He has been my very good friend, classmate, officemate, and co-conspirator on the design, building, and testing of the driving simulator used in this study. This process would have been more difficult and not nearly as fun without his knowledge, dedication, and wit. Thanks Bill!

I would like to thank my Virginia Tech thesis committee, Dr. John Casali, Grado Professor and Head of the Industrial and Systems Engineering Department, Dr. Gary Robinson, Research Professor and Auditory Systems Laboratory Manager, and Dr. Tonya Smith-Jackson, Assistant Professor and Assessment and Cognitive Ergonomics Laboratory Manager. Their commitment to teaching and research excellence is the reason Virginia Tech enjoys such a positive reputation. I have been honored to study and conduct my research under their careful and talented guidance.

Thanks also to the VPI statistics department for their advice and support, Dr. Robinson for that extra effort of support during the data analysis and reporting phases of my thesis work, and to the VPI electrical and mechanical support personnel: Will Vest, Kelcie Bower, Randy Waldron, Jeff Snider, Phillip Ratcliff, and Ronald Stables. Your expertise, timely response, and professionalism were truly integral to the success of this research.

Last, but certainly not least, to the many friends I have known or have met during my time here at Virginia Tech, I thank you for your friendship, loyalty, input into my research and thesis, and of course all the fun and good times we have enjoyed together. It is difficult to imagine life without sharing it with such wonderful people as yourselves. In no particular order, thanks to Tom Davis, Sybille Klenzendorf, Aaron Mooney, Jeff Lancaster, Anthony (Tony) Atkins, Elaine Oliver, Ryan Washington, and all of you whose names I may have unwittingly left out – you all know how much I appreciate you in your own special way!

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

INTRODUCTION

Simulators of innumerable types have long been developed and employed to help people represent, better understand, and study the real world. Simulators provide many advantages over the real world, such as cost savings, reduction of hazards, repeatability of presentations, accuracy of measurement, and reduction of time to complete tasks under observation. One of the most important factors in simulation is the ability to create a convincing level of similarity (presence) to the real world environment being simulated. Creating this sense of realism is one of the major challenges facing any type of simulation. Space flight simulators, for example, are designed to immerse astronauts in a simulated environment that closely approximates the real world environment in which they will be working. These types of simulations are essential in training astronauts in the complex and delicate missions that are performed in the very hazardous and costly environment of space, before they even leave the ground. This "virtual environment" (VE) ensures a greater level of control and safety for the astronauts to train in, and potentially make mistakes in, without posing great risk to themselves or the loss of high-cost systems in the vacuum of space. While not always computer-generated, virtual environments can generally be described as "computer-generated three-dimensional models, wherein a participant can interact intuitively in real time with the environment or objects within it, and to some extent have a feeling of actually 'being there' (the notion of presence)" (Wilson, 1996). The level of fidelity required in such a simulation is critical in convincing the human senses that they are actually operating in the real world. Visual fidelity is the degree to which visual features in the virtual environment conform to visual features in the real environment (Rinalducci, 1996). In other words, the greater the conformity, the greater the fidelity.

Driving simulation is in many ways similar to aircraft flight, space flight, and underwater environment simulation in that it allows people to be trained in conditions that, in the real world, could pose potential threats to themselves or the general public. As with the aforementioned advanced simulation systems, driving simulators must be designed to recreate the real world of driving as realistically as possible to convince the human senses that the simulation is real, or as real as possible for a given application.

Two of the most critical elements relating to driving simulator realism are visual displays and force feedback (Gordon, 1966). Visual displays provide the user with a visual representation of the real world. Force feedback provides physical cues and responses from the simulator controls that the user interacts with directly. Vehicle motion, steering feedback, vibration, and pedal and control response are examples of these types of cues and responses. In order to accurately represent an actual driving scenario, these two elements, along with many others, must be represented in such a way as to convince the user's senses that they are in the real world. Studies of steering force feedback and display type have been conducted using driving simulators to determine the effects of each on the performance of the user-vehicle system. There has been no research to date, however, to determine whether steering force feedback used in conjunction with a particular type of display system will create a greater level of presence within a virtual environment, and whether that increased presence has a significant impact on driver performance. If a significant increase in performance can be achieved with a specific feedback and display combination, then low-cost driving simulators like the one developed for this research could be considered a viable tool for use by the Department of Motor Vehicles (DMV) for driver license testing. The Virginia DMV has recently expressed an interest in this type of driving simulator application.

BACKGROUND

History of Simulation

A simulator is "a device that generates test conditions approximating actual or operational conditions" (Webster, 1984). Long before the age of computers and high-tech gadgetry, people have used the tools available at the time to represent or simulate some portion of the real world. Since humans have waged war on themselves since the beginning of recorded history, simulating the real world has been used extensively in the area of armed conflict. Before sending people and machinery forward into battle for conquest or defense, battle plans, strategies, and tactics were first developed and practiced on a simulated battlefield (Bradley, 1999). Such battlefield simulations may have been as simple as moving sticks around on the ground to simulate troop movements or enemy fortifications. Of course, the actual significance of this was the ability to test the feasibility of a strategy before a single person or piece of equipment was sent to the actual battlefield. This not only saved time, money, and lives, it also built confidence in the leadership and individual soldier being deployed to the battlefield. As an example, Operation Overlord (1944 D-Day Invasion) was simulated in England for months before the actual landings in Normandy (Bradley, 1999). Simulated German bunkers, fortifications, and positions were used to represent actual positions known to be in place in France. The ability to simulate the invasion allowed the allied forces to train thousands of troops on specific missions and tactics without placing them in harm's way and ultimately led to a successful campaign and probably saved the lives of untold numbers of soldiers. Battlefield simulations in more technology-based and usually "virtual" environments are routinely used and improved by today's military (Johnson and Stewart, 1999). The U.S. D.O.D. is continuously exploring potential uses of synthetic environments for pre-mission planning and rehearsal (Bell, Mastaglio, et al., 1993; Landry, 1994; Sottilare, 1995). Post Gulf War simulation battles such as "73 Easting" (Atwood, Winsch, et al., 1994) for instance, allow soldiers to adopt any virtual viewpoint on the battlefield. The soldiers can take a bird's eye view and watch the battle unfold from above or observe the battle from a commander's position (friendly or hostile). This virtual simulation capability is currently in use at Fort Knox, Kentucky and provides today's soldiers and military planners with invaluable tactical information before committing troops or equipment to any future battlefield.

While the military did not invent the notion of simulation, it certainly helped in its development, and continues to pioneer the way in which simulations are conducted. In 1947, MIT, in conjunction with the U.S. Navy, began development of Project Whirlwind (Laplante, Rose, et al., 1995). This project was conceived to develop an airplane trainer/analyzer to simulate the aerodynamic forces acting upon the pilot's controls. The "simulator" was the first high-speed electronic digital computer able to operate in "real-time". For the first time, a device was developed and used where the pilot's reactions in the simulator were as realistic (real-time) as those same reactions in the real world. This technology and the use of real-time computer systems continued to develop through projects like the NASA Mercury, Gemini, Apollo, and STS (Space Shuttle) programs. Today, everything from airplanes to space shuttles, automobiles, submarines, and new buildings is simulated at some point in its evolution, using computers.

Driving Simulators

Driving simulators have been around nearly as long as the automobile itself. They have been evolving for nearly 90 years and have been used for research, training, examination, vehicle design, roadway visualization, forensics, product testing and consumer market research (Wachtel, 1993). In recent years, the major automobile manufacturers around the world have employed the use of simulator technology to further their design, development and research efforts. Driving simulators allow researchers to observe the dynamics between the automobile and the driver on the road. Highly realistic data can be collected in a safe manner while the vehicle movements and driver responses are observed over a wide range of situations (Neray and DeMarco, 1998). Often, a researcher needs a critical piece of information that, in the real world, would be too difficult or dangerous to obtain. Placing human beings in a potentially hazardous situation to obtain research information is unethical and forbidden in modern U.S. research. Realistic driving simulations fill the void that previously existed between what data could be collected in the real world and what remained unknown due to the safety concerns. Driving simulators are currently being used in research for everything from vehicle system development to human factors studies by enabling researchers to reproduce actual driving conditions in a safe and tightly controlled environment (Lee, Kim, et al., 1998).

Driving simulators are generally thought of as "high-tech" devices. Throughout the literature, there is less discussion of the results and their application to real world problems, e.g., driver test scores, training time, accident reduction, etc., than there is about simulator technology itself. The driving simulator community, at least in the U.S., appears to be so caught up with the technology and the need to improve simulator performance that they fail to realize that its not only the simulator performance that counts, but also the driver performance (Wachtel, 1997). This study focused its primary attention and efforts on which design elements were most appropriate for a low-to-medium cost diving simulator, based upon measured "human in the loop" performance data.

The primary technology employed in most modern driving simulators is that which creates a virtual environment, or VE, in which the participant may interact. A virtual environment is a computer-generated three-dimensional model in which a participant can interact intuitively in real time with the environment or objects within it, and to some extent have a feeling of actually 'being there' (Wilson, 1999). The computer-generated displays provide information in the visual, auditory, and kinesthetic modalities (Slater and Usoh, 1993). Kinesthetics is a sensory experience derived from a sense mediated by end organs located in muscles, tendons, and joints, and stimulated by bodily movements and tensions. Virtual environments for driving simulators represent a challenge to developers. The environments require a combination of high-resolution visual, auditory, and haptic feedback in addition to modeling and control of believable agents and scenarios (Cremer, Kearney, et al., 1996). These requirements are essential to providing a high level of realism or presence to the person using the system.

The driving simulator used for this research was developed under contract by Virginia Tech's Auditory Systems Laboratory, with subcontractor assistance from Northeastern University. The VT-UVA-Carilion driving simulator (Penhallegon and Perala, 2002), APPENDIX C, was developed, in part, to determine the viability of using a low-to-medium cost, low-to-medium fidelity, PC-based driving simulator as a method of testing new drivers by the Virginia Department of Motor Vehicles (DMV). The first objective of the project was to integrate the necessary hardware and software components into a working "proof of concept" prototype simulator. Simulation software developed by Dr. Ronald Mourant at Northeastern University was integrated with the simulator hardware assembled by the Virginia Tech team.

Presence in Virtual Environments

Presence is generally defined as a subjective experience wherein a person is physically located in one place, but has the feeling or notion they are in another place or environment. As it is applied to a virtual environment, presence is the extent to which participants of a VE allow themselves to be convinced that they are somewhere other than where they physically are while experiencing the effects of a computer-generated simulation (Slater, Usoh, et al., 1994). It is believed that an increase in presence can positively affect the performance of a person within a virtual environment. This research attempted to support this theory by manipulating VE presence using particular combinations of display type and levels of steering force feedback.

In order for presence to be achieved and subsequently, operationally effective in a VE, a user's attention must be allowed to shift from the physical environment to the virtual environment. However, presence does not require the total displacement of attention from the user's physical surroundings (Witmer and Singer, 1998). There is debate whether a theoretical presence threshold exists that would need to be reached before presence is experienced in a VE. Assuming a threshold does exist, however, it is also reasonable to assume that increasing one's allocation of attentional resources beyond that threshold should result in a heightened sense of presence (Witmer and Singer, 1998). One way to assist in this increase of resources is by increasing the level of realism within the VE.

Creating a more realistic or believable VE experience is only a portion of what is required to achieve presence. According to Fontaine (1992), focus is also a key factor in presence. Focus occurs when a person directs attention toward an object of interest. Common everyday tasks, for instance, may require less focus than would new or unfamiliar tasks. These "novel" tasks or environments would require a broad level of focus. Fontaine (1992) also suggests that in order to achieve a high level of presence in a VE, this type of broad focus is necessary (Fontaine, 1992). McGreevey (1992) asserts that the experience of presence is based in attention to continuities, connectedness, and coherence of the stimulus flow (McGreevy, 1992). This means that experiencing presence in a VE requires the ability to focus on one meaningfully coherent set of stimuli (in the VE) to the exclusion of unrelated stimuli (in the physical environment). Physical environment stimuli are still integral to the coherent understanding of the whole environment in order to achieve presence. Feedback from the simulator seat, steering wheel, and control surfaces of a driving simulator, for instance, are stimuli in the physical environment and focusing attention on these stimuli is essential to achieving an encompassing environment (virtual and physical) that will help create a level of presence. Barfield and Weghorst (1993) suggest that a number of interacting factors might influence presence, including display fidelity, environmental stability, sensory bandwidth, interactive fidelity, and characteristics of the individual, task and context.

The simulator used in this study has characteristics that consider display fidelity, interaction fidelity, and individual participant characteristics (via a screening process) in order to increase the level of presence within the VE.

Hendrix and Barfield (1996) suggest that future subjective questionnaires evaluating presence within VEs should focus on the interactivity of the input devices used to manipulate virtual objects, system features such as update rates, and sensor delays in response to human movements (Hendrix and Barfield, 1996). Two other factors that are necessary for experiencing presence in virtual environments are involvement and immersion (Witmer and Singer, 1994; Witmer and Singer, 1998).

Involvement. Involvement is a psychological state experienced as a consequence of focusing one's energy and attention on a coherent set of stimuli or meaningfully-related activities and events. As users focus attention on stimuli (relative virtual and physical stimuli) within a VE, they become more involved in the VE experience. This increased level of involvement assists in leading the user to an increased sense of presence within the VE (Witmer and Singer, 1998). Conversely, if a user focuses attention on stimuli outside the VE, for instance, if they are sick or are preoccupied with personal problems, their level of involvement within the VE will decrease. This will subsequently decrease the level of presence within the VE. The level of involvement will vary according to how well the activities and events attract and hold the user's attention (Howe and Sharkey, 1998). In a VE such as a driving simulator, having the user perform tasks that are directly related to the environment (i.e., driving) as well as the notion that inattentiveness could result in a "crash" within the environment should provide sufficient attraction to hold the user's attention while in the VE.

Immersion. Immersion is also a psychological state and is characterized by the perception of being enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences (Witmer and Singer, 1994). As with involvement, a VE that produces a greater sense of immersion will produce higher levels of presence. Some factors affecting immersion are isolation from the physical environment, perception of self-inclusion within the VE, and natural modes of interaction and control.

One way of providing a measure of visual isolation in a driving simulator VE is by the use of a head-mounted display (HMD). Despite being involved in the VE through the presentation of coherent and meaningful stimuli, if the user perceives they are outside the simulated environment looking in, the immersive aspect of presence is lost (Pierce, Pausch, et al., 1999; Witmer and Singer, 1994). Using a direct-view display (D-V) like a CRT (cathode-ray tube) or plasma-based display does not provide a level of isolation comparable to an HMD (Ruddle, Payne, et al., 1998).

If a driving simulator can provide the user with the ability to drive, look, and interact with elements inside the VE, then the user has a greater sense of self inclusion within the VE. The user will be more immersed in the VE if self-inclusion is increased (Barfield, Zeltzer, et al., 1995; Pierce, Pausch, et al., 1999; Witmer and Singer, 1994). One factor that makes this possible is a realistic looking and acting/reacting environment. Visual, auditory and haptic elements play an important role in making a more realistic VE (Barfield, Zeltzer, et al., 1995; Pierce, Pausch, et al., 1999; Witmer and Singer, 1994).

The more control a person has over the task environment or their interaction in the VE, the greater the level of immersion, and, subsequently, presence within the VE (Sheridan, 1992). A more natural mode of control within the VE may also enhance immersion/presence. If the mode of control is artificial or requires learning new responses in the environment, presence may be diminished until those responses become well learned (Zeltzer, 1992). Noticeable delays between the action and the result will also diminish the sense of presence in the VE (Frank, Casali, et al., 1988a; Held and Durlach, 1992). A modern PC-based video game (flight simulator, driving simulator, etc.) for instance, may lead to a high level of involvement by the user yet have poor immersive qualities. The level of immersion would be diminished by the less-than-realistic VE, usually consisting of a PC monitor, inadequate sound reproduction, and limited or non-existent haptic controls (seat, steering wheel, pedals, etc.).

It can be concluded that the level or strength of presence experienced by a user in a VE is a function of both individual user differences and the characteristics of the VE. This research focused on the latter by looking at two specific elements of a driving simulator, visual display type and presence/absence of steering force feedback, and determining whether the increased level of presence created by certain conditions represented in these two elements increased driver performance.

Measuring presence. According to Sheridan (1992), presence is a subjective sensation or mental manifestation that is not easily amenable to objective physiological definition and measurement. Although Sheridan does not dismiss the notion of objectively measuring presence, he concedes, "Subjective report is the essential basic measurement" (Sheridan, 1992). With this in mind, part of this research included the examination of participant's responses to subjective questionnaires regarding the level of presence experienced while using the driving simulator developed for this experiment.

Spending exorbitant amounts of money and resources on a simulator that employs features including a six-degree-of-freedom motion-based platform and a high-end front projection simulated environment could certainly enhance the participant's level of presence. This research was limited in scope, however, due to the ultimate application objective of the simulator. Although the primary criteria for this research included "low-cost and medium-fidelity," increasing the participant's level of presence could still be achieved by focusing on the factors most relevant to creating a realistic virtual environment: visual, auditory, and haptic sensation (Barfield, Zeltzer, et al., 1995; Brookhuis, DeWaard, et al., 1994; Liu, 2001). As mentioned above, this research focused on two of these factors (visual displays and steering force feedback) and how their interaction affected presence and performance. Past research has shown that when present under daytime driving conditions, the visual stimulus is the most important element to a participant in a VE, (Barfield, Zeltzer, et al., 1995; Brookhuis, DeWaard, et al., 1994; Hirota and Hirose, 1995; Lee, Yoo, et al., 1997; Liu and Chang, 1995). Another vital stimulus in these environments is haptic sensation (Gordon, 1966; Hirota and Hirose, 1995; Liu and Chang, 1995). Auditory stimuli are also important in the development of a VE simulator. The driving simulator for this research employed a sufficiently realistic level of auditory stimuli for the simulator's application, although auditory stimuli were not actually part of the focus of this study (Penhallegon and Perala, 2002).

By subjectively measuring the level of presence in the VT-UVA-Carilion prototype driving simulator, it was hoped that subsequent "production" versions of the simulator could be enhanced by ensuring that adequate levels of presence were attainable. The Singer and Witmer method of measuring presence in a VE was used for this purpose (Singer and Witmer, 1996). However, since presence is a factor of both the vividness of an experience and the level of interaction (Sheridan, 1992; Steuer, 1992), subjective reports alone may not be able to confirm that adequate levels of presence are occurring. It was hoped the performance measures collected during this study would provide the objective support necessary to determine whether the level of presence was sufficient to increase driving performance.

Simulator Displays

The development of virtual environments over the years has concentrated on simulating those elements that task human vision, "which is reasonable considering how much of the brain is devoted to visual processing" (McNeely, 1993). Since visual cues are most significant in controlling and maneuvering a vehicle during driving, it would seem reasonable that the key element for ensuring high fidelity in driving simulation is a realistic visual system. Processing of high-resolution graphics in the visual system is essential for the driver to have realistic driving feel and the ability to react to the driving environment precisely (Lee, Kim, et al., 1998).

It has been shown that visual display factors strongly influence the participant's sense of presence within VEs. Tests conducted by Slater and Usoh (1993) indicated the importance of providing users of VEs with spatial cues that will emulate spatial perception in real world environments. In other words, the fidelity with which a virtual environment synthesizes depth, space, and volume strongly affects the degree of presence experienced by the virtual environment participant (Slater and Usoh, 1993). Slater, et al. (1994) discovered a significant difference in the reported level of presence as a function of monoscopic and stereoscopic viewing conditions. In addition, differences in reported levels of presence between the 10, 50 and 90 degree geometric fields of view (GFOV) indicated that the bandwidth of the spatial information provided to the viewer also contributed to the sense of presence (Hendrix and Barfield, 1996). It was also shown that the fidelity of the interaction between the virtual environment participant and the virtual environment influenced presence. This conclusion is supported by the finding that head tracking, and thus motion parallax, increased the sense of presence, as did the ability to "reach into" the virtual environment (Slater and Usoh, 1993; Slater, Usoh, et al., 1994). A head tracker is a device that works in conjunction with an HMD and provides input to the computer system that allows for the interactive update of visual displays in response to the position and orientation of the wearer's head (Stuart, 1996). Head tracking also increases the perceptual fidelity of the system (Gigante, 1994) and provides a greater level of immersion in VEs without a wide field of view (FOV). This is because while using an HMD with a head tracker, the visual display dynamically updates to reflect the viewpoint of the user. For the purposes of driving simulation, head tracking allows the driver to see peripheral imagery external to the vehicle during head turning movements (e.g., looking left or right before making a turn).

Many driving simulators, from low-cost to high-end, employ a wide array of display options such as projection, direct-view (CRT, LCD, plasma), and head-mounted (Levine and Mourant, 1995;

Weir and Clark, 1995). This research tesed two of the more common display types used in lower-cost VEs; a direct-view display and a head-mounted display (Penhallegon and Perala, 2002).

Direct-view. Direct-view displays are those 'traditional' displays used as computer screens, video monitors, etc. and include CRTs (cathode-ray tube), LCDs (liquid crystal display), projection-based displays and plasma displays. Although there is no industry-standard term or acronym for all non-head-mounted displays, for the purposes of this study, all displays in this category will be referred to as direct-view displays or D-Vs. When using desktop displays, people receive feedback on their movements from visual changes in the displayed scene and the motor actions of their fingers on the interface devices (Ruddle, Payne, et al., 1998). Visual continuity during changes of view direction is achieved by constraining the rate at which the view direction is allowed to change; even with a graphics supercomputer, the equivalent of a glance over the shoulder takes one to two seconds. The process of glancing becomes more like an implicit instruction to "rotate until you are facing the intended direction and then rotate back." This changes the work required to integrate the information that is gained during the rotation with the user's existing spatial knowledge. With D-Vs (as opposed to HMDs, mentioned later), these types of seemingly trivial and natural tasks begin to feel mechanical and unnatural. When a head or body movement is executed using a D-V, the sense of realism (presence, immersion, etc.) is severely lacking. In fact, when a head turn is made within a VE using a D-V, the person's physical attributes remain the same, but the images and visual environment changes. This is a very unnatural experience for the user. By contrast, the visual feedback that people receive when using an immersive display (HMD) is supplemented by vestibular (relating to the sense of equilibrium) and kinesthetic feedback from their changes of direction (Ruddle, Payne, et al., 1999). The effect of this additional feedback on the user's ability to navigate is not known, but data from some real-world studies suggest that vestibular and kinesthetic feedback helps users to develop spatial knowledge and that physical changes of direction are more important than physical translationary movements for the development of that knowledge (Presson and Montello, 1994; Rieser, 1989).

Unlike an HMD system, where the display is very close to the user's eyes, a typical viewing distance for a desktop display used in a VE is approximately 24in. (Ruddle, Payne, et al., 1999). This distance between the user and the display further removes the user from the level of presence required to be fully immersed and involved in the VE by reducing the field of view of the display. These limitations are factors that should, according to the author's hypothesis, reduce performance when used in a driving simulator. Traditional direct-view displays (with the exception of projections on a curved screen, which can produce a 180° or more FOV) are also very heavy, large, and have a limited FOV (unless multiple displays are used) compared with HMD displays.

Head-mounted. A head-mounted display (HMD) is a projected-image display device that is worn on a person's head like a hat. The 'hat' is typically a molded plastic shell that houses the display electronics and provides a mounting point for the I/O and power cables. Two small displays (usually a 1-inch square LCD or miniature cathode-array tube) are set at the front of the HMD shell, a few inches from the face (some HMDs accommodate a user's eyeglasses). The HMD electronics and optical elements (usually housed at the rear of the shell) magnify, collimate, and project imagery via a mirror combiner into the eyes such that the original image appears at optical infinity (Barfield and Weghorst, 1993). Images may be presented to both eyes simultaneously (biocular display) or by overlapping the images in the shared visual field space (binocular display) (Kramer, Roberts, et al., 1998).

One important factor to consider when determining which type of display should be used for a particular application, is the FOV of the display. FOV is the angle through which you see the virtual world. A narrow FOV shows the observer a smaller part of the world with more detail, whereas a wide FOV shows the observer a larger part of the world with less detail (Roehl, 1996). This is analogous to a zoom lens on a camera versus a wide-angle lens. Navigating VEs with a restricted FOV increases the angle to which (and the number of times) users must rotate their head in order to notice what they are walking past. The geometric field of view (GFOV) of VEs may be made greater (or smaller) than the physical field of view (PFOV) by altering the viewing parameters of the VE, but this produces a distortion. For example, setting the GFOV to be greater than the PFOV produces the effect of looking through a wide-angle camera lens, and makes objects seem farther away and smaller than they actually are. A small GFOV (e.g., ten degrees) adversely affects the user's sense of presence in VEs when compared with larger GFOVs (e.g., fifty or ninety degrees) (Hendrix and Barfield, 1996). Levine and Mourant (1995) have suggested that driving simulators in particular, may require FOVs of greater than 100 degrees due to the importance of peripheral cues (Levine and Mourant, 1995). Although theory is limited, narrow FOVs may hinder task performances such as maneuvering, grasping objects and locating moving targets (Witmer, Bailey, et al., 1996). Wider FOVs may improve performance and also feelings of involvement and presence, but this comes at the expense of greater weight and size of the HMD and possibly lower image resolution (Wilson, 1997). Casali and Frank (1988) also suggest that having a large FOV could lead to an increased degree of simulator sickness (Casali and Frank, 1988; Kennedy, Lilienthal, et al., 1987). Studies by Mon-Williams (1993) indicate that visual discomfort and symptoms of nausea have been shown to be reduced with the evolution of HMD systems (Mon-Williams, Wann, et al., 1993). Use of early systems showed high rates of these symptoms and studies using later generation HMDs showed much less dramatic problems (Rushton, Mon-Williams, et al., 1994).

One of the most basic trade-offs in HMD design involves FOV versus perceived resolution. Roehl (1996) concedes the tradeoff is simple: either a wide FOV with lower apparent resolution, or a narrow FOV with higher apparent resolution (Roehl, 1996). Many of today's low-cost HMDs use similar resolutions, generally around 60,000 pixels each of red, green, and blue color elements (180,000 total pixel resolution). This equates roughly to a screen resolution of 320 x 240 (assuming an approximately 1-inch display). If a wider FOV is used, the same 180K pixels must be spread out across that larger space. This produces an effect known as pixellation, or jagged, blocky pixels. Some HMDs use filters to reduce this effect, however the filters tend to soften the edges of the individual pixels which makes them appear less sharp to the viewer. Conversely, if higher resolution is desired, a narrower FOV must be used. This will produce smaller on-screen elements and images or features that appear farther in the distance.

In terms of performance, Ruddle, et al. (1999) found that participants navigated virtual buildings twelve percent quicker when using an HMD compared with D-V use. This increased speed was derived from changes in behavior between the two display types (HMD and direct-view). When using the desktop display, participants often stopped before altering their direction of view to look into rooms to see if they contained any furniture or to look down corridors at junctions. By contrast, participants spent approximately eight percent less time stationary when using the HMD and "looked around" more while they were moving (Ruddle, Payne, et al., 1999). One explanation for this behavioral difference may be that the HMD provided an interface in which changes in view direction were natural (i.e., head and body movements). The physical movements that people make when they use immersive displays provide kinesthetic and vestibular feedback to changes in their orientation that is not present when people use desktop displays. This additional feedback may help people to develop spatial knowledge while navigating within a VE. People typically use abstract interfaces (e.g., mouse, keyboard, joystick) to control their translationary movements and changes of direction with desktop displays. With immersive displays (HMDs), people typically use abstract interfaces to perform translationary movements, but physically turn around to change direction. Ruddle, et al. (1998) found that participants developed a significantly more accurate sense of relative straight-line distance when they used the HMD than when they used the desktop display. This may be caused by the general perceptual differences that are caused by being "inside" immersive VEs (Ruddle, Payne, et al., 1998). It was hypothesized that these differences, and inherent 'quality' of the HMD will allow for increased performance during this study. The participants traversed a virtual driving course and it was hoped that having the ability to 'look around' this VE without stopping, turning, looking, and resuming motion, whould improve their ability to perform required tasks.

In order to provide a functional and enjoyable experience, most successful HMD-based VE systems must overcome at least five key problems relating to the experience (Pierce, Pausch, et al., 1999):

1. Entering a virtual world is a jarring experience. An abrupt transition from the real world to the virtual world forces users to spend time adjusting to the new space.

2. Users do not turn their heads. It is believed this is because guests have been trained by viewing television and film screens, where head turning is counterproductive, and do not fully grasp that they can turn their heads while wearing an HMD.

3. Putting on an HMD is an isolating experience – users do not talk to each other. In multiperson VE worlds, users have trouble identifying which avatars (an image representing a user in a multi-user VE) are their friends, and wearing an HMD can discourage conversation.

4. Putting on the equipment is cumbersome. To maintain high throughput, entertainment applications need to load and unload users quickly. Because the HMD blocks out the real world, users have a hard time finding and grabbing any objects they need to hold as part of the experience.

5. Users do not know when to take off the HMD. When the virtual experience ends, many guests are not sure if the experience is over. Virtual experiences need to clearly communicate when the experience has ended.

While HMDs appear to be the ‘better’ solution in terms of presence, immersion, involvement and overall enjoyable VE experience, they are not without problems or controversy. It has been reported that the use of HMD systems can cause changes in the human visual system (Yeow and Taylor, 1989). This should be of concern to people who use HMD systems for research purposes or even entertainment. Temporary changes in accommodative and binocular status have been recorded following reading, using a computer display, and using a head-mounted display (Yeow and Taylor, 1989). Wilson (1995) notes that changes are to be expected because adaptation to the environment is a major characteristic of biological systems; therefore, changes per se are not the concern. Only changes that may have a negative effect on function or comfort, or those that may have an impact over an extended period of use are of interest (Wilson, 1995). As an example, the fact that riding in a car can cause motion sickness for some people is not considered reason enough to ban the use of cars for transportation. Other concerns regarding the ill effects of HMD use fall into four categories (Peli, 1998):

1. Simulator sickness resulting, theoretically, from vestibular-visual conflicts
2. Accommodative difficulty presumed to be associated with instrument myopia
3. Binocular function difficulties due to a mismatch between the device and the individual user’s visual system [e.g. different inter-pupillary distances (IPDs)]
4. Binocular (and possibly accommodative) difficulties associated with the de-coupling of the natural relationship between accommodation and convergence in stereo binocular HMDs employing image disparity.

Peli (1998) found that the average changes reported by (Yeow and Taylor, 1989) following device use (HMD and CRT) are small in all cases and never approach a level of meaningful change. None of the parameters tested showed a statistically significant interaction between the device used and time-of-test in the analysis of variance (ANOVA). Peli concluded that the HMD in either mono or stereo mode resulted in no changes in any of the parameters tested that were statistically different from those induced by the CRT. He further concluded that the changes in each of these variables were too small to be clinically meaningful (Peli, 1998).

Despite considerable improvements in the past two or three years, many HMDs still present fitting difficulties for many participants. Irritation, discomfort, and a lack of motivation to use the equipment because of these issues have been found to be problems with HMDs and related equipment (Bolas, 1994). Users of HMDs still have problems adapting to motion within a VE. For instance, when users navigate VEs with displays that do not provide peripheral vision, they sometimes accidentally travel past their targets (Ruddle, Payne, et al., 1998). Although peripheral vision may be simulated by providing peripheral 'view ports' at the sides of the displays, not all HMDs offer this feature. As better and more innovative technology becomes available, researchers will consider these and many other problems regarding HMDs, and hopefully design them out of the system (where feasible).

Fidelity. As briefly mentioned earlier, Rinalducci (1996) defines visual fidelity as the degree to which visual features in the virtual environment conform to visual features in the real environment. This means that the greater the conformity to the real world, the greater the fidelity. One would also expect visual features in the virtual world to affect performance in the same way as visual features in the real world. Rinalducci identifies cues for fidelity as including visual motion (perception of self-motion embraces optical flow rate, discontinuities, and optical edge rate), color, stereopsis, depth cues (pictorial and physiological), texture, luminance, field size and spatial resolution (Rinalducci, 1996).

Equipment fidelity refers to the degree to which the simulator duplicates the appearance and feel of the actual system, while environmental fidelity refers to sensory simulation of the actual task, and psychological fidelity refers to the degree to which the simulator is perceived by the trainee to duplicate the operational equipment and the actual task situation (Rinalducci, 1996).

Symptoms analogous to those of motion sickness are common in VE systems that present optical depictions of inertial motion of the user (vection). This is sometimes referred to as virtual induced motion sickness (VIMS) (Frank, Casali, et al., 1988a).

Steering Force Feedback

Although drivers obtain a substantial amount of information for driving from vision, information from other sensory modalities may also provide relevant information about the state of the car or even the surrounding environment. Gordon (1966) found that sensory inputs such as *steering wheel feel* and *transverse acceleration* ("seat-of-the-pants" feel) were ranked closely behind *vision of the road ahead* by drivers (Gordon, 1966). Also, as more devices with visual interfaces, e.g., navigation systems, are introduced into the vehicle it is likely that the visual sensory channel may become overloaded. By distributing information through the other sensory modalities such as audition or kinesthesis, it may be possible to spread the cognitive load on the driver over a greater pool of resources (Liu and Chang, 1995).

An integral part of successfully manipulating objects is the sensation of touch or force. Experiments with telerobots (robots controlled from a distance) show that the sensation of force and contact improves the efficiency and accuracy of such tasks (Shimoga, 1993). Unfortunately in a VE, it is not possible to actually grasp a virtual object in the same manner as a real object would be grasped, because virtual objects are defined in the computer, while the user exists in the real world. Thus, there must be some intermediate device that provides the user with the effects of touch, either through the VE itself or in a physical model of the object, which then communicates information to the VE and displays the virtual object to the user. One way to accomplish this in a driving simulator is through the use of active steering wheel force feedback. Somewhat similar to tactile feedback, which is sensed by receptors close to the skin, force feedback is sensed by deeper receptors in the body such as muscle attachments to bones and joints (Sadhu, 2001). Force feedback devices can apply forces and can push or resist the body's motion. Force feedback in VEs is provided through steering wheels, foot pedals, joysticks, mice, data gloves and other such devices. The control force loading system acts as an interface between the driving simulator and the driver, in that it senses driver input and feeds it back to the vehicle computational dynamics model, then displays vehicle operating conditions on the instrument panels, updates the roadway display, and generates reaction forces and torques in the driving mechanism for kinesthetic cue. (Lee, Kim, et al., 1998).

Most of the vehicle steering control models available today are based on the fundamental assumption that drivers steer their vehicles in a continuous error-correcting mode with constant visual feedback, i.e. closed loop (Godthelp, 1985). Steering force feedback works in concert with visual feedback for driving tasks. According to the 1985 Godthelp study, steering force feedback may help to reduce steering errors under conditions without immediate visual feedback. The results of the 1980 Godthelp experiment showed that the presence of steering force feedback in a driving simulator improves accuracy in reproducing steering-wheel movements (Godthelp, 1980). According to Allen, et al. (1998), the primary motivation for providing high fidelity vehicle dynamics in a driving simulator is to achieve realistic feel and motion cueing and to be able to provide hardware-in-the-loop interaction with elements such as steering and braking systems.

Liu and Chang (1995) showed that the addition of steering torque decreased steering variance when the driver is controlling a simulated vehicle after a turn or skid. Tests without steering force feedback showed that drivers overcorrected their steering and performed mild weaving patterns as they exited sharp curves, while steering force feedback enabled the drivers to exit curves with little extraneous steering correction. Also, the variance in steering angle when torque was not present was twice as large as when torque was present. When the steering force feedback was disabled, subjects had trouble returning cleanly to the prescribed path after correcting their skid (for this particular test); subjects overshot the path and then had to turn back to return. With the steering force feedback enabled, subjects were able to return directly to the prescribed path after correcting their skid. None of the subjects overshot the path with the steering force feedback enabled. The research also showed that a slight performance improvement was obtained with the addition of torque in the straight sections of road following a curve.

In a virtual environment, each type of interface must correspond to a cross section of the boundary between the real world and virtual world. If the flow of information is cut across this boundary, there are three types of cross sections on which to base a steering force feedback device (Shimoga, 1993):

- surface of a tool
- surface of the user (skin)
- surface of an object

An interface that corresponds to the first cross section (surface of a tool) obviously allows manipulation only through indirect contact (i.e., steering wheel used to control a virtual automobile). A steering force feedback device based on this interface must simulate the relationship between the position and force applied to the tool (Brooks, Ouh-Young, et al., 1990).

Segel's 1964 classic simulator study concluded that drivers relied on steering information in order to perform better during driving tasks. He also concluded that drivers had difficulty in positioning the steering wheel at low feedback torques. A normal range for steering torque under non-emergency conditions is 0-3.5Nm (Liu and Chang, 1995). While there are individual preferences on force level from the standpoint of the physical effort required, there is general agreement that (Segel, 1964):

1. Too light a force gradient makes for difficulty in precise positioning of the steering wheel. This causes both over and undershooting of the desired path.

2. With light force gradients, drivers become more aware of the magnitude of wheel displacement. Wheel displacement appears to increase as the force gradient decreases.

3. There is some optimum steering force gradient, below which the straight ahead position of the wheel is poorly defined. Above this optimum, the response of the car-driver combination is slowed down, causing undershooting on turn entry. On the other hand, some drivers complained that high force gradients made their turn recoveries too rapid, resulting in overshooting of the desired path.

4. The precision of the steady-state turn is influenced by force level to a lesser degree than the precision of the passing maneuvers. Similarly, the size of the steering displacement has less influence on the precision of the steady-state turn than it does on the passing maneuvers. Many of the drivers believed that the steering motions required to perform the passing maneuvers were too large. Some of them indicated that large steering motions resulted in slowing up the car-driver response.

Since interaction with VEs is not completely natural because of the use of real-world sensors, effectors (a device used to produce a desired change in an object in response to input) and input devices to control elements in a virtual environment, appropriate and meaningful feedback on control actions and physical movements will remain an important criterion, and one that relates strongly to the technical limitations of virtual reality (VR)/VE (Wilson, 1997). Since creation of a "perfect" representation of tactile and steering force feedback is unlikely to be technically possible (at least in the foreseeable future), VR system developers need to know how much information is required and what approximations are acceptable to give satisfactory performance. As more sensory and muscle channels are occupied with ever more sophisticated systems, we will need to understand the consequences for performance when a larger number of channels are occupied with the VE and a smaller number with the real world. Also, as VE sensory channels increase, the consequences for performance or well-being of the participant if the sensed VE does not behave as expected (spatially or temporally for instance) may well be more serious (Wilson, 1997).

Simulator-Induced Sickness

A factor that could have presented an undesirable and confounding variable in the data captured during this study was the phenomenon known as simulator-induced sickness. Simulator-induced sickness, or SIS, presents a real problem to the usability and results achieved in virtual environments, particularly driving simulators (Stanney, Mourant, et al., 1998). SIS may be mitigated by identifying those individuals susceptible to the sickness before they are placed in a virtual environment (a driving simulator in this case). One method that has been successfully used to screen for susceptibility to simulator sickness is the Mental Rotation Test (MRT) (Peters, Laeng, et al., 1995; Vandenberg and Kuse, 1978), described in more detail in the Mental Rotation section.

Simulator-induced sickness is a form of motion sickness that occurs as a result of exposure to simulators or virtual environments, and poses a serious threat to the usability of Virtual Reality (VR) systems (Stanney, Mourant, et al., 1998). Driving and flight simulators have a tendency to induce acute, residual, and sometimes after-effect symptoms of discomfort in operators and passengers (Casali and Wierwille, 1986; Kennedy, Lane, et al., 1992). Having similar characteristics to and sometimes synonymous with motion sickness, cybersickness (Stanney, Kennedy, et al., 1997), Virtual Reality Induced Symptoms and Effects (VRISE) (Wilson, 1997), Visually Induced Motion Sickness (VIMS) (Hettinger and Riccio, 1992; Rinalducci, 1996), and Simulator Adaptation Syndrome (SAS) (Weir and Clark, 1995), it is difficult to determine when and to what degree the symptoms will become manifest. Symptoms may include pallor, altered cardiovascular and respiratory states, increased gastric activity, slight headache, dizziness, oculomotor discomfort, disorientation, and nausea (Casali and Frank, 1988; Kennedy, Lane, et al., 1993).

SIS can be induced by a conflict of cues, distortion of cues, an absence of cues, or the presence of motion cues which have a direct somatic influence (Casali, 1986). Causative factors include: wide field of view (e.g., greater than 50-60 degrees laterally), apparent motion at and below 0.2Hz causing somatic discomfort, cueing delays, and lack of synchronization between visual, motion, and audio cues (Frank, Casali, et al., 1988b). This can be more significant for visual vs. motion delays greater than about 100ms. Optical distortion and other visual artifacts include audio cueing phase mismatch in the presence of motion vibration, use of driving scenarios and tasks which involve large amplitude and rapid turning maneuvers or large longitudinal accelerations. Recognizing and accounting for these factors can reduce SIS (Casali and Wierwille, 1986; Weir and Clark, 1995).

Perhaps the most widely accepted theoretical explanations of SIS are grounded in the concept of sensory conflict. The general premise is that discrepancies between sensory "inputs" and expectations based on past experience constitute "conflict," which must be resolved through processing discrepancy into agreement; (Stoffregen, Hettinger, et al., 2000). The magnitude and/or duration of discrepancy-related conflict are believed to determine the severity and duration of motion sickness. Researchers believe, however, that conflict theory is difficult to adequately define and that "in its present form, it may be untestable" (Ebenholtz, Cohen, et al., 1994). The visual system is registering self-movement based upon the graphical rendering of the objects in the environment. However, the vestibular system does not detect any actual movement, beyond perhaps the user's fidgeting in the chair. To the extent that the perceptual systems cannot adequately deal with the conflicting information, simulator sickness results. The illusory self-motion produced at such times, known as vection, appears to be an essential factor in producing simulator sickness (Hettinger, Berbaum, et al., 1990). One suggestion to reducing vection is to add a motion base to simulators.

Lag (also known as transport delay) occurs when a noticeable delay exists between the time a physical motion is made (e.g., turning one's head or the steering wheel) and the time the computer takes to respond with a corresponding change in the display, over and above the lag inherent in the actual vehicle dynamics (Frank, Casali, et al., 1988b). Lag and asynchrony between two different inputs (visual and inertial) are often cited in connection with cybersickness (Kennedy, Lilienthal, et al., 1987). It is unclear exactly the degree to which visual system lag affects simulator-induced sickness. However, Casali and Wierwille (1980) and Frank, et al. (1988a) reported that visual lags of 170, 300, and 340ms produced mild discomforting effects in participants during the use of motion-base simulators and that visual lag was more disruptive to user performance and comfort than motion lag. In fixed-base simulators, however, it has been shown that lags of 108-285ms had no effect on simulator-induced sickness (Uliano, Kennedy, et al., 1986). User adaptation to the VE should be rapid if the lags are constant or not at all if they are variable (Kennedy, Lilienthal, et al., 1987).

Horizontal FOV is also a potential variable in the causation of cybersickness. FOV is categorized in terms of wide and narrow horizontal FOV. The literature reveals mixed results regarding which FOV (wide or narrow) contributes to motion sickness. Studies have shown both wide and narrow horizontal fields of view can lead to motion sickness. Lestienne et al. (1977) found that participants who viewed a wide horizontal FOV experienced intense sensations of motion sickness and Andersen and Braunstein (1985) have shown that participants suffer nausea when the horizontal FOV is restricted (Andersen and Braunstein, 1985; Lestienne, Soechting, et al., 1977). These findings suggest other factors may be involved, perhaps in conjunction with FOV, in creating motion sickness. This study uses a 27 degree FOV with high resolution in both the head-mounted display and the direct-view display. Details and hardware specifications are discussed in the Apparatus section.

Reports that VR use can be difficult, disorienting, uncomfortable, and nauseogenic have appeared with increasing frequency in the popular media, although the number of published scientifically supportable studies is small and interpretation of them is not easy at present (Kolasinski, 1996; Regan and Price, 1994). A framework of potential influencing factors has been produced, identifying relevant characteristics of VR technical systems, VE design, circumstances of use and individual participants. An array of symptoms and effects have been identified, some similar to those found with other types of simulators and in transportation, but the etiology is sufficiently different to justify a new term: Virtual Reality Induced Symptoms and Effects (VRISE). There is evidence for onset of symptoms of sickness, akin to simulator or motion sickness but with some constituent experiences different from either of the other two better established phenomena (Wilson, 1997).

Visually induced motion sickness (VIMS) may become more common with VEs. VIMS appears to be more frequently observed when there are excessive lags between head movements and visual display recomputation in HMDs and when observers experience visually produced self-motion (vection) in the absence of physical motion (Hettinger and Riccio, 1992). Visually induced motion sickness contributes to cybersickness (Rinalducci, 1996).

VE systems that are utilized for training may not be optimally used if users focus on the discomfort they feel rather than on the task they are learning (Ehrlich, 2000). For instance, users may restrict head movements to alleviate disorientation or nausea, or close their eyes periodically to relieve oculomotor discomfort (Kolasinski, 1996). Users may become preoccupied with their felt discomfort and efforts to diminish it rather than being fully engaged in the alternate world being presented (Witmer and Singer, 1998). SIS also degrades the validity and generalizability of the research results from a simulation, unless the real-world vehicle causes simulator-induced sickness under the same conditions. These factors warrant the use of some tested means to screen out those participants who might be more vulnerable than others to SIS.

One approach to moderating SIS is to allow the participant to have greater control within the VE through the manipulation of the level of interactive control provided to participants. Casali and

Wierwille (1986) determined that crewmembers and copilots are more susceptible, compared with pilots, to simulator-induced sickness because they have little or no control over the simulator's movements (Casali and Wierwille, 1986). Lackner (1990) suggested that the driver of a simulator becomes less sick than the passengers because the driver can control or better anticipate the motion (Lackner, 1990). The driving simulator used in this study allowed the participant to control all linear and angular (yaw) motion (forward driving, turning, stopping, etc.) through the software interface.

Mental rotation. It has been determined that screening for SIS susceptibility is possible using what is known as the Mental Rotation Test (MRT). The MRT was developed by Steven Vandenberg and Allan Kuse for use in determining spatial ability (Vandenberg and Kuse, 1978). Unlike tests such as the Simulator Sickness Questionnaire (SSQ), which measures the level of sickness experienced after using a simulator, the MRT measures a person's susceptibility to sickness before using a simulator. People who score high on the MRT are generally considered less likely to develop SIS symptoms while in a virtual environment (Parker and Harm, 1992). Conversely, those who score low on the MRT are considered to be "at risk" to develop SIS symptoms. Although there is evidence to suggest that mental rotation results vary by gender - males generally score higher (Delgado and Prieto, 1997; Masters and Sanders, 1993; Richardson, 1994), both males and females were screened for this study using the MRT until an equal number of each gender were selected in order to satisfy the participant gender requirements of the study (four males, four females).

Potential participants were screened for this study using the Vandenberg and Kuse version of the MRT. The MRT consists of twenty sets of 3-D drawings (APPENDIX A). Each set has an original object on the left that must be correctly matched with two exact (but spatially re-arranged) objects on the right. Each MRT was completed within the allotted time of six minutes (Vandenberg and Kuse, 1978).

Research Voids

The literature review has explored past research in the areas of driving simulators using direct-view and head-mounted displays, the use of steering force feedback in driving simulators, and some factors for perceived presence while using a driving simulator in a virtual environment. The literature review has also looked at simulator-induced sickness, its causes and implications, as well as ways to identify and potentially mitigate its negative effects.

What the literature does not reveal, however, is how these factors affect performance in a very specific setting, i.e., a driver licensing test course, and using a low-to-medium cost driving simulator comprised primarily of off-the-shelf components. This study differs from previous research in that it has used a low-to-medium cost driving simulator that incorporated an off-the-shelf, low-cost, head-mounted display and head tracker system, and a commercially available, relatively large flat-panel direct-view display, instead of expensive HMDs and large front projection systems or comparatively small desktop PC monitors. This research has also used a custom-built virtual driving environment modeled after a real-world Virginia DMV driver licensing test course. The DMV course VE provided the author with an opportunity to conduct research in a controlled environment that relates directly to a real-world application of the factors of interest. Another difference between this research and previous research is the desire to find a combination of display type and steering force feedback that will create a greater level of perceived presence in the VE for the participant.

RESEARCH GOAL

The goal of this research was to determine the significant performance differences associated with different display types, levels of steering force feedback, and the interaction between these two factors. It was also hoped that with a specific combination of display type and steering force feedback, a greater level of fidelity could be achieved, thereby creating a higher level of perceived presence within the VE for the participant. Achieving this goal will provide support to previous research results that suggest performance increases with the use of each of these factors in isolation, as well as demonstrate that not only is this increase not adversely affected when the two factors are combined, but will instead, increase further. This research was conducted at Virginia Tech and is described in more detail in the methodology section.

Hypotheses

It is hypothesized that active steering force feedback will significantly (statistically) improve driver-vehicle performance in a driving simulator compared to no steering force feedback. It is further hypothesized that the use of a head-mounted display will significantly (statistically) improve driver-vehicle performance in a driving simulator compared to a direct-view display. While no specific combination of display type and feedback level has been shown to increase perceived presence in a VE, it is hoped that the combination of HMD and active steering force feedback will be more 'realistic' and create a higher fidelity experience for the user, thereby increasing the user's perceived presence while in this particular VE. This level of perceived presence was measured using the Presence Questionnaire.

METHODOLOGY

Experimental Design

This experiment was a full factorial (2x2x2x4), mixed-factor design (Figure 1). The experiment was designed around a low-to-medium cost (about $70,000) PC-based driving simulator developed under contract by Virginia Tech's Auditory Systems Laboratory, with subcontractor assistance from Northeastern University. The simulator consisted of the driver's console, vehicle dynamics computer and scene generator, active steering, and two different display types (Penhallegon and Perala, 2002) described in more detail in the Apparatus section.

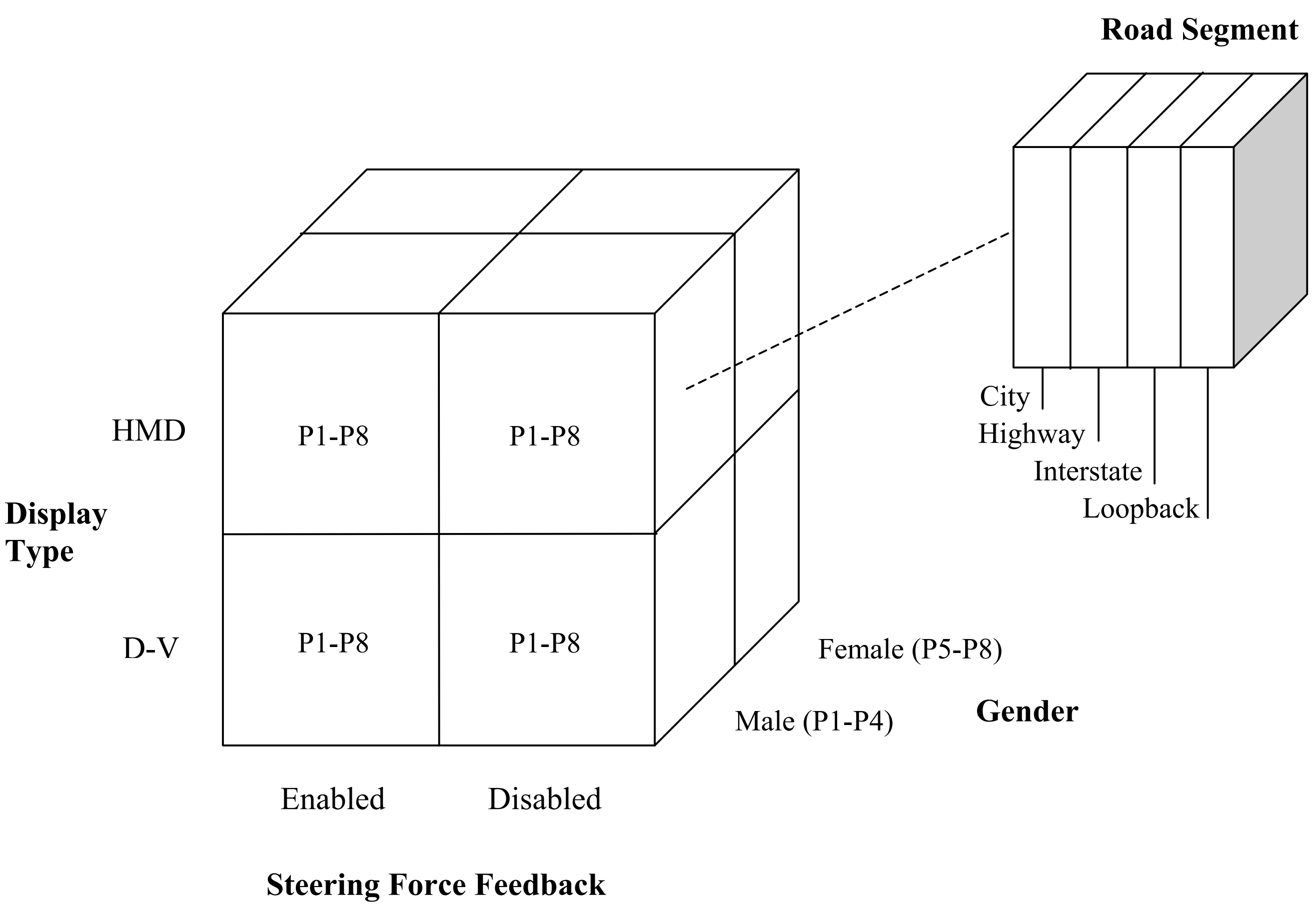


Figure 1. Experimental design block diagram.

Independent variables. The independent variables for this experiment were *Steering Force Feedback*, *Display Type*, *Segment* and *Gender*, Figure 1. *Display Type*, *Steering Force Feedback*, and *Segment* were within-subject variables, where each participant received each possible treatment combination, and *Gender* was a between-subject variable.

The two levels of *Steering Force Feedback* were *enabled* and *disabled*. When *Steering Force Feedback* was *enabled*, 3Nm of torque was applied to the steering column of the driving simulator. This is within the normal operating range (0-3.5Nm) for a steering torque motor under non-emergency conditions (Liu and Chang, 1995). The torque motor was controlled by the simulation software and created realistic, dynamic steering force feedback for the driver. When *Steering Force Feedback* was *disabled*, the torque motor was disengaged and the steering wheel was in a "spring-centered" mode. In this mode there was no active steering force feedback to the driver, simply a spring which returned the steering wheel to a null position when released.

The two levels of *Display Type* were *head-mounted display* and *direct-view display*. The *head-mounted display* was a head-mounted projection system (IO Systems, Inc. i-Glasses SVGA) that projected the simulated driving environment, stereoscopically (biocular, 3-D), onto fixed-position, high-resolution displays that sat approximately 3in. from the driver's eyes (Pierce, Pausch, et al., 1999). The *direct-view display* was a 50in. plasma display manufactured by NEC. It was located at a distance of 7.5ft. from the driver's eyepoint. The specific technologies for the two display types used in this experiment are described in more detail in the Apparatus section.

The four levels of *Segment* were *city*, *highway*, *interstate*, and *loopback* with speed limit zones of 35mph, 45mph, 65mph, and 65mph, respectively. In-depth explanations of these road segments appears later in the text. Although gender effect was not a primary consideration or goal, the experiment balanced conditions across gender to determine if there was a significant effect.

The independent variables were manipulated throughout the experiment to create the four VE conditions for the participant. The presentation of the independent variables was determined using a Balanced Latin Square in order to reduce the potential of confounding the results by allowing practice effects to influence the participant's driving behavior. This is discussed in more detail in the procedures section.

Dependent variables. The experiment had two classes of dependent variables: objective driving performance measures and subjective ratings (Table 1). The driving performance measures were collected by the simulator computer during each session and saved as a text file. These data were captured throughout the simulation and were sampled approximately every 125ms (8 times per second). Driving performance measures included: lane deviation (ft.), speed control (mph), steering wheel angle (deg.), and time to complete the course (min.). Subjective preferences were collected using the Presence Questionnaire (PQ) and Immersive Tendencies Questionnaire (ITQ). The PQ and ITQ are internally consistent measures with high reliability (Cronbach's alpha levels of 0.88 and 0.76, respectively) (Witmer and Singer, 1998).

The Data Reduction section provides detail concerning analysis of these data. The subjective preferences were obtained by asking each participant to complete the Presence Questionnaire after the completion of each treatment.

The Presence Questionnaire, developed by Witmer and Singer (1998), was used to determine the perceived level of presence the participant experienced while using the simulator (Witmer and Singer, 1998) (APPENDIX B). The PQ measures the degree to which individuals experience presence in a virtual environment and uses a seven-point Likert-type scale that is based on the semantic differential principle (Dyer, Matthews, et al., 1976). Like the semantic differential, each item is anchored at the ends by opposing descriptors; however, the PQ includes a midpoint anchor. Test participants were asked to place an “X” in the appropriate box of the scale that most closely matched their answer to the given question. A sample question from the Presence Questionnaire and its relevant scale is shown in Figure 2, while the full questionnaire appears in APPENDIX B.

TABLE 1.

Dependent variables

Dependent Variables	Levels
Objective driving performance measures	Lane deviation, speed control, steering wheel angle, time to complete the course
Subjective measures	Perceived level of presence, steering force feedback preference, display type preference

18. How involved were you in the virtual environment experience?

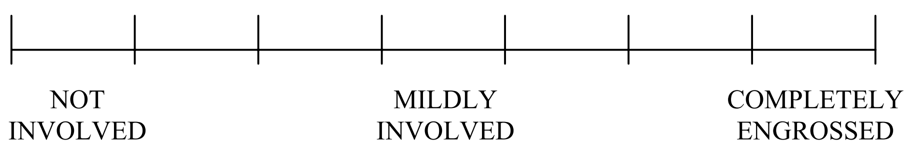


Figure 2. Example question and scale from the PQ.

The Immersive Tendencies Questionnaire (ITQ), developed by Witmer and Singer (1998), measures the propensity of individuals to be involved or immersed in a virtual environment (Witmer and Singer, 1998) and like the PQ, uses a seven-point Likert-type scale based on the semantic differential principle (Dyer, Matthews, et al., 1976). Also like the PQ, each item in the ITQ is anchored at the ends by opposing descriptors and includes a midpoint anchor. The test participants were asked to place an “X” in the appropriate box of the scale that most closely matched their answer to the given question. A sample question from the ITQ and its relevant scale is shown in Figure 3, while the full questionnaire appears in APPENDIX G.

10. How easily can you switch your attention from the task in which you are currently involved to a new task?

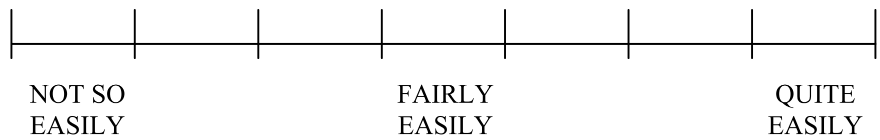


Figure 3. Example question and scale from the ITQ.

Apparatus

Console. The console of the fixed-base driving simulator developed for this study was a modified Advanced Therapy Products, Inc. (ATP) Driving Console WT-2000 shown in Figure 4 (Penhallegon and Perala, 2002). The console was equipped with an acoustically-driven, vibrating seat which allowed for the simulation of rumble strips. The vibration frequency of roadside rumble strips was calculated and determined to be 80-104Hz at highway and interstate speeds (Penhallegon and Perala, 2002). The seat produced vibrations from 5-120Hz based on a voltage signal output from the controlling computer, which was proportional to vehicle speed. During the experiment it was determined that the large magnet which comprised the acoustic portion of the vibrating seat was causing magnetic interference with the HMD head-tracker. This interference caused the VE driving scene to drift either left or right during the pre-testing phase of the experiment. It was determined this drift, and subsequent requirement of the driver to reach up and repeatedly push a reset button on the head tracker, would have a significant negative impact on the experimental results. For this reason, the magnet was removed, thereby rendering seat vibration inoperable. The console was also equipped with active feedback steering, optical encoder position sensor, an automatic transmission floor shifter, a speedometer and tachometer, and latching, self-canceling turn signals with dashboard indicators.

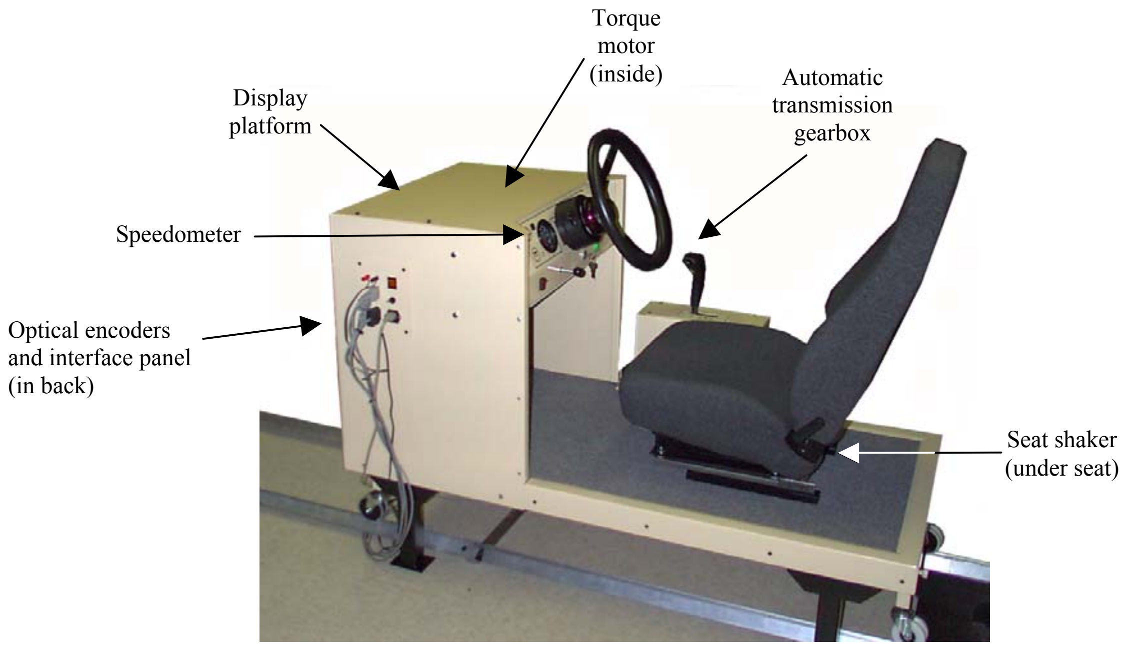


Figure 4. Modified ATP driving console WT-2000.

Display. Two different displays were used with the simulator during different experimental sessions. The first was an NEC PlasmaSync 50MP1 50in. flat panel monitor, Figure 5. The PlasmaSync 50MP1 display was placed at 7.5ft. from the driver's eyepoint, providing a 27 degree horizontal FOV. The second display was the IO Systems, Inc. i-Glasses SVGA 3-D HMD, Figure 6. The i-Glasses SVGA 3-D HMD had a 27 degree horizontal FOV, an image size representation of 76in. at 13ft., and an SVGA addressability of (800x600 pixels). See (Penhallegon and Perala, 2002), APPENDIX C, for complete display specifications.

Steering system. The steering system used with the simulator consisted of a standard, 12in., 3-position-tilt, padded steering wheel affixed to the steering column of the driving console. The steering wheel was connected to a torque motor assembly and provided velocity-dependent, active force-feedback to the driver when in the "force feedback enabled" mode. Optical encoders sensed the position of the steering wheel during vehicle operation and relayed the position to the computer. Steering wheel velocity and position information were relayed through a quadrature card (digital input/output interface) to the torque motor. The steering wheel could be operated in three independent modes: free-rotation, spring-centering, and active resistance through the torque-motor.

Steering force feedback was measured on the simulator console steering wheel to determine the amount of torque during non-emergency driving conditions. Two force feedback modes were used for the experiment: force feedback enabled (FFE) and force feedback disabled (FFD). In FFE mode, active steering resistance was provided by the torque motor linked to the steering column. In FFD mode, passive steering wheel resistance was provided by a spring-centering mechanism. A Mark-10 model EG10 digital force gauge was used to measure force on the steering wheel in each mode. Torque was calculated using a moment arm of 6 inches (0.1524 m); the distance from the center of the steering wheel to the force gauge attached to the steering wheel handgrip (Table 2).

TABLE 2.
Steering force feedback levels

Force feedback mode	Measured force (N)	Moment arm (m)	Calculated torque (Nm)
FFE	~20	0.1524	3.048
FFD	~5	0.1524	0.762

Figure 5. NEC PlasmaSync 50MP1 display.

Figure 6. IO Systems, Inc. i-Glasses SVGA 3-D head-mounted display.

Computer. The simulator was controlled by an IBM-compatible personal computer running simulation software jointly developed by the VT Auditory Systems Laboratory and by Dr. Ronald Mourant through a subcontract to the industrial engineering department at Northeastern University in Boston, Massachusetts. The simulated driving environment, or driving course, was a direct representation of a portion of the DMV test route in Charlottesville, Virginia. The computer was a Dell Precision Workstation 420 configured specifically for this application with dual 1.0 GHz Pentium III processors, 1GB of RAM, an nVIDIA GeForce4 4600 graphics accelerator card with 128MB of VRAM, 73GB Ultra SCSI and 20GB ATA IDE hard drives, a 16X DVD and 12x/8x/32x CDRW combo drive, a Creative Labs Sound Blaster Live! Platinum 5.1 Card, a 100BaseT Ethernet card, Microsoft Windows 2000 Professional operating system, and a 21in. Dell Ultrascan P1110 monitor.

Figure 7 shows the VT-UVA-Carilion driving simulator and experimental environment used for this research. Surrounding the simulator on three sides is a set of floor-to-ceiling black drapes. This enclosure was included to visually separate the driving environment from the rest of the laboratory, thereby minimizing any visual distractions for the driver. The closed-loop block diagram developed for the simulator is depicted in Figure 8.

Figure 7. VT-UVA-Carilion driving simulator and experimental environment.

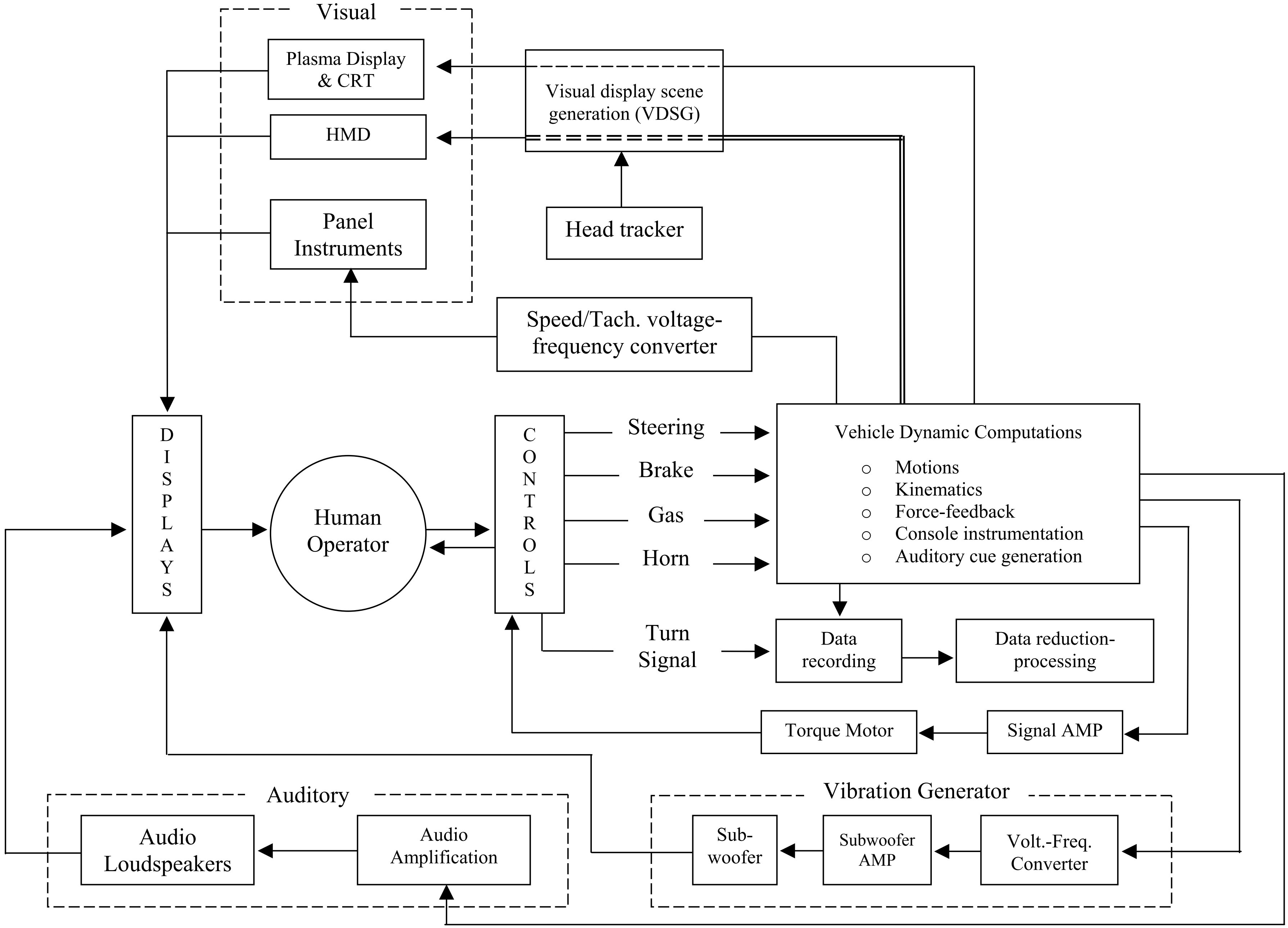


Figure 8. Closed-loop simulator block diagram.

Participants

Eight randomly selected people from the Virginia Tech/Blacksburg, Virginia area were recruited as participants for this study. Because they were randomly selected, the participants represented a wide range of driving abilities, habits, and preferences. Participants were adults (over the age of 18) and required to hold a valid United States driver's license. If the participants required the use of eyeglasses or contact lenses for real world driving, they were required to use the same during the experiment. All participants were compensated for their time and effort at a rate of $8.00 per hour. Experimental descriptions, procedures, and participant consent forms were reviewed and approved by the Virginia Tech Internal Review Board (IRB) in accordance with IRB standards and procedures for utilization of human participants for investigative research (APPENDIX D). The Informed Consent form was read and signed by each participant before any screening, pre-testing, or experimentation took place (APPENDIX E).

Pre-Experimental Procedures

Participant screening. After reading and signing the Informed Consent form, potential participants were asked to complete a short Participant Screening Form (APPENDIX F). This form solicited general information regarding the potential participant's health and well-being pertinent to simulator usage (Yoo, 1999). The Participant Screening form did not collect any personal information. Information collected was used for statistical purposes and as a potential disqualifier for the experiment. For example, being under the influence of drugs, alcohol, or the effects of a virtual environment within the previous 24 hours could have contaminated (biased) the data collected during the experiment; therefore, that potential participant would have been ineligible to participate in the study.

To further reduce bias, potential participants were required to have at least 20/30 (corrected or uncorrected) visual acuity and be non-colorblind. Tests for colorblindness and visual acuity were conducted using the Ishihara color test and a static visual acuity test using Landolt-C rings, respectively (Yoo, 1999).

Following the initial participant screening and prior to actual selection, prospective participants were required to undergo and successfully pass a simulator-induced sickness screening process. This screening process was designed to assist the experimenter in determining a potential participant's susceptibility to simulator-induced sickness. This was accomplished by using the Mental Rotation Test (APPENDIX A) described earlier. This test is designed to evaluate spatial rotation ability. Once the prospective participant passed the simulator-induced sickness screening process, he or she was considered an active participant in the experiment. All of the potential participants who took the MRT scored within the acceptable limits for the test, therefore no potential participants were disqualified due to susceptibility to simulator-induced sickness.

Pre-testing. A series of pre-tests were conducted using volunteers from the student community at Virginia Tech. The pre-tests involved setting up the hardware and software, running the driving scenarios with the various conditions applied, and timing the sessions and setup between each session. This allowed the experimenter to get a clear perception of what was involved in running actual participants and to ensure data were being properly gathered and stored. Pre-testing also allowed for problems to present themselves so they could be addressed before the actual experiments began.

Experimental Procedures

General. During the experiment, the participants were asked to drive on a simulated roadway course used by the Virginia DMV in Charlottesville, Virginia, Figure 9. The driving scenario involved driving along straight road segments, with changes in gradient to maintain speed, curved segments to maintain speed and lane position, and cars were passed at highway and interstate roadway speeds to change steering wheel angle. During non-passing or while maneuvering, participants were instructed to maintain a centered, right-lane position and to maintain the posted speed limit. Participants were asked to drive the course twice in order to increase the treatment time and compile enough relevant data to draw meaningful comparisons. The total time to drive the course twice was approximately 15 minutes.

Figure 9. Screenshot of driving course.

A total of four different treatments were presented to each participant, with each occurring in separate sessions conducted on separate days. In order to reduce the effects of practice on the outcome of the data, the treatments were randomized using a Balanced Latin Square (Table 3). For treatment 'A', participants drove the course using the direct-view display with steering force feedback enabled (D-V/FFE). Treatment 'B' included the direct-view display with steering force feedback disabled (D-V/FFD). Treatment 'C' included the head-mounted display with steering force feedback enabled (HMD/FFE). Treatment 'D' included the head-mounted display with steering force feedback disabled (HMD/FFD).

TABLE 3.

Balanced Latin Square

	Participants							
	Male				Female			
	1	2	3	4	5	6	7	8
Treatment	A	B	C	D	A	B	C	D
	B	C	D	A	B	C	D	A
	D	A	B	C	D	A	B	C
	C	D	A	B	C	D	A	B

A=D-V/FFE B=D-V/FFD C=HMD/FFE D=HMD/FFD

Where,

D-V = Direct-view Display

HMD = Head-mounted Display

FFE = Steering Force Feedback Enabled

FFD = Steering Force Feedback Disabled

Experimental session. As previously mentioned, before entering the simulator for the first time, each participant was asked to complete the Immersive Tendencies Questionnaire. The participant was then asked to enter the simulator. The experimenter explained the functions of the simulator controls and demonstrated how each operated. Based upon past driving simulator research conducted at Virginia Tech, the participant was allowed to drive the simulated driving course once (using the appropriate display type for the particular treatment condition) to become familiar with the vehicle handling characteristics, display, route, and procedures. During the session, the experimenter verbally presented instructions as the participant operated the vehicle (e.g., turn left at the next stop sign). Although this did not occur during the study, if simulator-induced sickness would have become manifest at any level, the experiment would have been stopped and attention would have been given to the participant's needs. Upon successful completion of the experimental session, the participant was asked to exit the simulator and complete the Presence Questionnaire (APPENDIX B). The participant was required to stay in the experiment area for 30 minutes following each experimental session to determine if post-treatment simulator-induced sickness would become manifest. If symptoms were present and considered significant enough to impair driving, arrangements were in place to drive the participant to their home. No participant required this service during the experiment. During this post-treatment period, an appointment for the following session was scheduled. There was a minimum 24-hour rest period between each session to allow for any latent effects to dissipate before continuing with the experiment. After completion of the experimental session and post-treatment period, the participant was asked not to drive a vehicle for 24 hours following the session, and was escorted out of the experiment area. Upon completion of all four experimental sessions, each participant was asked to complete a short preference survey detailing which display type and level of force feedback they preferred and why. The participant was then thanked for their cooperation, compensated for their time and escorted out of the experiment area.

Driving scenario. The simulated driving course was modeled from existing roads in the Charlottesville, Virginia area, Figure 9. While the course provided for a single driving scenario, it was comprised of four distinct segments. Autonomous traffic densities were calculated for each segment to provide a more dynamic driving scenario (Penhallegon and Perala, 2002). The course began in the parking lot of the Charlottesville, Virginia DMV, which opened onto road segment 1.

Segment 1 was a 1.2-mile, two-lane city street. Each participant drove along this segment in a right-lane, centered position and was instructed to obey all traffic signs and laws and maintain the posted speed limit of 35mph. No cars were passed along this segment.

Segment 2 was a 0.6-mile, four-lane, divided highway. Each participant drove along this segment in a right-lane, centered position and was instructed to obey all traffic signs and laws, and maintain the posted speed limit of 45mph. Each participant was instructed to pass vehicles where appropriate while driving along this segment, then return to a right-lane, centered position upon completion of the maneuver.

Segment 3 was a 1.8-mile, four-lane, interstate roadway. Each participant drove along this segment in a right-lane, centered position and was instructed to obey all traffic signs and laws, and maintain the posted speed limit of 65mph. Each participant was instructed to pass vehicles where appropriate, while driving along this segment, then return to right-lane, centered position upon completion of the maneuver.

Each participant was instructed to return to the DMV parking lot, via a "loopback road" segment and drive the course a second time. The loopback road, segment 4, was a 2.9-mile, four-lane (non-divided) highway with a posted speed limit of 65mph. Each participant was instructed to pass vehicles where appropriate while driving along this segment. The driving scenario ended after each participant drove into the DMV parking lot after the second time around the course.

DATA REDUCTION

Performance Measures

Performance data from each experimental session were collected by the simulation software and saved to a local file on the simulator computer for analysis. Performance measures of interest including steering wheel angle, lane position, vehicle speed, and time to complete the course were captured throughout the simulation approximately every 125ms (8 times per second). These data were reduced to tabular form and placed into a Microsoft Excel spreadsheet in the categories: mean time to complete the course (min.), mean lane deviation (ft.), mean speed limit deviation (mph), and mean steering wheel angle variance (deg.) (APPENDIX H). The resulting data table was analyzed with the PC-Based Statistical Analysis Software (SAS) using the *proc anova* procedure.

Since multiple dependent measures were collected, a multivariate analysis of variance (MANOVA) using a Wilks' *Lambda* test was conducted to determine if significant effects were present in the data. An analysis of variance (ANOVA) was then conducted on each of the dependent variables tested in the MANOVA to determine the statistical significance of main effects and interactions. Simple effect *F*-tests were performed on significant interactions to determine their loci of significance.

Subjective Measures

The Presence Questionnaires and Immersive Tendencies Questionnaires were used to collect subjective data from each participant relative to perceived level of presence during operation of the simulator for each treatment condition. An analysis of covariance (ANCOVA) was used to analyze these data to determine if a certain treatment combination (A=D-V/FFE, B=D-V/FFD, C=HMD/FFE, or D=HMD/FFD) would be more 'realistic' than another combination and create a higher fidelity experience for the user, thereby increasing their perceived level of presence.

Participant preference regarding steering force feedback and display type was collected as survey data on the Participant Screening Form. These data were collected for comparison purposes and reported using descriptive statistics.

Missing Data

During the data reduction phase, it was discovered that a portion of data was missing from participant 2 in treatment A (D-V/FFE). For unknown reasons, the computer stopped collecting data while participant 2 was entering the loopback road segment of the simulation. The total amount of lost data represented 1822ft. (approximately 19sec.). This missing data represented 2.6% of the total 68,640ft. driven during one of four experimental sessions. Since the experiment had concluded and plans were underway to ship the simulator to its next destination, it was imperative to determine if the missing data would significantly affect the results of the study. If the data were compromised in any way by the missing data, participant 2 data would be discarded and a new participant would be found to run each of the four sessions. ANOVAs were conducted for all dependent measures to determine if participant 2 data was significantly different from those participants who were not missing data.

DATA ANALYSIS AND RESULTS

Missing Data Results

For the participant 2 missing data, significance was observed in lap ($F_{1,7} = 9.80$, $p = 0.0166$) and subject ($F_{7,7} = 4.72$, $p = 0.0290$) for the mean speed limit deviation dependent measure (Table 4). To determine the nature of the significance in relation to the complete data sets of the other male participants, a linear contrast was conducted. The contrast compared the participant 2 missing data with the other male participant data. The results of the linear contrast showed no significance ($p = 0.2839$) between participant 2 data and the other three male participants. Participant 2 data were therefore considered valid for inclusion and analysis with the rest of the collected data.

TABLE 4.
ANOVA Table for participant 2 missing data

Source	Num DF	Den DF	*F*	*p*
lap	1	7	9.80	0.0166*
subject	7	7	4.72	0.0290*

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
Is Subject 2 Data Different	-3.6290	3.1273	7	-1.16	0.2839[1]

* Statistically significant effect at p≤0.05.
[1] Non-significant results of linear contrast between participant 2 and all male participants.

MANOVA Results

Dependent variables included in the overall model were: mean time to the complete course (min.), mean lane deviation (ft.), mean speed limit deviation (mph), and mean steering wheel angle variance (deg.). Independent variables included in the model were: Gender, Display, Feedback, Segment and all interaction combinations. Significance was observed in Gender Display, Feedback, Segment, and Segment-by-Display in the overall MANOVA model using the Wilk's *Lambda* test (Table 5). Based upon these results, individual ANOVAs were conducted on each of the dependent variables. Only those significant main effects and interactions found in the ANOVAs that were also significant in the MANOVA were reported. This was done because individual ANOVAs do not provide adequate protection against making Type I errors (when a true hypothesis is rejected). Performing the MANOVA first, ensures that if significant differences are found between population means, "the researcher can be confident that real differences actually exist" and ANOVAs can then be used to determine where the differences actually occur (Johnson, 1998).

TABLE 5.
MANOVA Table

Source	Wilk's *Lambda*	F Value	Num DF	Den DF	Pr > F
Gender (G)	0.72	11.97	4	125	<0.0001*
Display (D)	0.55	25.39	4	125	0.0272*
D x G	0.94	2.17	4	125	0.0764
Feedback (F)	0.94	6.99	4	125	0.0071*
F x G	0.94	1.94	4	125	0.1072
F x D	0.91	3.19	4	125	0.0956
F x D x G	0.98	0.70	4	125	0.5958
Segment (SG)	0.02	98.29	12	331.01	<0.0001*
SG x G	0.83	2.00	12	331.01	0.3239
SG x D	0.60	5.89	12	331.01	<0.0001*
SG x D x G	0.94	0.67	12	331.01	0.7846
SG x F	0.93	0.78	12	331.01	0.668
SG x F x G	0.92	0.90	12	331.01	0.5439
SG x D x F	0.94	0.66	12	331.01	0.7926
SG x D x F x G	0.89	1.28	12	331.01	0.2303

* Statistically significant effect at $p \leq 0.05$.

ANOVA Results for Main Effects and Interactions

Individual ANOVAs were conducted on each of the four dependent variables: mean time to complete the course, mean lane deviation, mean speed limit deviation and mean steering wheel angle variance. Post-hoc analysis using the Student-Newman Keuls test was conducted on significant main effects with more than two levels. Simple effect *F*-tests were performed on significant interactions to determine the nature of any significant main effects. Results of these analyses follow.

Mean time to complete the course. Statistically significant differences were observed in Gender ($F_{1,6} = 10.40$, $p = 0.0180$), Segment ($F_{3,18} = 742.75$, $p < 0.0001$) and the interaction of Segment-by-Display ($F_{3,18} = 8.87$, $p = 0.0008$) for the dependent variable mean time to complete the course. The ANOVA summary table for mean time to complete the course is provided in Table 6.

For the main effect of Gender, female participants completed the course in significantly shorter time than male participants (17.29min. vs. 18.39min., respectively), Figure 10. Post-hoc analysis using the Student-Newman Keuls (SNK) test was conducted on the main effect of Segment. Results showed that participants took significantly longer time to drive the city segment (6.45min.), followed by the loopback (5.39min.), interstate (3.80min.), and highway (2.21min.) segments, Figure 11.

A simple-effect *F*-test was conducted on the Segment-by-Display interaction for mean time to complete the course to determine how the main effect of Segment differed at each level of Display and how the main effect of Display differed at each level of Segment. Results of the Segment-by-Display interaction analysis revealed that the simple main effect of Segment was significant for D-V ($F_{1,18} = 180.19$, $p < 0.0001$), Figure 12 and HMD ($F_{1,18} = 232.25$, $p < 0.0001$), Figure 13. Participants using both displays performed significantly different across the four segments, but similarly to one another within each segment. The simple main effect of Display was significant in the city segment ($F_{1,6} = 9.53$, $p = 0.0023$), Figure 14. Participants using the HMD drove significantly slower in the city segment.

TABLE 6.

ANOVA Table for *mean time to complete the course*

Source	df	SS	MS	*F*	*p*
Between Subjects					
Gender (G)	1	4369.93	4369.93	10.40	0.0180*
Subjects/Gender (S/G)	6	2521.81	420.30		
Within Subjects					
Display (D)	1	90.10	90.10	0.40	0.5481
D x G	1	55.84	55.84	0.25	0.6343
D x S/G	6	1335.39	222.56		
Feedback (F)	1	1516.75	1516.75	3.41	0.1145
F x G	1	68.51	68.51	0.15	0.7085
F x S/G	6	2672.27	445.37		
F x D	1	1.61	1.61	0.01	0.9361
F x D x G	1	98.91	98.91	0.43	0.5370
F x D x S/G	6	1385.14	230.85		
Segment (SG)	3	593181.55	197727.18	742.75	<0.0001*
SG x G	3	2268.95	756.31	2.84	0.0669
SG x S/G	18	4791.79	266.21		
SG x D	3	5348.02	1782.67	8.87	0.0008*
SG x D x G	3	36.42	12.14	0.06	0.9799
SG x D x S/G	18	3654.45	174.02		
SG x F	3	738.21	246.07	0.73	0.5496
SG x F x G	3	330.52	110.17	0.33	0.8072
SG x F x S/G	18	6430.56	306.214		
SG x D x F	3	209.56	69.85	0.21	0.8856
SG x D x F x G	3	792.81	264.27	0.81	0.5057
SG x D x F x S/G	18	5884.97	326.94		
Total	127				

* Statistically significant effect at $p \leq 0.05$ and matching MANOVA results.

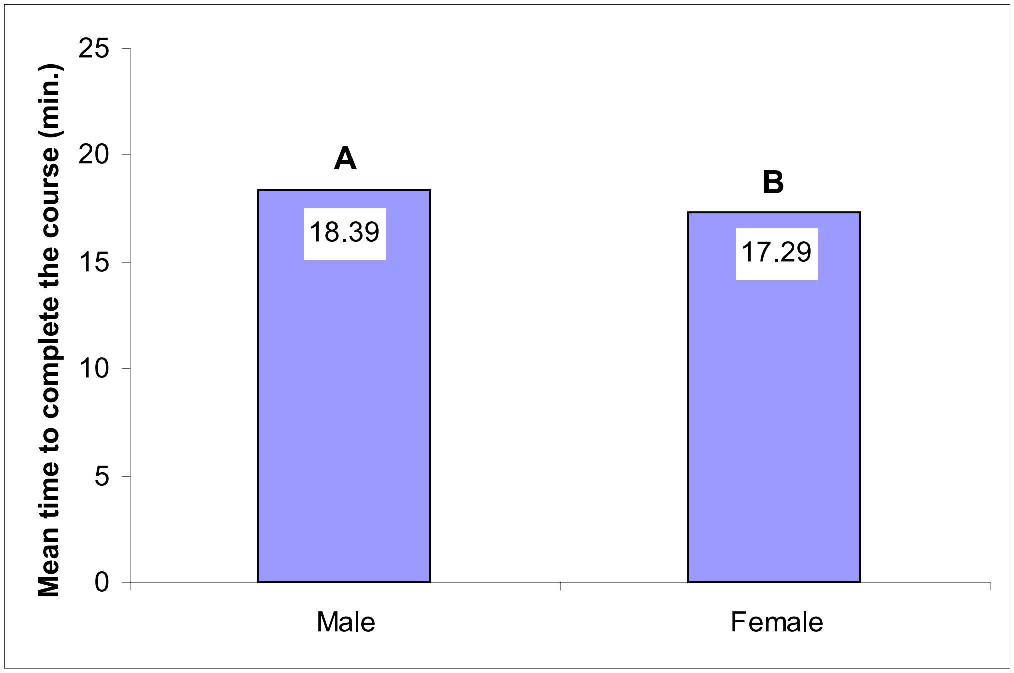


Figure 10. Gender main effect for the *mean time to complete the course* dependent measure (Means with different letters are significantly different at $p \le 0.05$).

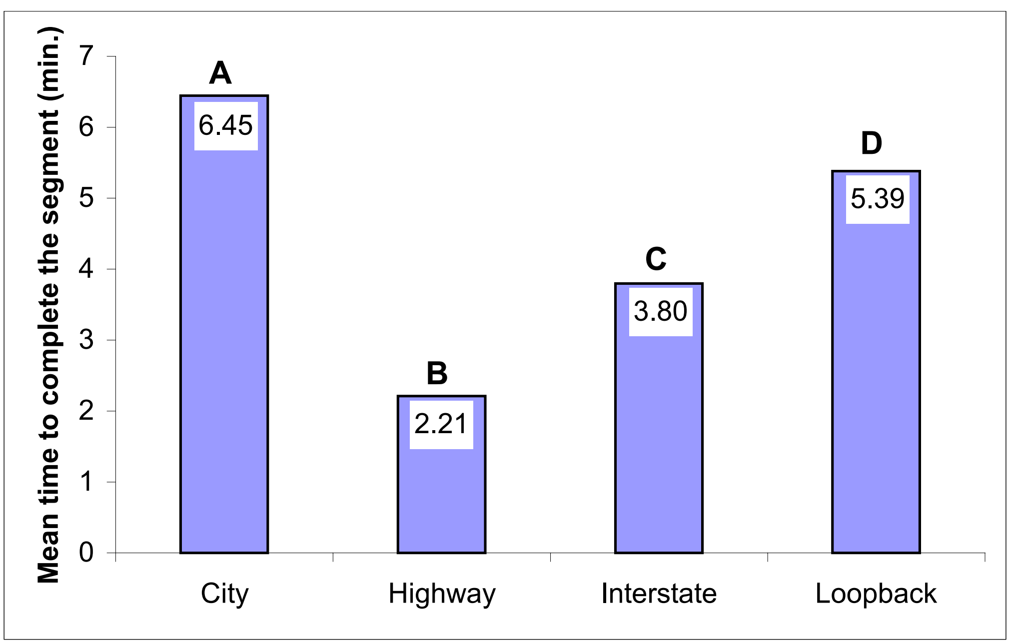


Figure 11. Segment main effect for the *mean time to complete the course* dependent measure (Means with different letters are significantly different at $p \le 0.05$).

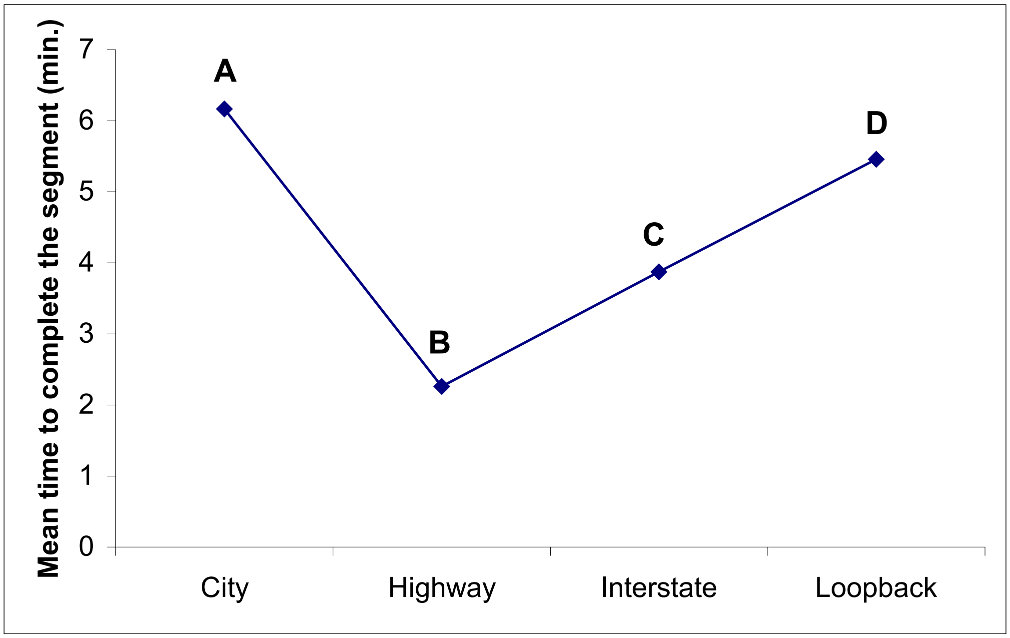


Figure 12. Simple main effect of segment for D-V for the *mean time to complete the course* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

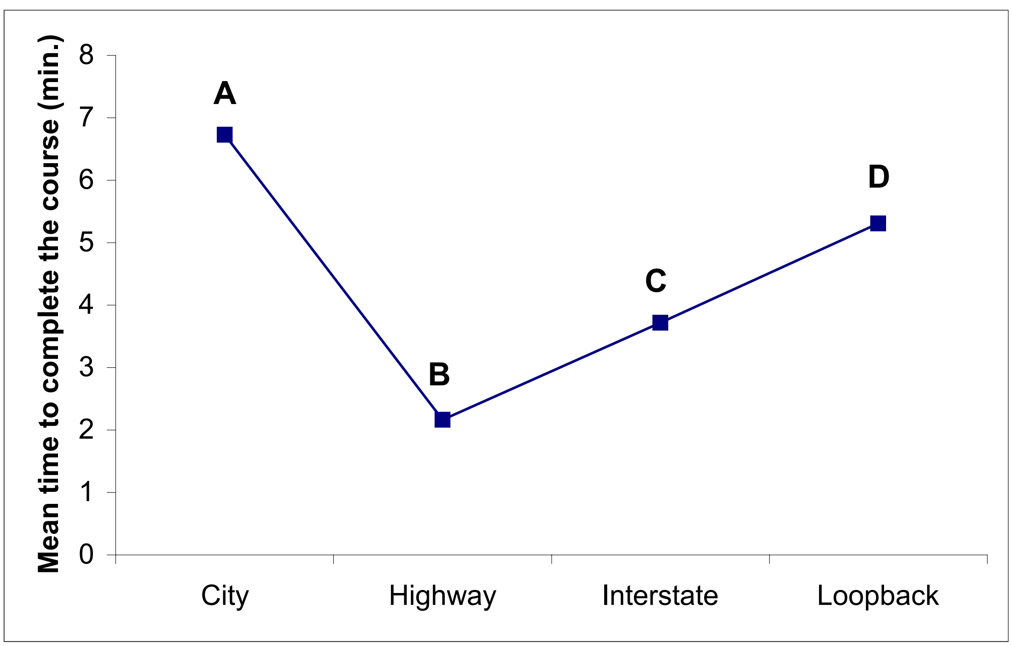


Figure 13. Simple main effect of segment for HMD for the *mean time to complete the course* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

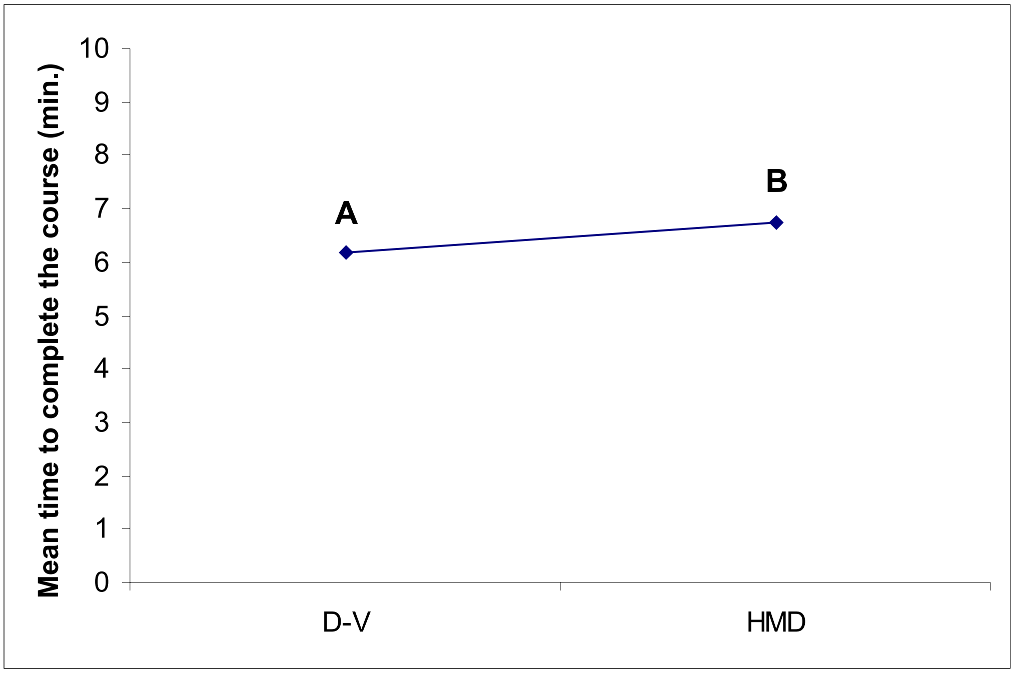


Figure 14. Simple main effect of display in the city segment for the *mean time to complete the course* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

Mean lane deviation. Statistically significant differences were observed in Display ($F_{1,6} = 30.21$, $p = 0.0015$), Feedback ($F_{1,6} = 7.19$, $p = 0.0364$), Segment ($F_{3,18} = 7.53$, $p = 0.0018$), and the interaction of Segment-by-Display ($F_{3,18} = 3.40$, $p = 0.0403$) for the dependent variable mean lane deviation. The ANOVA summary table for mean lane deviation is provided in Table 7.

For the main effect of Display, mean lane deviation when using the HMD was significantly less than when using the D-V. Participants deviated from the center-lane position on average 0.056ft. using the HMD and 0.157ft. using the D-V, Figure 15. For the main effect of Feedback, the absence of active steering force feedback resulted in a significantly lower mean lane deviation than with steering force feedback enabled. Participants deviated from the center-lane position on average 0.123ft. with steering force feedback enabled and 0.090ft. with steering force feedback disabled, Figure 16. A post-hoc analysis using the SNK test was conducted on the main effect of Segment. Results showed that mean lane deviation was significantly different between the city segment (0.05ft.) and both the highway and interstate segments (0.16ft. and 0.13ft., respectively). Highway and interstate segments were not significantly different from one another. The loopback segment (0.09ft.) was significantly different from the highway segment (0.16ft.), but not significantly different from the city segment or the interstate segment, Figure 17.

A simple-effect F-test was conducted on the Segment-by-Display interaction for mean lane deviation to determine how the main effect of Segment differed at each level of Display and how the main effect of Display differed at each level of Segment. Results of the Segment-by-Display interaction revealed that the simple main effect of Segment was significant during use of the HMD ($F = 10.04$, $p < 0.0001$), Figure 18. The effect of segment was significant for HMD in all levels of segment except between the city and loopback segments, Figure 18. When using the HMD, participants exhibited the least lane deviation in the city and loopback segments, and the greatest deviation in the highway segment. Results of the Segment-by-Display interaction also revealed that the simple main effect of Segment was significant during use of the D-V ($F = 3.03$, $p = 0.0302$), Figure 19. The effect of segment was significant for D-V in all levels of segment except between the highway and interstate segments, Figure 19. When using the D-V display, participants exhibited the least lane deviation in the city segment and the greatest deviation in the highway and interstate segments. The simple main effect of Display was significant at Segment levels, city ($F = 15.94$, $p < 0.0001$), Figure 20, interstate ($F = 17.02$, $p < 0.0001$), Figure 21, and loopback ($F = 19.62$, $p < 0.0001$), Figure 22. Participants exhibited greater lane deviation in these road segments when using the D-V display. The highway level of Segment was not significant across display types.

TABLE 7.

ANOVA Table for *mean lane deviation*

Source	df	SS	MS	*F*	*p*
Between Subjects					
Gender (G)	1	0.33	0.33	2.74	0.1486
Subjects/Gender (S/G)	6	0.72	0.12		
Within Subjects					
Display (D)	1	1.45	1.45	30.21	0.0015*
D x G	1	0.01	0.01	0.33	0.5874
D x S/G	6	0.28	0.04		
Feedback (F)	1	0.15	0.15	7.19	0.0364*
F x G	1	0.13	0.13	6.31	0.0458
F x S/G	6	0.12	0.02		
F x D	1	0.28	0.28	5.40	0.0591
F x D x G	1	0.00	0.00	0.00	0.9662
F x D x S/G	6	0.31	0.05		
Segment (SG)	3	1.00	0.33	7.53	0.0018*
SG x G	3	0.07	0.02	0.58	0.6372
SG x S/G	18	0.79	0.04		
SG x D	3	0.20	0.06	3.40	0.0403*
SG x D x G	3	0.06	0.02	1.17	0.3496
SG x D x S/G	18	0.36	0.02		
SG x F	3	0.02	0.00	0.64	0.5978
SG x F x G	3	0.04	0.01	0.94	0.4400
SG x F x S/G	18	0.26	0.01		
SG x D x F	3	0.06	0.02	1.15	0.3576
SG x D x F x G	3	0.04	0.01	0.81	0.5062
SG x D x F x S/G	18	0.33	0.01		
Total	127				

* Statistically significant effect at $p \leq 0.05$ and matching MANOVA results.

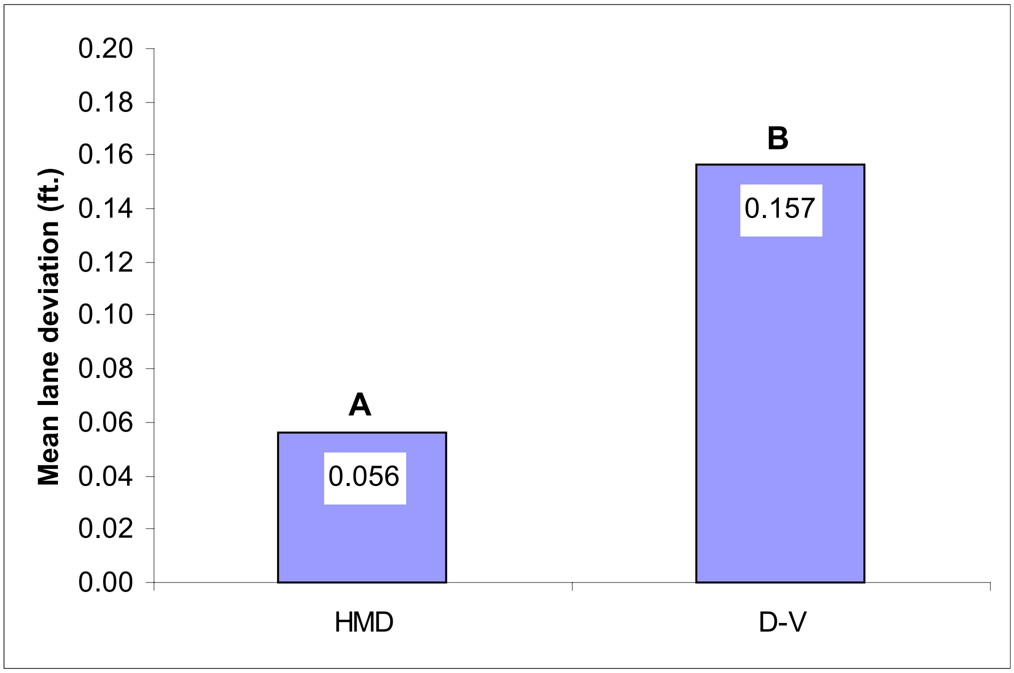


Figure 15. Display main effect for the *mean lane deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

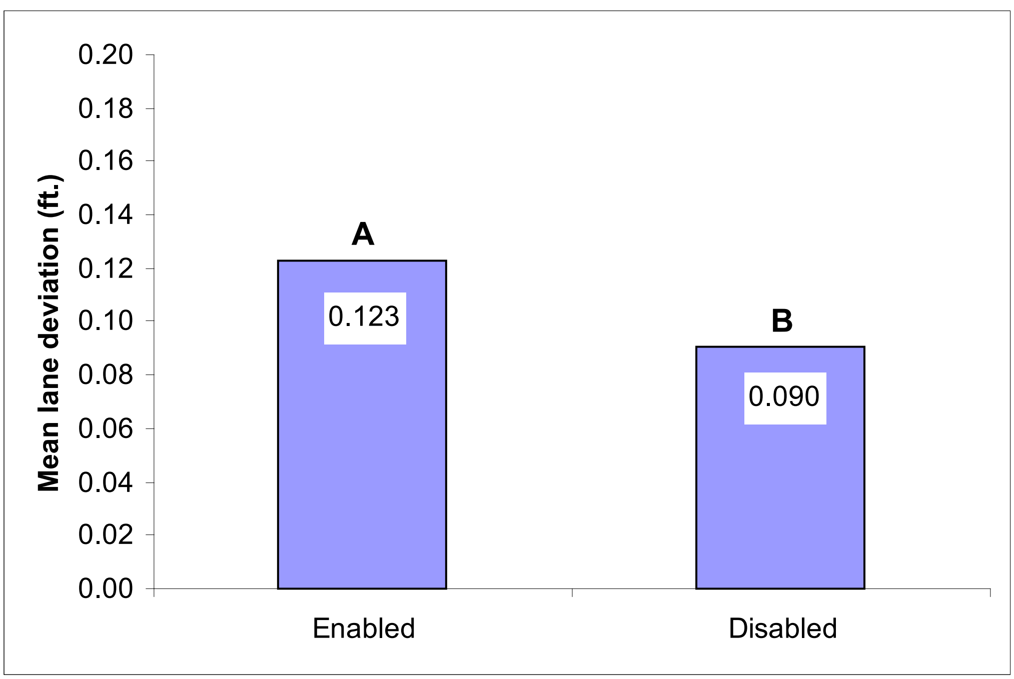


Figure 16. Feedback main effect for the *mean lane deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

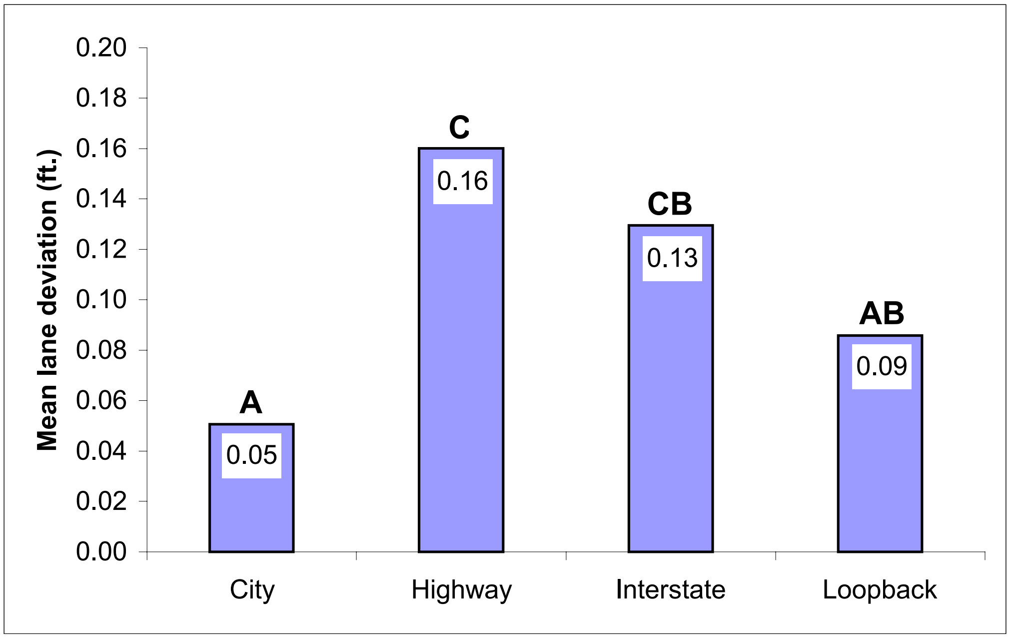


Figure 17. Segment main effect for *mean lane deviation* (Means with different letters are significantly different at $p \leq 0.05$).

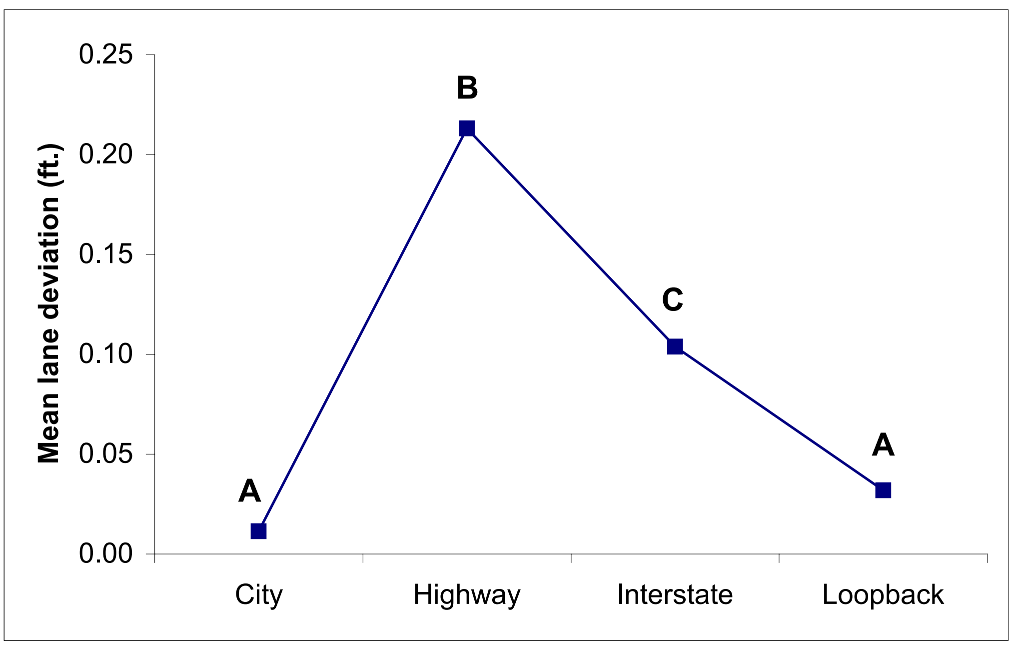


Figure 18. Simple effect of segment for HMD for the *mean lane deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

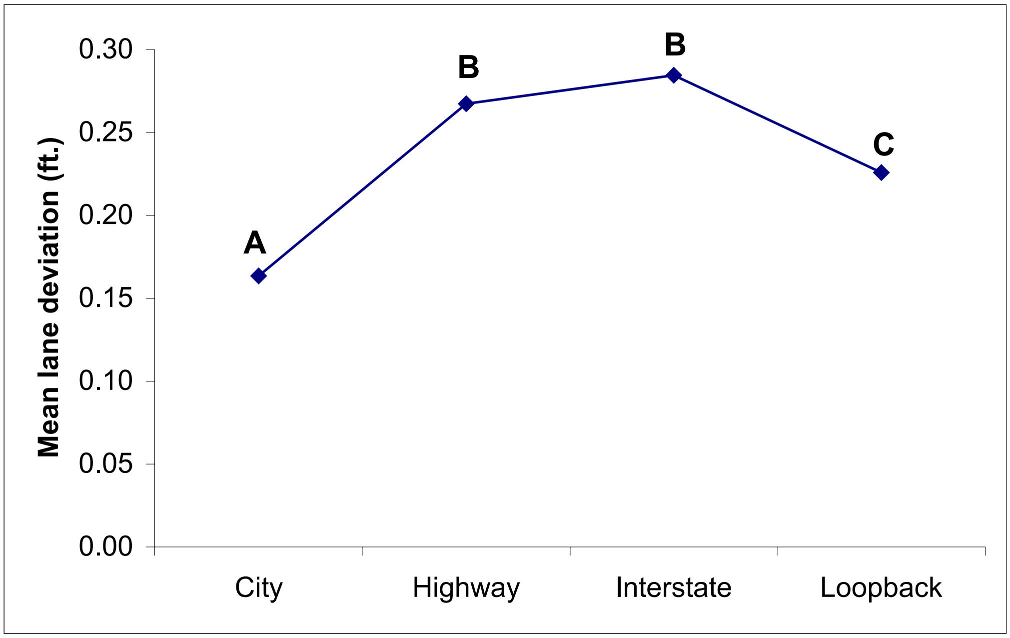


Figure 19. Simple effect of segment for D-V for the *mean lane deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

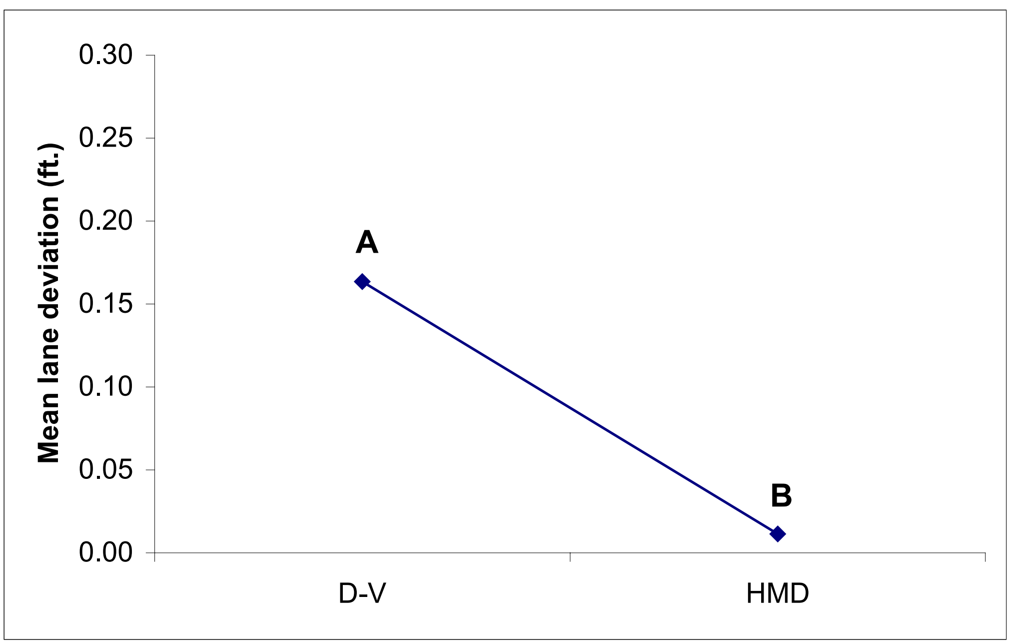


Figure 20. Simple main effect of display in the city segment for the *mean lane deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

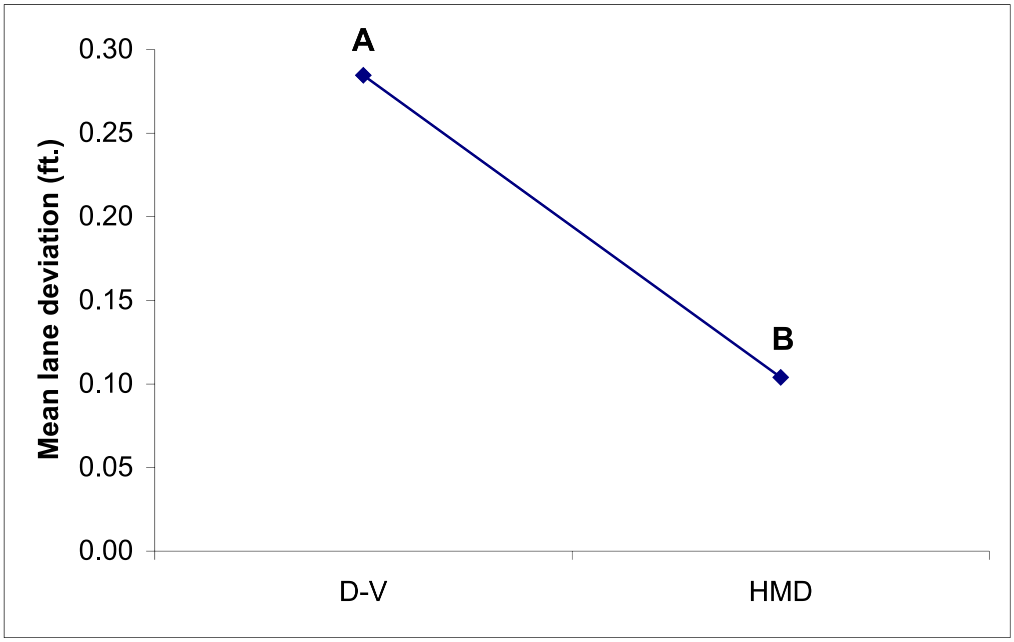


Figure 21. Simple main effect of display in the interstate segment for the *mean lane deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

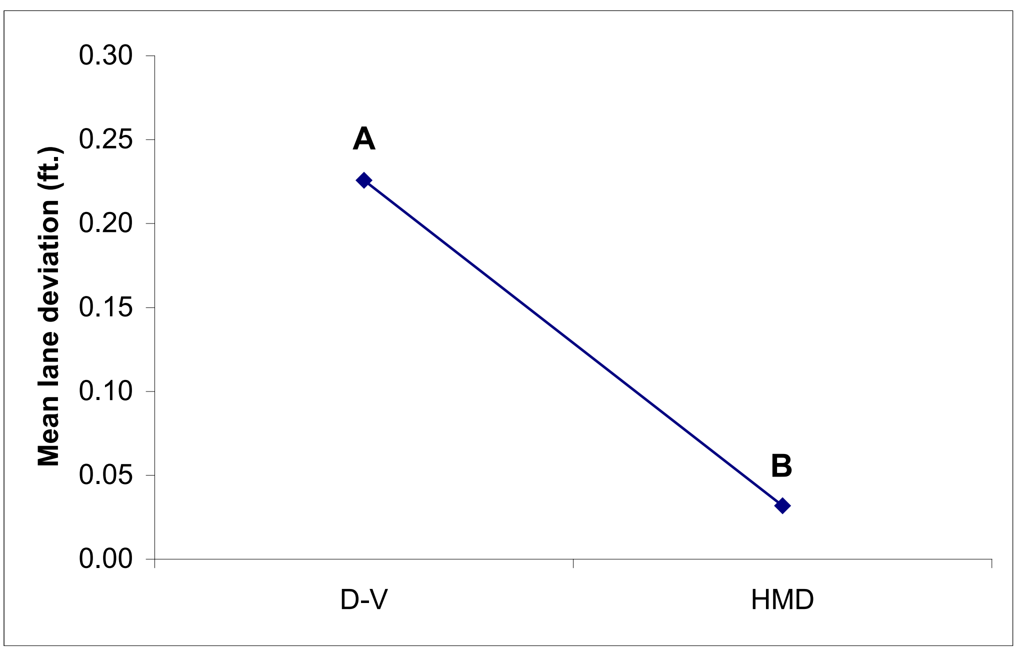


Figure 22. Simple main effect of display in the loopback segment for the *mean lane deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

Mean speed limit deviation. Statistically significant differences were observed in Display ($F_{1,6} = 25.27$, $p = 0.0024$), Segment ($F_{3,18} = 27.20$, $p < 0.0001$), and the interaction of Segment-by-Display ($F_{3,18} = 28.78$, $p < 0.0001$) for the dependent variable mean speed limit deviation. The ANOVA summary table for mean speed limit deviation is provided in Table 8.

For the main effect of Display, mean speed limit deviation when using the HMD was significantly less than with the D-V. Participants drove, on average, 2.7mph below the speed limit when using the HMD and 3.9mph below the speed limit when using the D-V, Figure 23. Post-hoc analysis using the SNK test was conducted on the main effect of Segment. Results showed that mean speed limit deviation was significantly different between the highway and interstate segments (1.90mph and 5.26mph, respectively), the highway and city segments (1.90mph and 2.97, respectively) and the highway and loopback segments (1.90mph and 3.17mph, respectively). Significant differences were also found between the interstate and city segments (5.26mph and 2.97mph, respectively) and the interstate and loopback segments (5.26mph and 3.17mph, respectively). Mean speed limit deviation was not significant between the city segment (2.97mph) and the loopback segment (3.17mph), Figure 24.

A simple-effect F-test was conducted on the Segment-by-Display interaction for mean speed limit deviation to determine how the main effect of Segment differed at each level of Display and how the main effect of Display differed at each level of Segment. Results of the Segment-by-Display interaction revealed that the simple main effect of Segment was significant during use of the HMD ($F = 16.17$, $p < 0.0001$), Figure 25. The effect of segment was significant for HMD in all levels of segment except between the highway and loopback segments, Figure 25. When using the HMD, participants exhibited the greatest speed limit deviation in the interstate state segment and the least deviation in the highway and loopback segments. Results of the Segment-by-Display interaction also revealed that the simple main effect of Segment was significant during use of the D-V display ($F = 22.01$, $p < 0.0001$), Figure 26. The effect of segment was significant for D-V in all levels of segment except between the city and highway segments, Figure 26. When using the D-V display, participants exhibited the greatest speed limit deviation in the interstate segment and the least deviation in the city and highway segments.

The simple main effect of Display was significant at Segment levels, city ($F = 4.28$, $p = 0.0395$), Figure 27, highway ($F = 5.18$, $p < 0.0237$), Figure 28, interstate ($F = 8.81$, $p = 0.0033$), Figure 29, and loopback ($F = 32.76$, $p < 0.0001$) Figure 30. Participants exhibited greater speed limit deviation when using the D-V display in the highway, interstate, and loopback segments. Greater speed limit deviation was exhibited in the city segment when participants used the HMD, Figure 27. Although both positive and negative deviations were captured, all mean speed limit deviations were below the posted speed limit. In other words, when participants deviated from the posted speed limit, they drove slower than the posted speed limit, so the greater their deviation from the posted speed limit, the slower they drove.

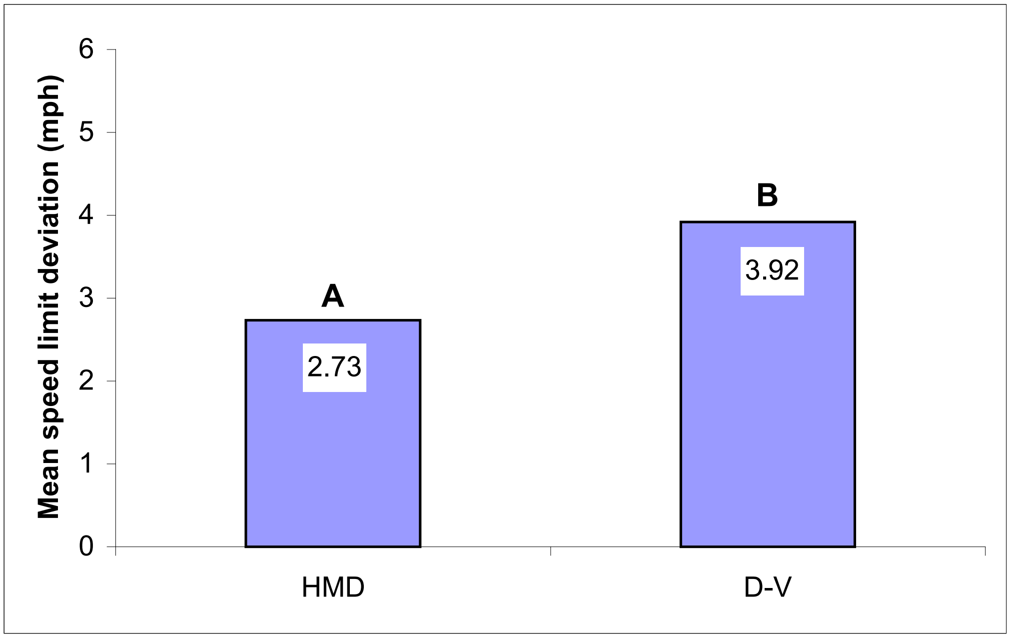


Figure 23. Display main effect for the *mean speed limit deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$. Values represent amount of deviation below the posted speed limit).

TABLE 8.

ANOVA Table for *mean speed limit deviation*

Source	df	SS	MS	*F*	*p*
Between Subjects					
Gender (G)	1	257.79	257.79	4.54	0.0770
Subjects/Gender (S/G)	6	340.38	56.73		
Within Subjects					
Display (D)	1	203.04	203.04	25.27	0.0024*
D x G	1	20.02	20.02	2.49	0.1655
D x S/G	6	48.21	8.03		
Feedback (F)	1	44.89	44.89	4.50	0.0781
F x G	1	2.03	2.03	0.20	0.6674
F x S/G	6	59.82	9.97		
F x D	1	2.94	2.94	0.17	0.6932
F x D x G	1	0.07	0.07	0.00	0.9510
F x D x S/G	6	103.10	17.18		
Segment (SG)	3	854.55	284.85	27.20	<0.0001*
SG x G	3	30.74	10.24	0.98	0.4247
SG x S/G	18	188.49	10.47		
SG x D	3	320.43	106.81	28.78	<0.0001*
SG x D x G	3	6.90	2.30	0.62	0.6108
SG x D x S/G	18	73.71	3.51		
SG x F	3	2.75	0.91	0.29	0.8318
SG x F x G	3	8.00	2.66	0.84	0.4876
SG x F x S/G	18	64.91	3.09		
SG x D x F	3	0.18	0.06	0.02	0.9958
SG x D x F x G	3	7.02	2.34	0.81	0.5062
SG x D x F x S/G	18	52.20	2.90		
Total	127				

* Statistically significant effect at $p \leq 0.05$ and matching MANOVA results.

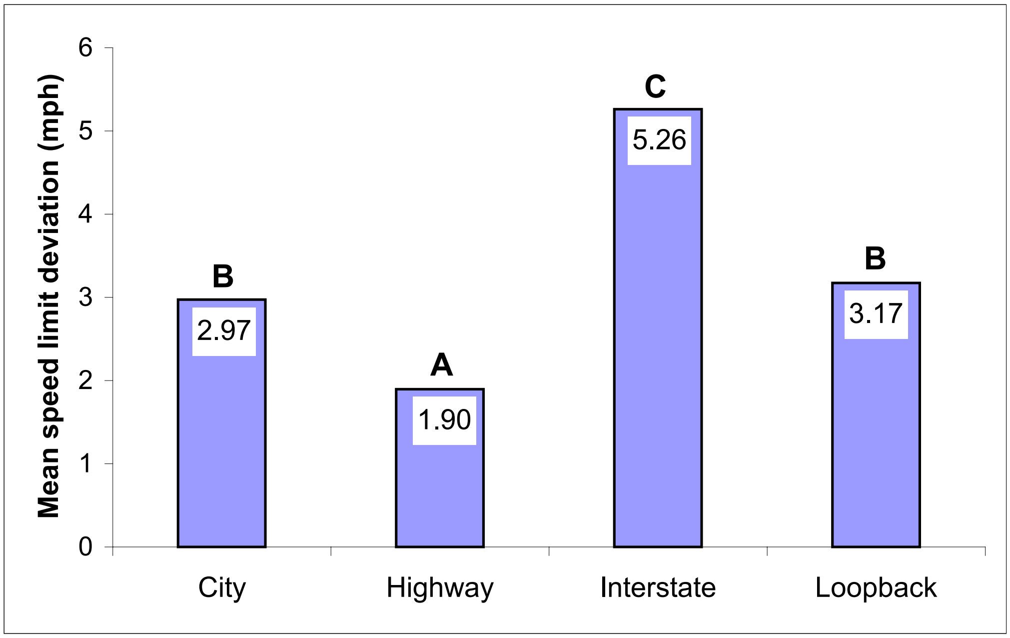


Figure 24. Segment main effect for *mean speed limit deviation* (Means with different letters are significantly different at $p \leq 0.05$. Values represent amount of deviation below the posted speed limit).

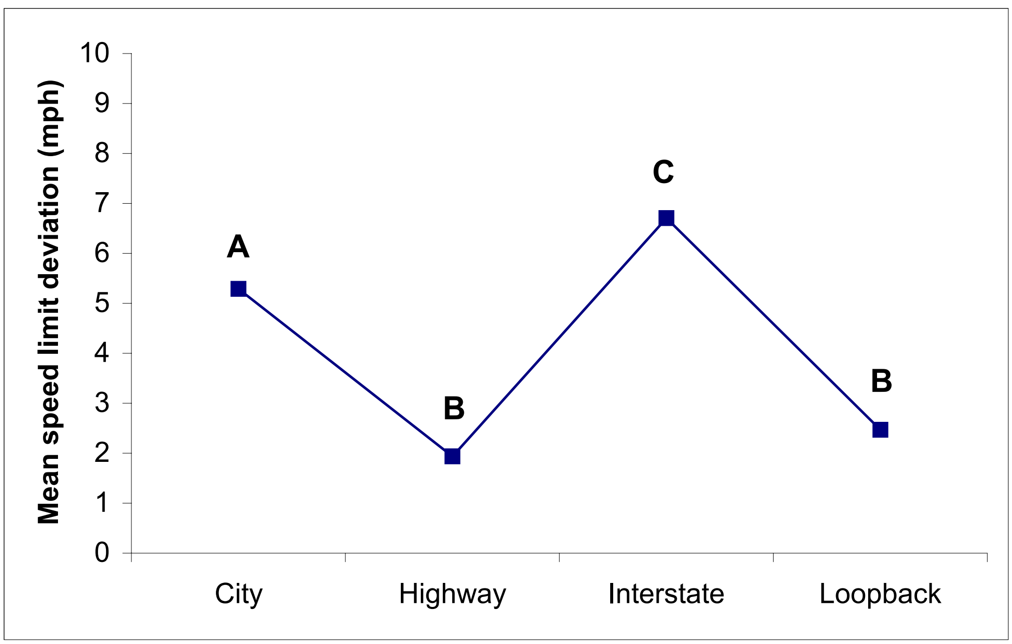


Figure 25. Simple effect of segment for HMD for the *mean speed limit deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$. Values represent amount of deviation below the posted speed limit).

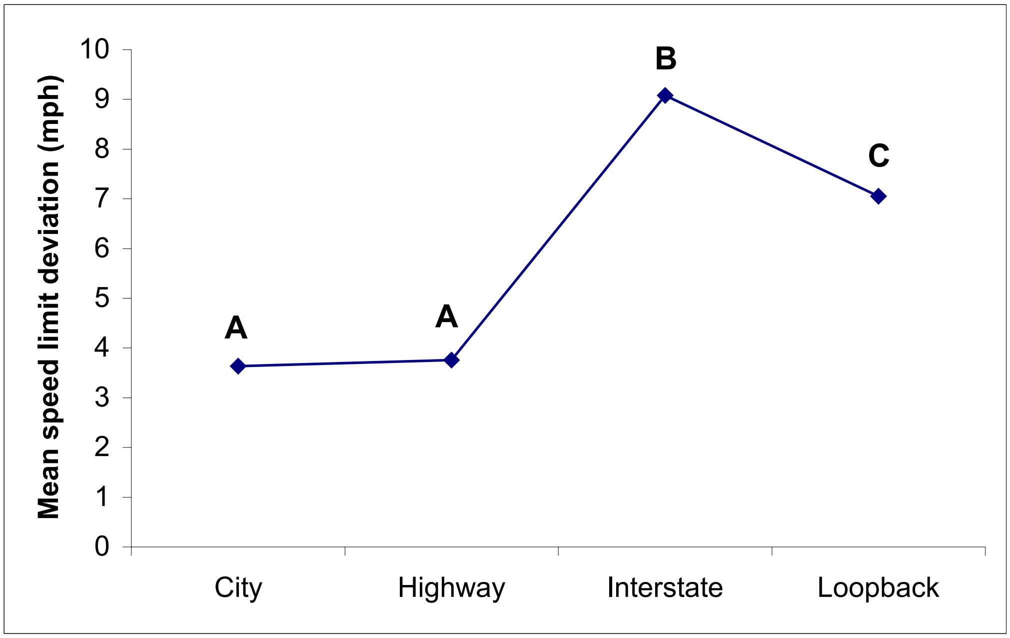


Figure 26. Simple effect of segment for D-V for the *mean speed limit deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$. Values represent amount of deviation below the posted speed limit).

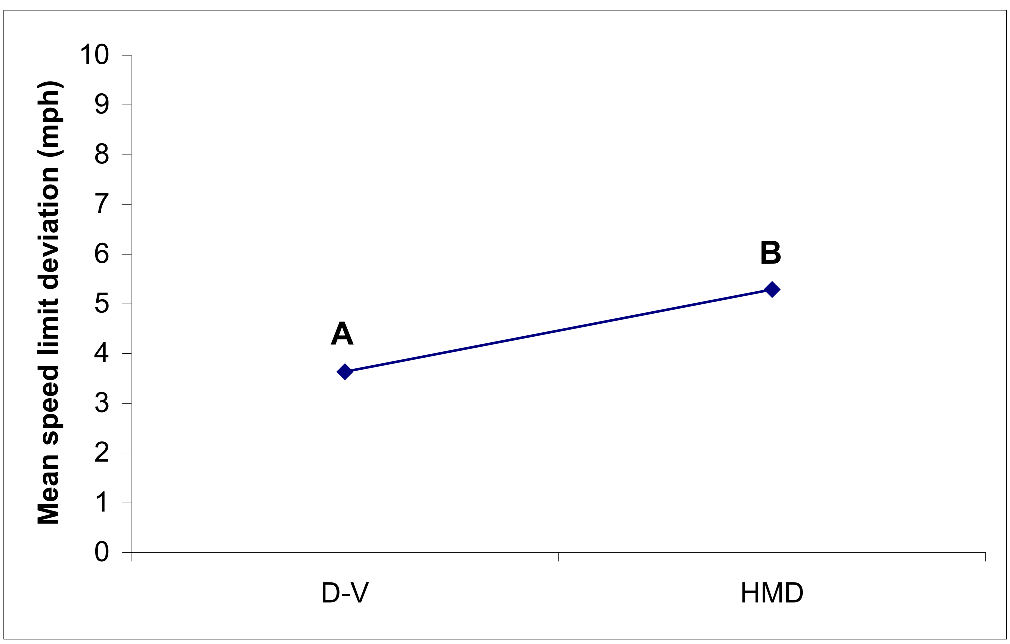


Figure 27. Simple main effect of display in the city segment for the *mean speed limit deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$. Values represent amount of deviation below the posted speed limit).

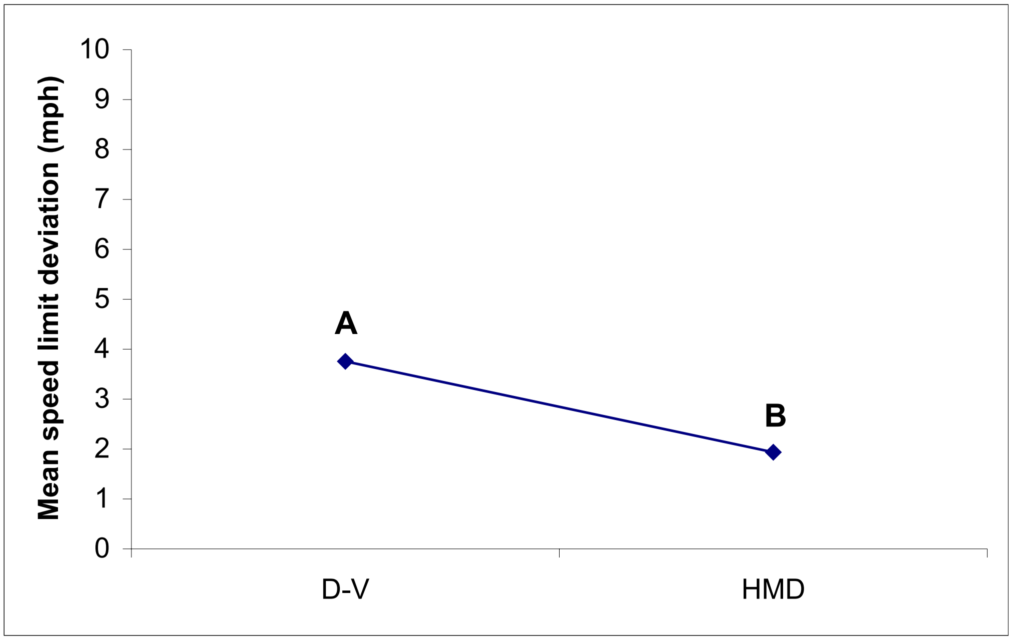


Figure 28. Simple main effect of display in the highway segment for the *mean speed limit deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$. Values represent amount of deviation below the posted speed limit).

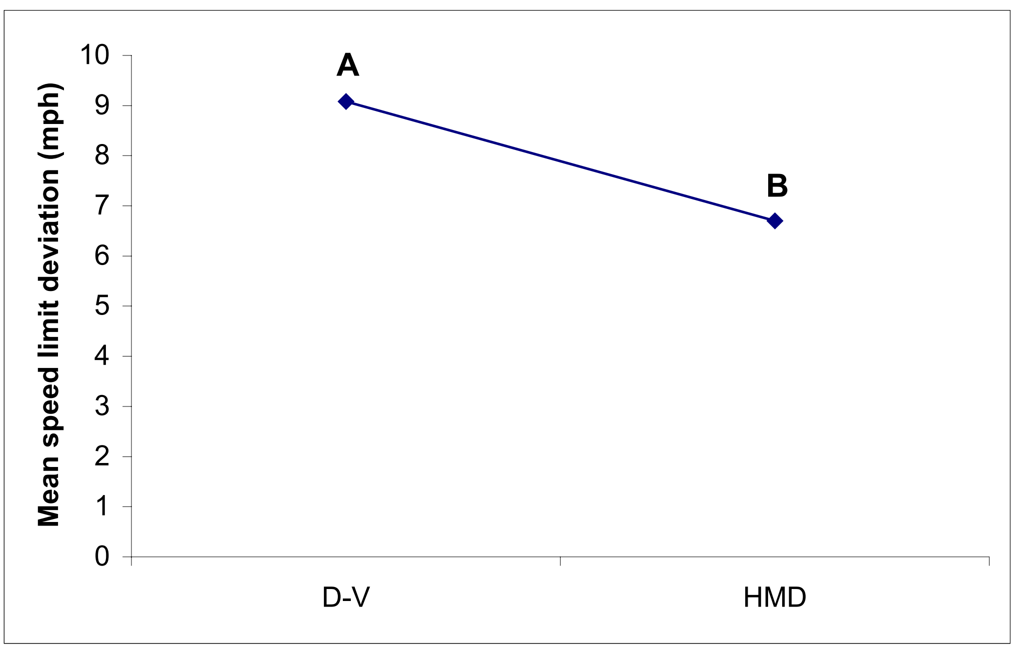


Figure 29. Simple main effect of display in the interstate segment for the *mean speed limit deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$. Values represent amount of deviation below the posted speed limit).

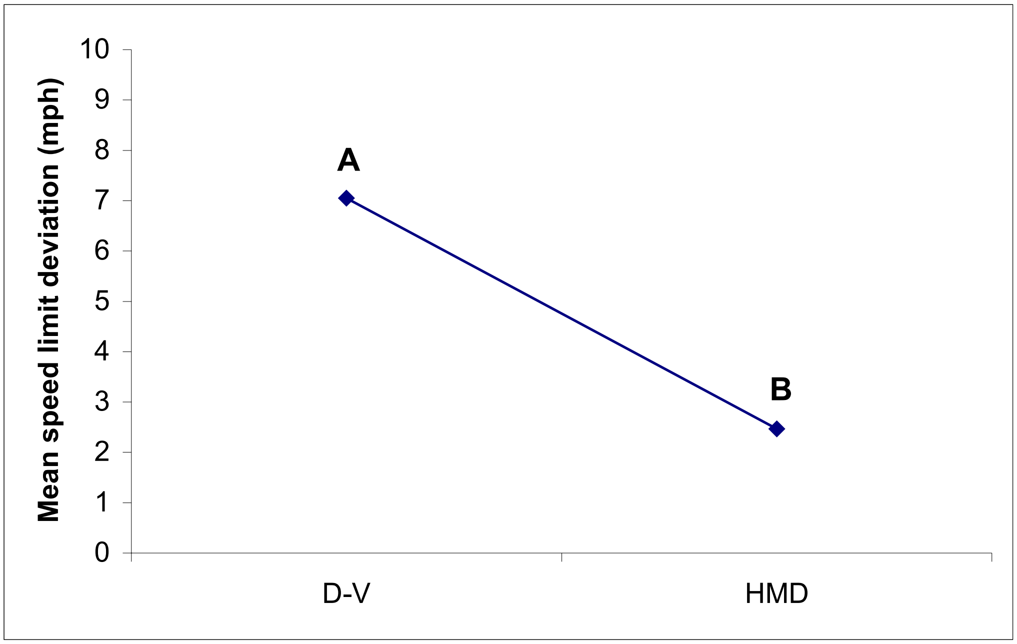


Figure 30. Simple main effect of display in the loopback segment for the *mean speed limit deviation* dependent measure (Means with different letters are significantly different at $p \leq 0.05$. Values represent amount of deviation below the posted speed limit).

Mean steering wheel angle variance. A statistically significant main effect was observed in Segment ($F_{3,18}$ = 32.33, p < 0.0001) for the mean steering wheel angle variance dependent variable, Figure 31. Post-hoc analysis using the SNK test was conducted on the main effect of Segment. Results showed that participants exhibited significantly greater steering wheel angle variance in the city road segment, Figure 31. The ANOVA summary table for mean steering wheel angle variance is provided in Table 9.

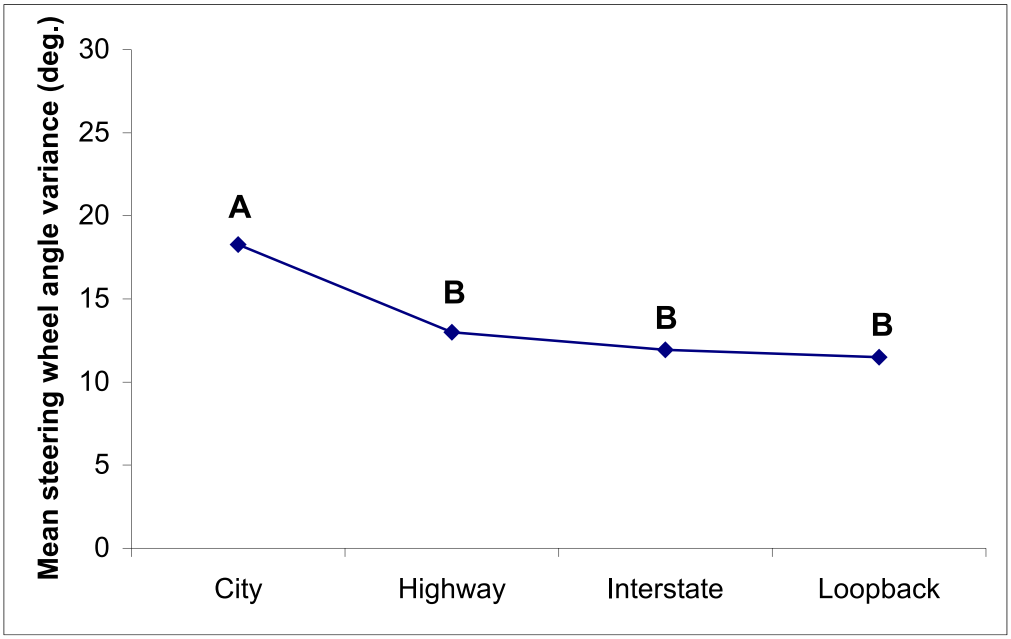


Figure 31. Simple main effect of segment for the *mean steering wheel angle variance* dependent measure (Means with different letters are significantly different at $p \leq 0.05$).

TABLE 9.

ANOVA Table for *mean steering wheel angle variance*

Source	df	SS	MS	*F*	*p*
Between Subjects					
Gender (G)	1	8590047.96	8590047.96	4.60	0.0757
Subjects/Gender (S/G)	6	11206131.60	1867688.60		
Within Subjects					
Display (D)	1	3141189.95	3141189.95	1.48	0.2697
D x G	1	2339786.96	2339786.96	1.10	0.3344
D x S/G	6	12746447.00	2124407.80		
Feedback (F)	1	4093157.38	4093157.38	1.57	0.2562
F x G	1	5903360.55	5903360.55	2.27	0.1826
F x S/G	6	15598858.00	2599809.70		
F x D	1	4468990.40	4468990.40	3.59	0.1069
F x D x G	1	6310330.12	6310330.12	5.07	0.0653
F x D x S/G	6	7468818.80	1244803.10		
Segment (SG)	3	185061964.10	61687321.40	32.33	<0.0001*
SG x G	3	24060506.40	8020168.80	4.20	0.0203
SG x S/G	18	34341063.00	1907836.80		
SG x D	3	10265406.24	3421802.08	1.63	0.2178
SG x D x G	3	7124196.96	2374732.32	1.13	0.3632
SG x D x S/G	18	37809782.10	2100543.50		
SG x F	3	13178896.02	4392965.34	1.74	0.1950
SG x F x G	3	18586654.37	6195551.46	2.45	0.0966
SG x F x S/G	18	45481566.90	2526753.70		
SG x D x F	3	12957897.38	4319299.13	3.44	0.0390
SG x D x F x G	3	18748202.77	6249400.92	4.98	0.0109
SG x D x F x S/G	18	22605588.50	1255866.00		
Total	127				

* Statistically significant effect at $p \leq 0.05$ and matching MANOVA results.

Simple main effect and interaction synopsis. The following table provides a brief summary of the main treatment effects and interactions (Table 10). Significant main effects and interactions are accompanied by their respective *p*-values and a brief synopsis of the significance. Post-hoc and interaction synopses are also provided.

TABLE 10.

Simple main effect and interaction synopsis

Dependent Measure	Gender main effect	Display main effect	Feedback main effect	Segment main effect	Post-hoc synopsis of Segment main effect	Segment-by-Display interaction effect	Interaction synopsis of Segment-by-Display interaction
Mean time to complete the course	Significant $p=0.0180$ Females took less time than males	Not Significant	Not Significant	Significant $p<0.0001$ (see post-hoc)	Significant differences between all levels	Significant $p=0.0008$ (see interaction synopsis)	-Participants using both displays performed significantly different across the four segments, but similarly to one another within each segment. -Participants using the HMD drove significantly slower in the city segment.
Mean lane deviation	Not Significant	Significant $p=0.0015$ Less lane deviation with HMD	Significant $p=0.0364$ Less lane deviation with steering force feedback disabled	Significant $p=0.0018$ (see post-hoc)	Significant differences between city/highway, city/interstate, and loopback/highway. No significant differences between loopback/city loopback/interstate and highway/interstate.	Significant $p=0.0403$ (see interaction synopsis)	-When using the HMD, participants exhibited the least lane deviation in the city and loopback segments, and the greatest deviation in the highway segment. -When using the D-V display, participants exhibited the least lane deviation in the city segment and the greatest deviation in the highway and interstate segments. -The simple main effect of Display was significant at Segment levels city, interstate, and loopback. Participants exhibited greater lane deviation in these segments when using the D-V display. -The highway segment was not significant across display types.
Mean speed limit deviation	Not Significant	Significant $p=0.0024$ Less speed limit deviation with HMD	Not Significant	Significant $p<0.0001$ (see post-hoc)	Significant differences between highway/interstate, highway/city, highway/loopback, interstate/city, and interstate/loopback). No significant differences between city and loopback.	Significant $p<0.0001$ (see interaction synopsis)	-When using the HMD, participants exhibited the greatest speed limit deviation in the interstate state segment and the least deviation in the highway and loopback segments. -When using the D-V display, participants exhibited the greatest speed limit deviation in the interstate segment and the least deviation in the city and highway segments. -Participants exhibited greater speed limit deviation when using the D-V display in the highway, interstate, and loopback segments. -Greater speed limit deviation was exhibited in the city segment when participants used the HMD.
Mean steering wheel angle variance	Not Significant	Not Significant	Not Significant	Significant $p<0.0001$ (see post-hoc)	Significant difference between city segment and the other three segments. No significant difference between highway, interstate, or loopback.	Not Significant	---

Questionnaire ANCOVA Results

The results of the ANCOVA showed no statistically significant effect ($F_{4,31} = 0.73$, $p = 0.5802$) between treatment and Presence Questionnaire results. In other words, there is no evidence that any one treatment combination produced a greater level of perceived presence than another (Table 11).

TABLE 11.

ANCOVA results for questionnaire data

Dependent Variable: pqall

Source	df	SS	MS	*F*	*p*
Model	4	509.48	127.37	0.73	0.5802
Error	27	4719.74	174.81		
Corrected Total	31	5229.22			

R-Square	Coeff Var	Root MSE	pqall Mean
0.09	14.01	13.22	94.34

Source	df	Type I SS	MS	*F*	*p*
Treatment	3	403.09	134.36	0.77	0.5216
ITQ	1	106.39	106.39	0.61	0.4421
Total	4				

* Statistically significant effect at $p \leq 0.05$.

Preference Survey Results

At the conclusion of the experiment, participants were asked which display type they preferred, HMD or Direct-view, and which level of steering force feedback they preferred, enabled or disabled. Both male and female participants preferred the head-mounted display and direct-view display equally (50% and 50% respectively). 100% of female participants and 75% of male participants preferred steering force feedback enabled as opposed to steering force feedback disabled, Figure 32. Both males and females cited lack of comfort and small screen size as the primary drawbacks with the head-mounted display. The large, crisp screen of the direct-view display was cited as its main advantage, but the lack of realism when turning corners or looking around the environment was the primary disadvantage. Both males and females cited a greater sense of realism and control with steering force feedback enabled, with only one participant stating that steering force feedback disabled was more realistic.

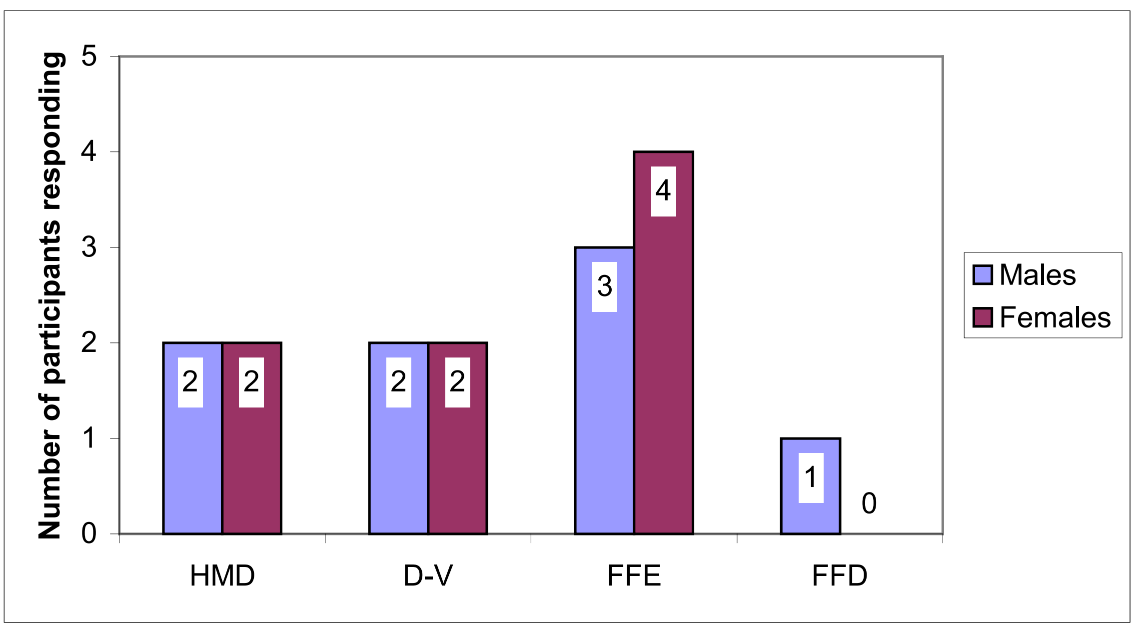


Figure 32. Survey results for display and feedback preference.

DISCUSSION

Performance Measures

The primary objective of this research was to determine if the use of specific levels of display type and steering force feedback would have a significant impact on driving performance and perceived levels of presence in a virtual environment driving simulator. It was hypothesized that active steering force feedback would significantly (statistically) improve driver-vehicle performance in a driving simulator compared to no steering force feedback. It was further hypothesized that the use of a head-mounted display would significantly (statistically) improve driver-vehicle performance in a driving simulator compared to a direct-view display. It was also hoped that the combination of HMD and active steering force feedback would be more 'realistic' and create a higher fidelity experience for the user, thereby increasing their perceived presence while in this particular VE.

Since similar research has been conducted in the past by other researchers, it was anticipated that the results of this experiment would closely match the outcome of that research. Previous research has shown that steering force feedback has a statistically significant effect on driving performance of the "human in the loop" in a driving simulator (Godthelp, 1980; Hirota and Hirose, 1995; Liu and Chang, 1995; Sadhu, 2001). It has also been shown that the use of a head-mounted display in a VE can create a greater level of presence for the participant, thereby providing a more realistic environment and a greater level of performance (Barfield, Zeltzer, et al., 1995; Bolas, 1994; Hendrix and Barfield, 1996). In order to achieve this goal, each of the factors of interest were used together in all possible combinations, a controlled experiment was conducted, and relevant data were collected, analyzed and reported. A discussion of the findings follows.

The first issue addressed in this study was whether or not the use of an HMD was significantly better than a D-V in terms of driving performance. It was expected that the use of an HMD would show significant decreases in time to complete the course, decreases in lane deviation, increases in speed control and decreases in steering wheel angle variance. It was also assumed that the driver would have an increased level of perceived presence during the simulation with the combination of HMD and active steering force feedback.

Mean time to complete the course. For the performance measure *mean time to complete the course,* there was significance in the main effect of Segment and in the Segment-by-Display interaction. Statistical differences were expected between each segment because speed was a controlled element within each segment and each segment was different in length. Results of the Segment-by-Display interaction revealed that participants who wore both the HMD and D-V performed relatively the same within each road segment but significantly different across each segment. In other words, both the HMD and D-V users drove slowest in the city segment, faster in the loopback segment, still faster in the interstate segment, and fastest in the highway segment. The only segment where the two displays differed significantly was the city segment. In the city segment, participants using the HMD drove significantly slower than participants using the D-V. It is believed that the reason for this is because the city segment is a much more confined, two-lane space compared with the other road segments. When users wore the HMD in the city segment, the generally more cautious method of driving was intensified because the user could turn their head (thereby changing the visual scene) while driving. Since this segment allowed little room for error in terms of lane deviation, when drivers would look around while driving, they reduced their speed. The reduction in speed was most probably a way for the driver to have a better perceived level of control in the more confined space. Another reason for the difference between display types in the city segment is when the drivers encountered stop signs, two different times in the city segment, the D-V users usually stopped at the stop sign, waited a second or two, and then drove off. The HMD wearers, on the other hand, could actually turn their heads left and right to check for traffic. When they came to the stop signs, they took more time before continuing because they actually checked left and right for cross-traffic; something they could not do when using the D-V.

Mean lane deviation. For the performance measure *mean lane deviation,* significance was found in the main effects of Display, Feedback, Segment, and the interaction of Segment-by-Display. For the main effect of Feedback, the absence of active steering force feedback resulted in significantly lower mean lane deviation than with steering force feedback enabled. This is contrary to the stated hypothesis which postulated that active steering force feedback would provide more control (i.e., less lane deviation) for the driver as well as a greater sense of realism. The latter is confirmed in the subject preference ratings discussed later. The author believes there are many reasons that steering force feedback enabled was not significant for this performance measure. The first is that the simulated driving course had a limited capacity to evaluate the true merits of active steering. For instance, it is believed that the integration of curves with realistic banking gradients would have provided a much better test of active steering usefulness than the flat and gentle curves used in this simulation. Long, curved turns at varying speeds and driving scenarios with more lane-changing activity would most probably yield higher lane deviations in the steering force feedback disabled mode and may produce a significant positive effect for the active feedback mode.

Results of the Segment-by-Display interaction simple-effect *F*-test revealed that the simple main effect of Segment was significant during use of the HMD in all levels of segment except between the city and loopback segments. Segment was also significant during use of the D-V in all levels of segment except between the highway and interstate segments. For the HMD, lane deviation between the city and loopback segments was statistically similar and was the lowest lane deviation across segments. Lane deviation in the interstate segment was significantly greater than in the city and loopback segments. Lane deviation in the highway segment was significantly greater than all other segments. It is assumed the reason the highway segment yielded the greatest lane deviation for HMD wearers is because when entering the highway segment, drivers tended to keep looking over their shoulders when making the left turn onto the highway. They looked over their shoulders to watch for oncoming traffic from the right, while making the turn, and therefore had to make more steering corrections than did the D-V users, to establish a right-lane, centered position. The same scenario occurred in the interstate section, only it was while merging onto the roadway. This did not require as much steering wheel correction since it was a merge maneuver instead of a 90-degree turn as in the highway segment. For just the opposite reason, the lane deviation for D-V users is the highest for both highway and interstate segments. Since the D-V user cannot look for oncoming traffic before entering each roadway, they assumed (or felt) that a car was about to run into them as they entered the roadway and either over or under corrected their steering in anticipation of a crash. Also to avoid a collision when entering these roadways, the drivers increased their speed to outrun a potential oncoming vehicle, thereby reducing their level of steering control and increasing their lane deviation. As expected, the city segment yielded the least lane deviation for each display type. It is believed the reason for this is because no cars were passed and no turns were made in the city segment, thereby reducing the chance for significant lane deviation. The loopback segment required vehicles be passed, creating the second highest level of significant lane deviation, however, no turns or merges were requried, thereby producing less lane deviation than the highway and loopback segments.

The simple main effect of display was significant at segment levels, city, interstate, and loopback. Participants exhibited greater lane deviation in these road segments when using the D-V. The highway segment was not significant across display types. It is assumed the reason HMD wearers exhibited less lane deviation is that when driving around curves and turning corners, the ability to look in the direction of the turn and have the environment react "naturally" by presenting the portions of the roadway and environment, that in the D-V would not be visible, helped the drivers maintain a more centered position in the driving lane. Also, when passing vehicles using the D-V, it was difficult for the driver to judge the distance between his or her car and the vehicle being passed. With the HMD, the driver could actually turn and look at the vehicle being passed, thereby maintaining a safe distance instead of giving an arbitrarily wider margin of safety when passing blindly with the D-V.

Mean speed limit deviation. The performance measure *mean speed limit deviation* showed significance for the main effects of Display, Segment, and the interaction of Segment-by-Display. Results of the Segment-by-Display interaction revealed that the simple main effect of Segment was significant for HMD in all levels of segment except between the highway and loopback segments. Further, Segment was significant for D-V in all levels of segment except between the city and highway segments. For the HMD, interstate had the highest speed limit deviation, followed by city, then loopback and highway. For the D-V, interstate again had the highest speed limit deviation, followed by loopback, then highway and city. These differences across segments are difficult to interpret because they could be caused by many factors including segment speed, road curvature, perceptual differences between drivers, and display characteristics. The latter was investigated and discussed in more detail. The simple main effect of Display was significant at all levels of segment. Participants exhibited greater speed limit deviation when using the D-V in the highway, interstate, and loopback segments. Greater speed limit deviation was exhibited in the city segment when participants used the HMD. In all cases, the deviation was below the posted speed limits. Similar to the reason for time to complete the course, it is believed the reason speed limit deviation was greater in the city segment for HMD wearers is because the city segment is a much more confined, 2-lane space compared with the other road segments. When users wore the HMD in the city segment, the generally more cautious method of driving was intensified because the user could turn their head (thereby changing the visual scene) while driving. Since this segment allowed little room for error, when drivers looked around while driving, they reduced their speed. The reduction in speed was most probably a way for the driver to have a better perceived level of control in the more confined space. Conversely, in the other segments, the roadway was far wider and presented a more open and broad field of view. Since the driver did not feel as confined, they were less likely to reduce their speed as much when looking around while wearing the HMD.

Mean steering wheel angle variance. Contrary to expectations, the performance measure *mean steering wheel angle variance* did not show significant main effect for Feedback.

The reason is assumed to be that, as with lane deviation, the simulated driving course had a limited capacity to evaluate the true merits of active steering. Perhaps if curves with realistic banking gradients were used instead of flat and gentle curves, active steering force feedback would have played a more vital role in driver performance. However, a statistically significant main effect for Segment was observed. Participants exhibited significantly greater steering wheel angle variance in the city road segment. In other words, participants had a greater number of steering wheel corrections in the city segment than in the other three segments. It is believed the reason for this is because, again, the city segment is a very confined space, both visually and spatially. Regardless of the display type in this case, in order for the driver to maintain a center-lane position between the center line and the 'wall' of trees to the vehicle's right-hand side, the driver continually steered left and right (steering wheel corrections) to reduce the perceived chance of hitting either on-coming traffic or the trees to the right. In the other segments, the roadway is more open and broad. These segments do not create a claustrophobic feeling, as does the city segment, so the driver is more relaxed and less likely to nervously (and constantly) correct for position as they did in the city segment.

Subjective Measures

ANCOVA. The results of the questionnaire ANCOVA showed no statistically significant effect between treatment and Presence Questionnaire results. What this means is there is no evidence that treatment affected PQ scores. In other words, the combination of HMD with force feedback enabled was no more significant in affecting realism than any other combination of display and feedback, therefore not producing greater levels of perceived presence for the participants. The literature states that there exists significance linking virtual realism with increased levels of perceived presence and that HMD and active steering force feedback provide a greater sense of realism. Therefore, given the results and the high reliability of the measurement method (PQ and ITQ), it can be concluded that either the fidelity of this particular simulator was not high enough to result in significant difference, or the sample size was not large enough. Due to many factors, the latter was limited to 8 participants. Ideally, 30 or more participants would have been more effective in increasing the statistical power of the study. In terms of fidelity, the active steering force feedback was “realistic” in that it produced between 2.5Nm and 3.0Nm of force for the driver under normal driving conditions. What made the system seem less realistic was a noticeable ‘dead spot’ at the centered position of the steering wheel. At this position, the active feedback seemed to drop to zero. When the driver turned the steering wheel through this point, a noticeable and distracting “bumping” or jolting effect was produced. This effect was mitigated as much as possible during initial setup and testing of the system, but could not be completely eliminated. Another factor that produced lower fidelity in the system was the display. The direct-view display was large, crisp, and positioned at a comfortable distance from the driver. The sense of realism, however, was considerably diminished because the display had no way of laterally moving the scene as the driver turned his or her head from one side to the other. The head-mounted display on the other hand, had this ability; however, it lacked the clarity and crispness of the direct-view display. Also further removing the driver from the feeling of immersion, the HMD was uncomfortable and was a very unfamiliar addition to the task of vehicle driving for most of the participants. Consequently, having a more “realistic” simulation by using the combination of HMD and active steering force feedback was offset by the inherent shortcomings of each factor. Larger, more expensive, and higher-fidelity systems have been shown to reduce or eliminate many of these problems.

However, this system was specifically designed to be low-to-medium cost and use off-the-shelf components. As the technology of these components is enhanced and more of the problems with fidelity and realism are addressed, the author believes lower-cost, low-to-medium fidelity systems such as the one used for this study, will provide significant levels of immersion and perceived presence for the user.

Participant survey. As with the objective data results, the subjective preference survey results are also mixed. The results are, however, more in line with the stated hypothesis. To reiterate the survey results, both male and female participants preferred the head-mounted display and direct-view display equally (50% and 50% respectively). As expected, 100% of the female participants and 75% of the male participants preferred active steering force feedback over the steering force feedback disabled condition. The primary drawbacks cited for the head-mounted display were the small screen size and the discomfort produced in the head and neck caused from the weight of the device on front of the head. Participants liked the large, crisp screen of the direct-view display, but the lack of realism when turning corners or looking around the environment was its primary disadvantage. The clear advantage cited for the head-mounted display was the ability of the driver to turn his or her head and view the environment in a full 360 degrees.

All participants, with the exception of one male, responded that they felt a greater sense of realism and control with steering force feedback enabled. Although the participant comments were in line with the stated hypothesis that HMD and active steering force feedback would be preferable and would create a greater sense of realism; for reasons previously stated, participant performance did not support this theory for all observed performance measures.

CONCLUSION

The review of the literature has shown that display type can have a significant impact on the driving performance of the 'human in the loop' in a virtual environment. Creating a greater level of presence within the VE has been shown to improve simulated driving performance. It has been shown that using an HMD can create a greater level of presence within a VE, which subsequently produces improved performance by the system user. It has also been shown that providing a more realistic level of steering force feedback can also provide a greater level of presence and therefore yield an increase in performance.

This research has addressed these issues and has come to many of the same conclusions. As previously stated, this study differed from previous research, however, in that it has used a low-to-medium cost driving simulator that incorporated an off-the-shelf, low-cost, head-mounted display and head tracker system, and a relatively large flat-panel direct-view display, instead of expensive HMDs and large front projection systems or comparatively small desktop PC monitors. This research also used a custom-built virtual driving environment modeled after a real-world Virginia DMV driver licensing test course. The DMV course VE provided the author with an opportunity to conduct research in a controlled environment that relates directly to a real-world application of the factors of interest. Another difference between this research and previous research was the desire to find a combination of display type and steering force feedback that would create a greater level of perceived presence in the VE for the participant.

The results of this research have shown that the use of a head-mounted display can significantly impact driving performance in terms of speed control and lane deviation. Speed control was significantly improved (increased) with the use of an HMD and lane deviation was significantly improved (decreased) with the use of an HMD. Contrary to the literature, however, results of this research showed that active steering force feedback had a significantly negative affect on driving performance by increasing average lane deviation.

The results of this study have shown differences in performance caused by specific levels of display type and steering force feedback. These results may allow future researchers to better design low-to-medium cost driving simulators for human-in-the-loop testing. It is hoped that this research will provide useful insight and guidance for any future low-to-medium fidelity driving simulator research. As the level of technology progresses and better components become less expensive to purchase and maintain, the author contends that those performance measures unaffected by the factors of interest in this study will exhibit significantly positive effects.

RECOMMENDATIONS FOR FURTHER RESEARCH

Continued research investigating the performance differences found in this study may be warranted. While results involving the head-mounted display were similar to previous research, results involving active steering force feedback were not. Further investigation should be undertaken to determine the specific conditions and circumstances that produced these results. Subsequent results should then be compared with previous research, which states that active steering force feedback should significantly decrease lane deviation. The author believes the primary factor that resulted in differences with previous research was the 'dead spot' at the zero position of the steering wheel. This sudden drop in torque (from 3Nm to zero) as the wheel entered this spot and sudden surge in torque (from zero to 3Nm) as the wheel passed through this point, was unnatural, unrealistic, and probably startled the drivers into taking a corrective action to compensate for the sudden change in steering wheel behavior. It is believed this overcompensation resulted in the significantly higher level of lane deviation present in the data. Perhaps future studies could conduct similar research with a higher fidelity steering system and compare the results with the findings from this study to determine if, in fact, the dead spot in the steering wheel was the actual cause of the differing results.

The level of fidelity produced by the particular HMD and head tracking system used in this study is also an area for future researchers to explore. The author believes the reason perceived levels of presence were not significant was because the HMD and head tracking system used was not adequate enough to immerse the user in the virtual environment. The images generated by the HMD were not sufficiently 'realistic' enough to convince the senses that the driver was actually 'in the environment'. Further removing the user from the environment was the fact that occasionally, the driver would need to reach up and press a reset button on the head tracker in order to re-center the scene. The annoyance and lack of realism caused by the scene 'drift' may be the greatest reasons for the lack of presence felt in the environment. While all attempts were made to eliminate the drift, best efforts were able to only reduce the effects. Future studies could perhaps investigate the cause of the drift or employ a tracking system that did not have this problem. Coupled with higher fidelity LCD screens, this improved HMD and head tracking system may be sufficient to adequately immerse the user in the virtual environment, thereby producing a significant level of presence. A summary of these recommendations is provided in Table 12.

TABLE 12.

Further research recommendations

	Current condition	Recommendations
Head-mounted display	• Low-cost i-Glasses LCD-based HMD • InterTrax2 head tracker	• Low-cost CRT-based HMD (when available) • Resolve tracker interference problem causing scene drift
Direct-view display	• NEC 50in. plasma	• Similar high-resolution flat-panel display • Multiple displays for a 360 degree view - difficult and expensive but may be the only way to match realism of an HMD
Steering force feedback	• ATP driving console standard torque motor	• Similar system producing torque in the range of 0-3Nm • Resolve "dead spot" problem at the centered position of the steering wheel
Virtual environment	• Custom designed virtual driving environment • Java-based	• Off-the-shelf, tested, and realistic virtual driving software with data collection capability • Should incorporate realistic curves with banking gradients and allow greater customization for driving tasks (passing vehicles, making turns, cornering, etc.)

REFERENCES

Andersen, G. J., and Braunstein, M. L. (1985). Induced self-motion in central vision. *Journal of Experimental Psychology: Human Perception and Performance, 11*(2), 122-132.

Atwood, N. K., Winsch, B. J., Quinkert, K. A., and Heiden, C. K. (1994). *Catalog of training tools for use in distributed interactive simulation (DIS) environments*. Alexandria, VA: U.S. Army Research Institute for Behavioral and Social Sciences.

Barfield, W., and Weghorst, S. (1993). *The sense of presence within virtual environments: A conceptual framework* (Working Paper). Washington: University of Washington.

Barfield, W., Zeltzer, D., Sheridan, T., and Slater, M. (1995). Presence and performance within virtual environments. In W. Barfield & T. A. F. III (Eds.), *Virtual Environments and Advanced Interface Design* (pp. 473-513). New York: Oxford University Press, Inc.

Bell, H. H., Mastaglio, T. W., and Moses, F. (1993). Using distributed interactive simulations for joint service training. *Military Simulation and Training, 5*, 28-30.

Bolas, M. T. (1994). Human factors in the design of an immersive system. *IEEE Computer Graphics and Applications, 14*, 55-59.

Bradley, O. N. (1999). *A Soldier's Story*. New York: The Modern Library.

Brookhuis, K., DeWaard, D., and Mulder, B. (1994). Measuring driving performance by car-following in traffic. *Ergonomics, 37*(3), 427-434.

Brooks, F. J., Ouh-Young, M., Batter, J. J., and Kilpatrick, P. J. (1990). Project GROPE - haptic displays for scientific visualization. *Computer Graphics (Proc. Siggraph), 24*(4), 177-185.

Casali, J. G. (1986). *Vehicular simulator-induced sickness, Volume I: An overview* (No. NTSC-TR86-012 (AD-A173226), Vol 3). Arlington, Virginia: U.S. Naval Training Systems Center.

Casali, J. G., and Frank, L. H. (1988, June). *Manifestation of visual/vestibular disruption in simulators: Severity and empirical measurement of symptomatology.* Paper presented at the Advisory Group for Aerospace Research & Development: Conference No. 433 Motion cues in flight simulation and simulator induced sickness, 7 Rue Ancelle 92200, Neuilly Sur Seine, France.

Casali, J. G., and Wierwille, W. W. (1980). The effects of various design alternatives on moving-base driving simulator discomfort. *Human Factors, 22*(6), 741-756.

Casali, J. G., and Wierwille, W. W. (1986). Potential Design Etiological Factors of Simulator Sickness and a Research Simulator Specification. *Transportation Research Record*(1059), 66-74.

Cremer, J., Kearney, J., and Papelis, Y. (1996, September 1996). Driving simulation: Challenges for VR technology. *IEEE Computer Graphics and Applications, 17,* 16-20.

Delgado, A. R., and Prieto, G. (1997). Mental rotation as a mediator for sex-related differences in visualizations. *Intelligence, 24*(3), 405-416.

Dyer, R., Matthews, J. J., Stulac, J. F., Wright, C. E., and Yudowitch, K. (1976). *Questionnaire construction manual, annex literature survey and bibliography*. Palo Alto, California: Operations Research Associates.

Ebenholtz, S. M., Cohen, M. M., and Linder, B. J. (1994). The possible role of nystagmus in motion sickness: A hypothesis. *Aviation, Space and Environmental Medicine, 65*, 1032-1035.

Ehrlich, J., A. (2000). *Effect of viewing conditions on sickness and distance estimation in a virtual environment* (Technical Report No. 1112). Alexandria, Virginia: U.S. Army Research Institute for the Behavioral and Social Sciences.

Fontaine, G. (1992). The experience of a sense of presence in intercultural and international encounters. *Presence: Teleoperators and Virtual Environments, 1*(4), 482-490.

Frank, L. H., Casali, J. G., and Wierwille, W. W. (1988a). Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator. *Human Factors, 30*(2), 201-217.

Frank, L. H., Casali, J. G., and Wierwille, W. W. (1988b, June). *Modeling operator control performance and well-being as a function of simulator visual and motion system transport delays.* Paper presented at the Advisory Group for Aerospace Research & Development: Conference No. 433 Motion cues in flight simulation and simulator induced sickness, 7 Rue Ancelle 92200, Neuilly Sur Seine, France.

Gigante, M. A. (1994). Virtual reality: enabling technologies. In H. Jones (Ed.), *Virtual reality systems* (pp. 15-25). London: Academic Press.

Godthelp, J. (1980, 1980). *Levels of steering control: reproduction of steering wheel movements.* Paper presented at the Proceedings of the 16th Annual Conference on Manual Control, Massachusetts Institute of Technology, Cambridge, MA.

Godthelp, J. (1985). Precognitive control: open- and closed-loop steering in a lane-change manoeuvre. *Ergonomics, 28*(10), 1419-1438.

Gordon, D. A. (1966). Experimental isolation of drivers' visual input. *Public Roads, 33*, 53-68.

Held, R., and Durlach, N. (1992). Telepresence. *Presence: Teleoperators and Virtual Environments, 1*(1), 109-112.

Hendrix, C., and Barfield, W. (1996). Presence within virtual environments as a function of visual display parameters. *Presence: Teleoperators and Virtual Environments, 5*, 274-289.

Hettinger, L. J., Berbaum, K. S., Kennedy, R. S., Dunlap, W. P., and Nolan, M. D. (1990). Vection and simulator sickness. *Military Psychology, 2*(3), 171-181.

Hettinger, L. J., and Riccio, G. E. (1992). Visually induced motion sickness in virtual environments. *Presence, 1*, 306-310.

Hirota, K., and Hirose, M. (1995). Providing force feedback in virtual environments. *IEEE Computer Graphics and Applications, 17*(16), 22-30.

Howe, T., and Sharkey, P. M. (1998). Identifying likely successful users of virtual reality systems. *Presence, 7*(3), 308-316.

Johnson, D. E. (1998). *Applied multivariate methods for data analysts*. Pacific Grove: Brooks/Cole Publishing Company.

Johnson, D. M., and Stewart, J. E. (1999). Use of virtual environments for the acquisition of spatial knowledge: Comparison among different visual displays. *Military Psychology, 11*(2), 129-148.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology, 3*(3), 203-220.

Kennedy, R. S., Lane, N. E., Lilienthal, M. G., Berbaum, K. S., and Hettinger, L. J. (1992). Profile analysis of simulator sickness symptoms: Application to virtual environment systems. *Presence: Teleoperators and Virtual Environments, 1*(3), 295-301.

Kennedy, R. S., Lilienthal, M. G., Berbaum, K. S., Dunlap, W. P., Mulligan, B. E., and Funaro, J. F. (1987). *Guidelines for alleviation of simulator sickness symptomatology* (No. NAVTRASYYCEN TR-87-007). Orlando, Florida: U.S. Naval Training Systems Center.

Kolasinski, E. M. (1996). *Prediction of simulator sickness in a virtual environment.* Unpublished Dissertation, University of Central Florida, Orlando, FL.

Kramer, P. D., Roberts, D. C., Shelhamer, M., and Zee, D. S. (1998). A versatile stereoscopic visual display system for vestibular and oculomotor research. *Journal of Vestibular Research, 8*(5), 363-379.

Lackner, J. (1990). *Human orientation, adaption, and movement control* (Tech. Report Motion sickness, visual displays, and armored vehicle design). Washington, D.C.: Ballistic Research Laboratory.

Landry, L. A. (1994). *The Aviation Combined Arms Tactical Trainer*: U.S. Army Aviation Digest, Professional Bulletin 1-94-2.

Laplante, P. A., Rose, E. P., and Gracia-Watson, M. (1995). An historical survey of early real-time computing developments in the U.S. *Real-Time Systems, 8*, 199-213.

Lee, G. C. H., Yoo, Y., and Jones, S. (1997). *Investigation of driving performance, vection, postural sway, and simulator sickness in a fixed-base driving simulator.* Paper presented at the Computers ind. Engng.

Lee, W.-S., Kim, J.-H., and Cho, J.-H. (1998, May 1998). *A driving simulator as a virtual reality tool.* Paper presented at the IEEE International Converence on Robotics & Automation, Leuven, Belgium.

Lestienne, F., Soechting, J., and Berthoz, A. (1977). Postural readjustments induced by linear motion of visual scenes. *Experimental Brain Research, 28*, 363-384.

Levine, O. H., and Mourant, R. R. (1995, January, 1995). *A driving simulator based on virtual environments technology.* Paper presented at the 74th Annual Meeting of the Transportation Research Board, Boston, MA.

Liu, A., and Chang, S. (1995). Force feedback in a stationary driving simulator. *IEEE, 1*, 1711-1716.

Liu, Y.-C. (2001). Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveller information systems. *Ergonomics, 44*(4), 425-442.

Masters, M. S., and Sanders, B. (1993). Is the gender difference in mental rotation disappearing? *Behavior Genetics, 23*(4), 337-341.

McGreevy, M. W. (1992). The presence of field geologists in Mars-like terrain. *Presence: Teleoperators and Virtual Environments, 1*(4), 375-403.

McNeely, W. A. (1993, September 18-22). *Robotic graphics: A new approach to force feedback for virtual reality.* Paper presented at the IEEE Virtual Reality International Symposium (1st), Seattle, WA.

Mon-Williams, M., Wann, J. P., and Rushton, S. (1993). *Binocular vision in a virtual world: visual deficits followring the wearing of a head-mounted display* (Research Note). Edinburg, UK: University of Edinburgh.

Neray, P., and DeMarco, O. (1998, September, 1998). Driving simulators: A new era. *Automotive Engineering, 98,* 50-53.

Parker, D. E., and Harm, D. L. (1992). Mental rotation: A key to mitigation of motion sickness in the virtual environment? *Presence: Teleoperators and Virtual Environments, 1*(3), 329-333.

Peli, E. (1998). The visual effects of head-mounted display (HMD) are not distinguishable form those of desk-top computer display. *Vision Research, 38*, 2053-2066.

Penhallegon, W. J., and Perala, C. H. (2002). *Development of the VT-UVA-Carilion driving simulator* (Technical Report No. 200201). Blacksburg, Virginia: Virginia Polytechnic Institute and State University.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., and Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition, 28*, 39-58.

Pierce, J. S., Pausch, R., Sturgill, C. B., and Christiansen, K. D. (1999). Designing a successful HMD-based experience. *Presence, 8*(4), 469-473.

Presson, C. C., and Montello, D. R. (1994). Updating after rotational and translational body movements: Coordinate structure of perspective space. *Perception, 23*, 1447-1455.

Regan, E. C., and Price, K. R. (1994). The frequency and occurrence and severity of side-effects of immersion virtual reality. *Aviation, Space, and Environmental Medicine, 65*, 527-530.

Richardson, J. T. E. (1994). Gender differences in mental rotation. *Perceptual and Motor Skills, 78*, 435-448.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory and Cognition, 15*, 1157-1165.

Rinalducci, E. J. (1996). Characteristics of visual fidelity in the virtual environment. *Presence, 5*(3), 330-345.

Roehl, B. (1996, March-April 1996). A comparison of low-cost HMDs. *Virtual Reality Special Report,* 19-22.

Ruddle, R. A., Payne, S. J., and Jones, D. M. (1998). Navigating large-scale "desk-top" virtual buildings: Effects of orientation aids and familiarity. *Presence: Teleoperators and Virtual Environments, 7*, 179-192.

Ruddle, R. A., Payne, S. J., and Jones, D. M. (1999). Navigating large-scale virtual environments: What differences occur between helmet-mounted and desk-top displays? *Presence, 8*(2), 157-168.

Rushton, S., Mon-Williams, M., and Wann, J. P. (1994). Binocular vision in a bi-ocular world: New-generation head-mounted displays avoid causing visual deficit. *Displays, 15*(4), 255-260.

Sadhu, P. (2001). *Effect of force feedback in virtual environments.* Unpublished Master of Science, Northeastern University, Boston, Massachusetts.

Segel, L. (1964). An investigation of automobile handling as implemented by a variable-steering automobile. *Human Factors, 6*, 333-341.

Sheridan, T. B. (1992). Musings on telepresence and virtual presence. *Presence: Teleoperators and Virtual Environments, 1*(1), 120-126.

Shimoga, K. (1993). *A study of perceptual feedback issues in dexterous telemanipulation.* Paper presented at the Proc. Virtual Reality Annual International Symposium, Piscataway, N.J.

Singer, M. J., and Witmer, B. G. (1996). Presence measures for virtual environments: Background & development (pp. 1-30). Draft ARI research note: U.S. Army Research Institute for the Behavioral and Social Sciences.

Slater, M., and Usoh, M. (1993). Representations systems, perceptual position, and presence in immersive virtual environments. *Presence, 2*(3), 221-233.

Slater, M., Usoh, M., and Steed, A. (1994). Depth of presence in virtual environments. *Presence, 3*(2), 130-144.

Sottilare, R. (1995). *Synthetic theatre of war - Europe*: Army Research , Development and Acquisition Bulletin PB 70-95-2.

Stanney, K. M., Kennedy, R. S., and Drexler, J. M. (1997). *Cybersickness is not simulator sickness.* Paper presented at the Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting.

Stanney, K. M., Mourant, R. R., and Kennedy, R. S. (1998). Human factors in virtual environments: A review of the literature. *Presence, 7*(4), 327-351.

Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *Journal of Communication, 42*(2), 73-93.

Stoffregen, T. A., Hettinger, L. J., Haas, M. W., Roe, M. M., and Smart, J. L. (2000). Postural instability and motion sickness in a fixed-base flight simulator. *Human Factors, 42*(3), 458-469.

Stuart, R. (1996). *The design of virtual environments*. New York: McGraw-Hill.

Uliano, K. C., Kennedy, R. S., and Lambert, E. Y. (1986). *Asynchronous visual delays and the development of simulator sickness.* Paper presented at the Human Factors and Ergonomics Society 30th Annual Meeting.

Vandenberg, S. G., and Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*, 599-604.

Wachtel, J. (1997, 1997). *Innovations in low-cost simulation technology for the training and testing of "high risk" drivers.* Paper presented at the IEEE Sixth Annual Human Factors Meeting, Orlando, Florida.

Wachtel, J. A. (1993, October 11-15). *Driving simulators - serious tools or frivolous toys?* Paper presented at the Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, Seattle, WA.

Webster. (1984). *Webster's II new Riverside university dictionary*. Boston, MA: Houghton Mifflin Company.

Weir, D. H., and Clark, A. J. (1995). *A survey of mid-level driving simulators* (SAE Technical Paper Series No. 950172). Detroit, Michigan: SAE International.

Wilson, J. R. (1995, December 7-11). *Factors of virtual environments and effects on participants.* Paper presented at the Academy '95, New Orleans, LA.

Wilson, J. R. (1996). Effects of participating in virtual environments: A review of current knowledge. *Safety Science, 23*(1), 39-51.

Wilson, J. R. (1997). Virtual environments and ergonomics: Needs and opportunities. *Ergonomics, 40*(10), 1057-1077.

Wilson, J. R. (1999). Virtual environments applications and applied ergonomics. *Applied Ergonomics, 30*, 3-9.

Witmer, B. G., Bailey, J. H., Knerr, B. W., and Parsons, K. C. (1996). Virtual spaces and real world places: Transfer of route knowledge. *International Journal of Human-Computer Studies, 45*, 413-428.

Witmer, B. G., and Singer, M. J. (1994). *Measuring presence in virtual environments* (Technical Report No. 1014). Alexandria, Virginia: U.S. Army Research Institute for the Behavioral and Social Sciences.

Witmer, B. G., and Singer, M. J. (1998). Measuring presense in virtual environments: A Presence Questionnaire. *Presence, 7*(3), 225-240.

Yeow, P. T., and Taylor, S. P. (1989). Effects of short-term VDT usage on visual functions. *American Academy of Optometry, 66*(7), 459-466.

Yoo, Y. H. (1999). *Prediction and quantification of individual differences in susceptibility to simulator sickness in fixed-base simulators.* Unpublished Dissertation, University of Central Florida, Orlando, FL.

Zeltzer, D. (1992). Autonomy, interaction, and presence. *Presence, 1*(1), 127-132.

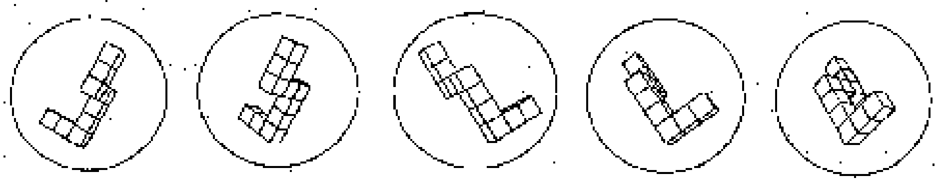
APPENDIX A - Mental Rotation Test

Name ______________________

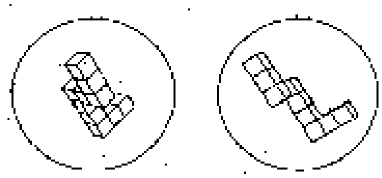
M.R.T. Test Date ______________________

____

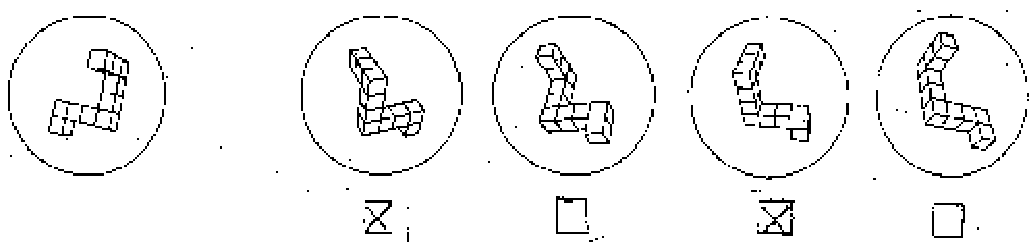
This is a test of your ability to look at a drawing of a given object and find the same object within a set of dissimilar objects. The only difference between the original object and the chosen object will be that they are presented at different angles. An illustration of this principle is given below, where the same single object is given in five different positions. Look at each of them to satisfy yourself that they are only presented at different angles from one another.



Below are two drawings of new objects. They cannot be made to match the above five drawings. Please note that you may not turn over the objects. Satisfy yourself that they are different from the above.



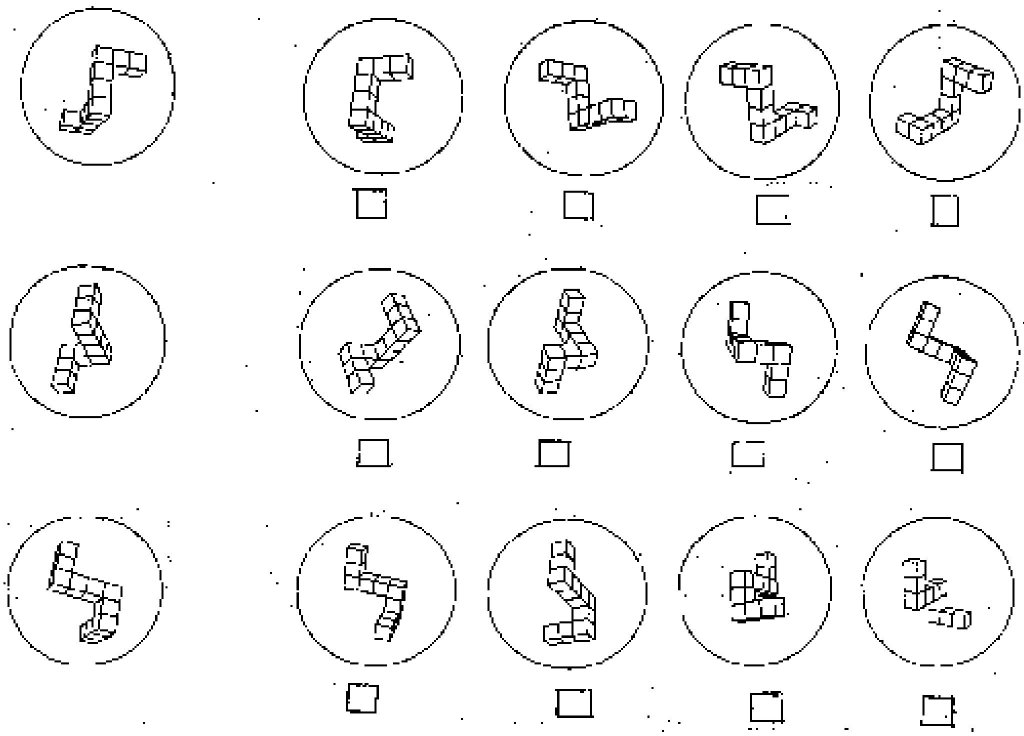
Now let's do some sample problems. For each problem there is a primary object on the far left. You are to determine which two of four objects to the right are the same object given on the far left. In each problem always <u>two</u> of the four drawings are the same object as the one on the left. You are to put Xs in the boxes below the correct ones, and leave the incorrect ones blank. The first sample problem is done for you.



Go to the next page

Adapted by S.G. Vandenberg, University of Colorado, July 15, 1971
Revised instructions by M. Crawford, U. of Wyoming, September, 1979

Do the rest of the sample problems yourself. Which two drawings of the four on the right show the same object as the one on the left? There are always two and only two correct answers for each problem. Put an X under the two correct drawings.

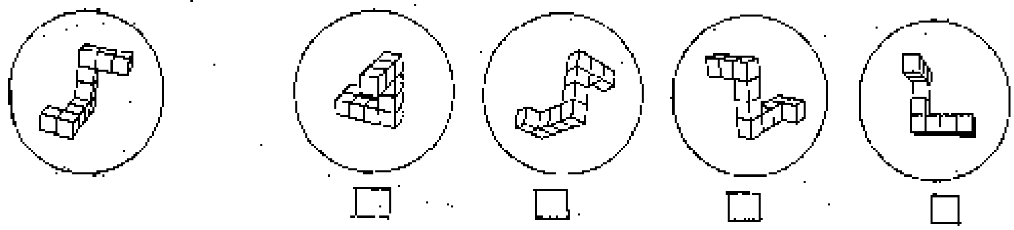


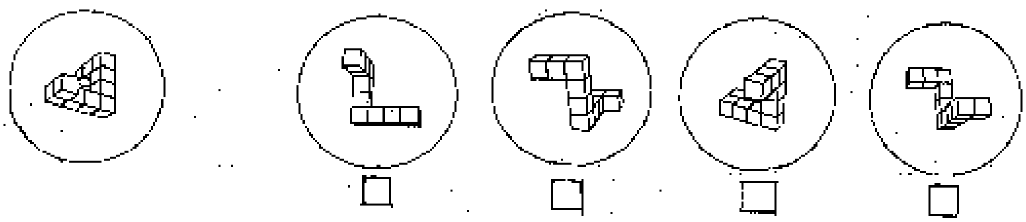
Answers: (1) first and second drawings are correct
(2) first and third drawings are correct
(3) second and third drawings are correct

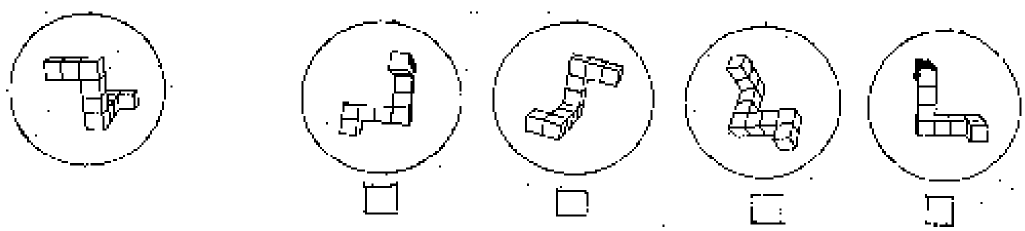
This test has two parts. You will have 3 minutes for each of the two parts. Each part has two pages. When you have finished Part I, STOP. Please do not go one to Part 2 until you are asked to do so. Remember: There are always two and only two correct answers for each item.

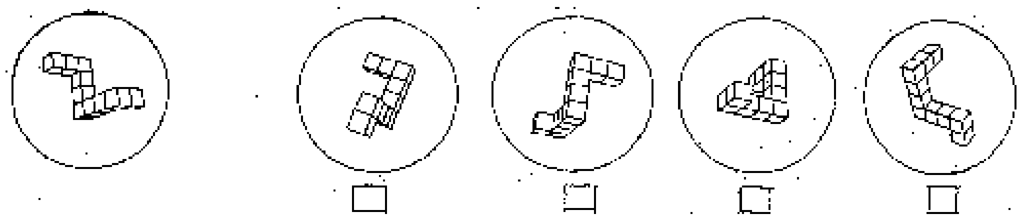
Work as quickly as you can without sacraficing accuracy. Your score on this test will reflect both the correct and incorrect responses. Therefore, it will not be to your advantage to guess unless you have some idea which choice is correct.

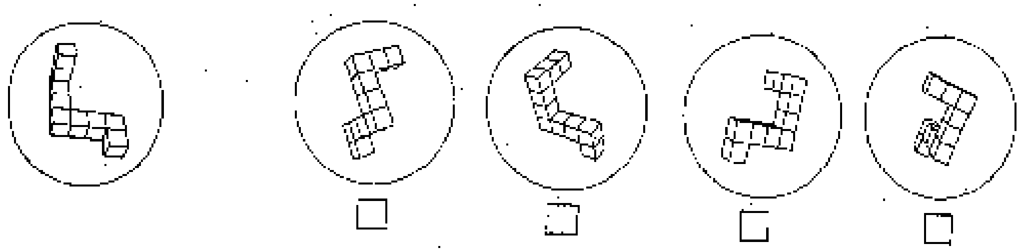
DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO

1. 

2. 

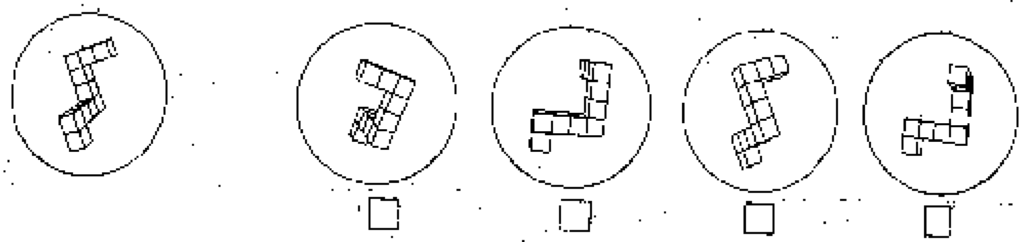
3. 

4. 

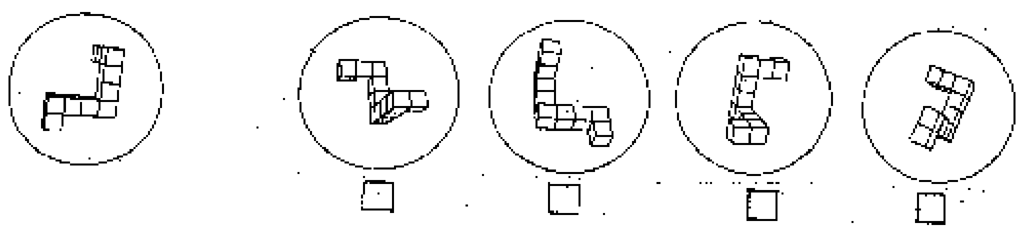
5. 

GO ON TO THE NEXT PAGE

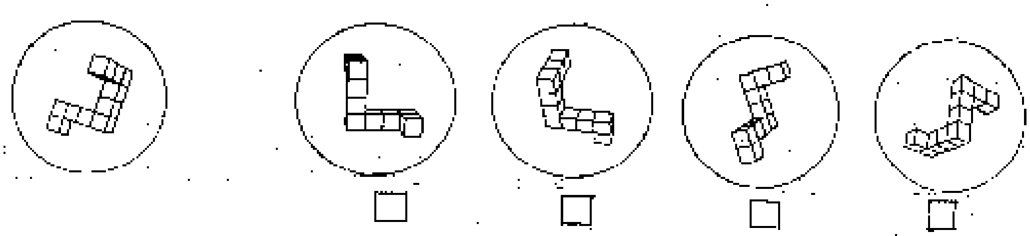
6.



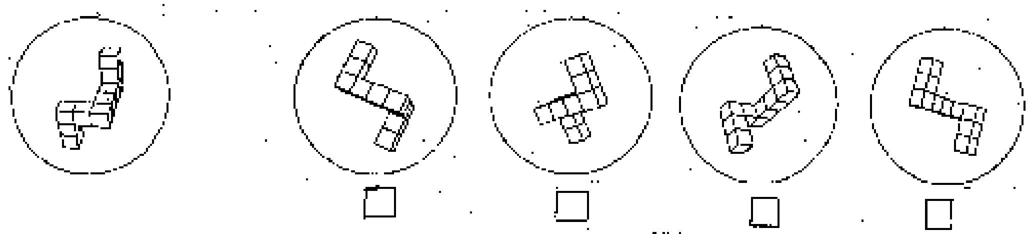
7.



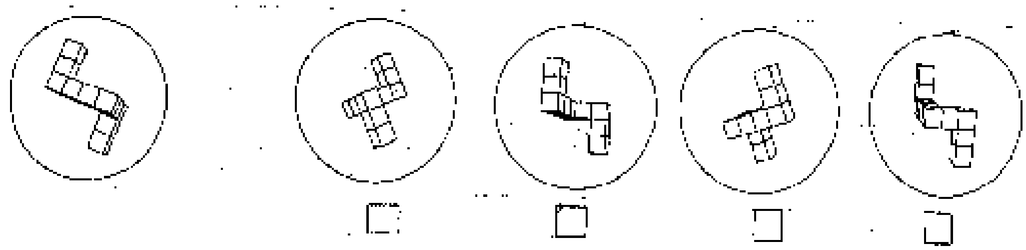
8.



9.

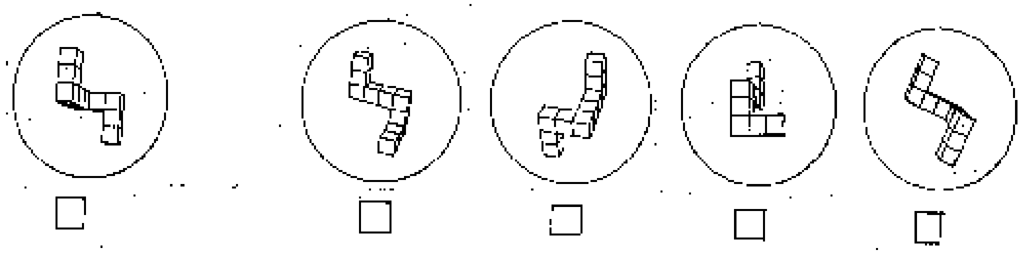


10.

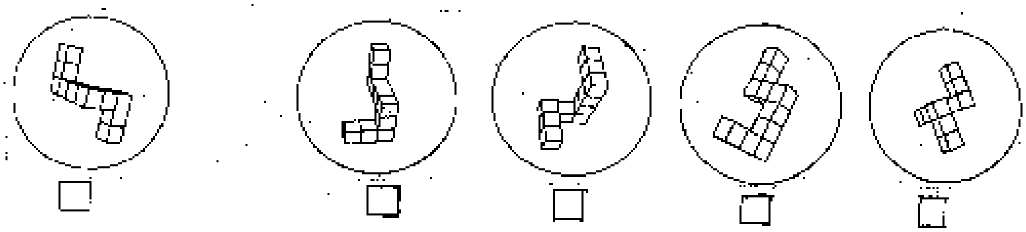


DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO. STOP

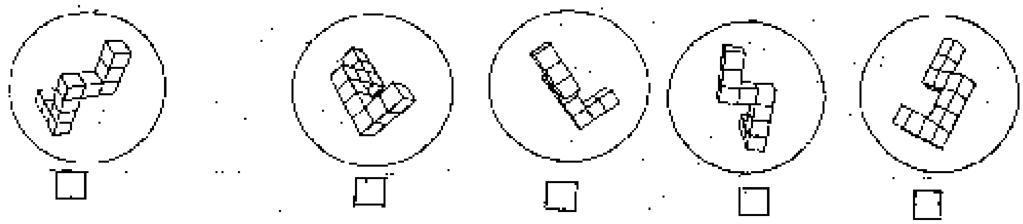
11.



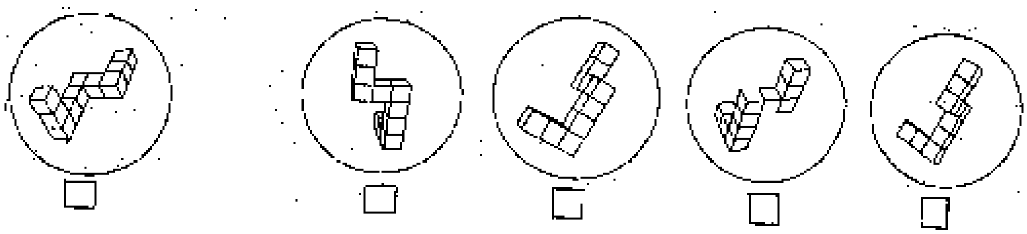
12.



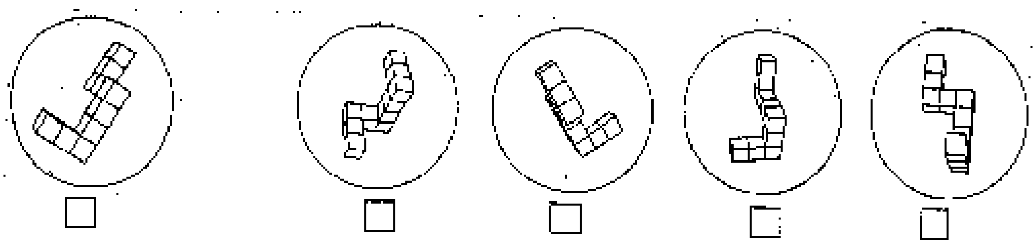
13.



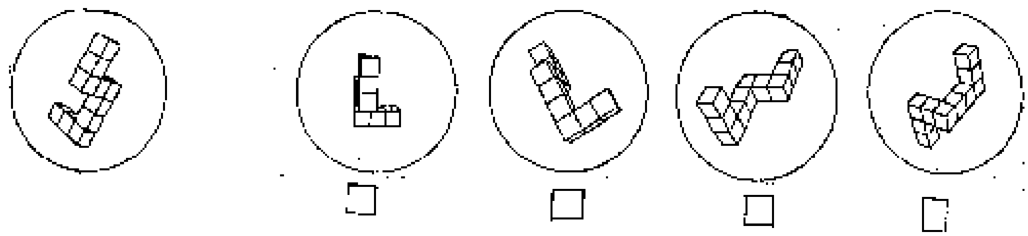
14.

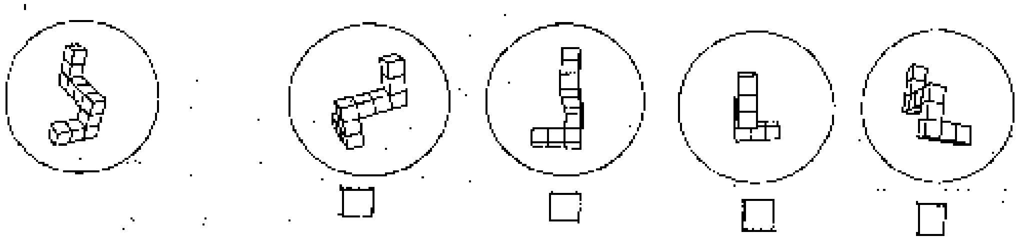


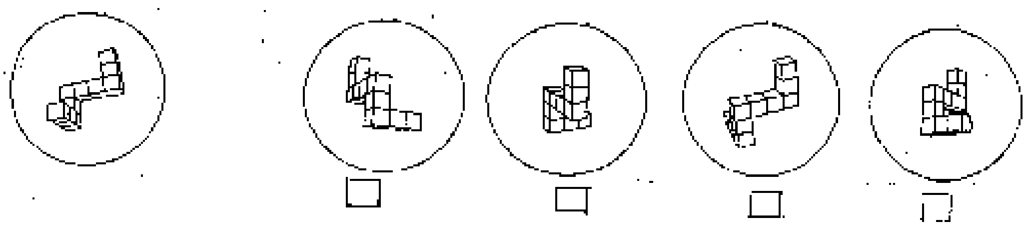
15.

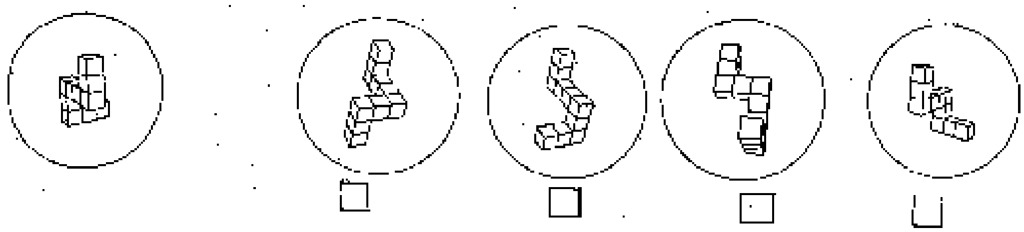


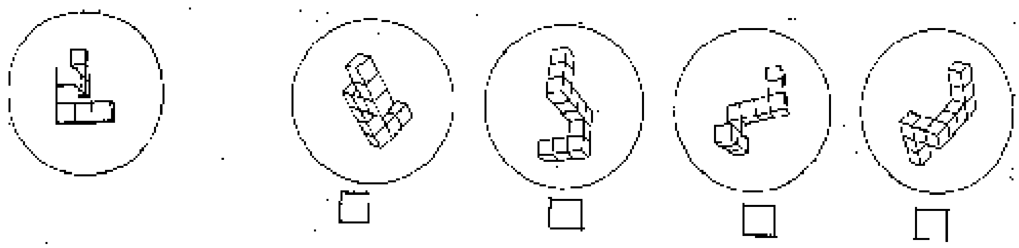
GO TO THE NEXT PAGE

16. 

17. 

18. 

19. 

20. 

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO. STOP

APPENDIX B - Presence Questionnaire

PRESENCE QUESTIONNAIRE
(Witmer & Singer, Vs. 3.0, Nov. 1994)

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?

|________|________|________|________|________|________|________|
NOT RESPONSIVE MODERATELY RESPONSIVE COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?

|________|________|________|________|________|________|________|
EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

4. How much did the visual aspects of the environment involve you?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

5. How much did the auditory aspects of the environment involve you?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

6. How natural was the mechanism which controlled movement through the environment?

|________|________|________|________|________|________|________|
EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

7. How compelling was your sense of objects moving through space?

|________|________|________|________|________|________|________|
NOT AT ALL MODERATELY COMPELLING VERY COMPELLING

8. How much did your experiences in the virtual environment seem consistent with your real world experiences?

|________|________|________|________|________|________|________|
NOT CONSISTENT MODERATELY CONSISTENT VERY CONSISTENT

9. Were you able to anticipate what would happen next in response to the actions that you performed?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

10. How completely were you able to actively survey or search the environment using vision?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

11. How well could you identify sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

12. How well could you localize sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

13. How well could you actively survey or search the virtual environment using touch?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

14. How compelling was your sense of moving around inside the virtual environment?

|________|________|________|________|________|________|________|
NOT COMPELLING MODERATELY COMPELLING VERY COMPELLING

15. How closely were you able to examine objects?

|________|________|________|________|________|________|________|

NOT AT ALL	PRETTY CLOSELY	VERY CLOSELY

16. How well could you examine objects from multiple viewpoints?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	EXTENSIVELY

17. How well could you move or manipulate objects in the virtual environment?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	EXTENSIVELY

18. How involved were you in the virtual environment experience?

|________|________|________|________|________|________|________|

NOT INVOLVED	MILDLY INVOLVED	COMPLETELY ENGROSSED

19. How much delay did you experience between your actions and expected outcomes?

|________|________|________|________|________|________|________|

NO DELAYS	MODERATE DELAYS	LONG DELAYS

20. How quickly did you adjust to the virtual environment experience?

|________|________|________|________|________|________|________|

NOT AT ALL	SLOWLY	LESS THAN ONE MINUTE

21. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|________|________|________|________|________|________|________|

NOT PROFICIENT	REASONABLY PROFICIENT	VERY PROFICIENT

22. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

|________|________|________|________|________|________|________|

NOT AT ALL INTERFERED SOMEWHAT PREVENTED TASK PERFORMANCE

23. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|________|________|________|________|________|________|________|

NOT AT ALL INTERFERED SOMEWHAT INTERFERED GREATLY

24. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

|________|________|________|________|________|________|________|

NOT AT ALL SOMEWHAT COMPLETELY

25. How completely were your senses engaged in this experience?

|________|________|________|________|________|________|________|

NOT ENGAGED MILDLY ENGAGED COMPLETELY ENGAGED

26. To what extent did events occurring outside the virtual environment distract from your experience in the virtual environment?

|________|________|________|________|________|________|________|

NOT AT ALL MODERATELY VERY MUCH

27. Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?

|________|________|________|________|________|________|________|

NOT AT ALL SOMEWHAT VERY MUCH

28. Were you involved in the experimental task to the extent that you lost track of time?

|________|________|________|________|________|________|________|

NOT AT ALL SOMEWHAT COMPLETELY

29. How easy was it to identify objects through physical interaction; like touching an object, walking over a surface, or bumping into a wall or object?

|________|________|________|________|________|________|________|

IMPOSSIBLE	MODERATELY DIFFICULT	VERY EASY

30. Were there moments during the virtual environment experience when you felt completely focused on the task or environment?

|________|________|________|________|________|________|________|

NONE	OCCASIONALLY	FREQUENTLY

31. How easily did you adjust to the control devices used to interact with the virtual environment?

|________|________|________|________|________|________|________|

DIFFICULT	MODERATE	EASILY

32. Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent?

|________|________|________|________|________|________|________|

NOT CONSISTENT	SOMEWHAT CONSISTENT	VERY CONSISTENT

APPENDIX C - Development of the VT-UVA-Carilion Driving Simulator

The VT-UVA-Carilion Driving Simulator technical report is available separately from the Auditory Systems Laboratory at Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24060. The complete reference for this technical report is:

Penhallegon, W. J., and Perala, C. H. (2002). *Development of the VT-UVA-Carilion driving simulator* (Audio Lab Report No. 3/18/02-1-HP, ISE Dept. Report No. 200201). Blacksburg, Virginia: Virginia Tech, Grado Department of Industrial and Systems Engineering, Auditory Systems Laboratory.

APPENDIX D - IRB Request for Approval of Research Proposal

Request for Approval of Research Proposal
Grado Department of Industrial and Systems Engineering
Virginia Polytechnic Institute and State University

Title: Effects Of Display Type And Force Feedback On Performance In A Medium-Fidelity Driving Simulator

Principle Investigators: Dr. John G. Casali, John Grado Professor, ISE Department Head
Dr. Gary S. Robinson, Research Associate Professor, ISE
Mr. Chuck H. Perala, Graduate Candidate, ISE
Grado Department of Industrial and Systems Engineering
Virginia Polytechnic Institute and State University

I. Justification of Project

Simulators have been developed and employed over the centuries to help us represent, better understand and study the real world. Simulators provide many advantages over the real world in terms of cost savings, reduction of hazards, and reduction of time to complete tasks under observation. One of the most important factors in simulation is the ability to create a convincing level of similarity (presence) to the real world environment being simulated. Creating this level of realism is one of the major challenges facing any type of virtual environment simulation.

It has been shown that head mounted displays can allow for greater presence in a virtual environment. It has also been shown that after vision, haptic response is one of the most important inputs for humans in a simulated environment. This research will attempt to determine if there is statistical significance in the interaction between two different display types; head mounted display (HMD) and direct-view display (D-V) and the presence or absence of steering force feedback in a medium-fidelity PC-based driving simulator. Participants will drive along a simulated driving course and performance data collected will include: lane deviation, speed, steering wheel angle deviation, and time to complete course, among others. The results of this research may help engineers and researchers build more effective (realistic) low-cost driving simulators for use in studying the effects of "humans in the loop" in virtual environments.

<u>Statement of the Problem</u>

Two of the most critical elements of driving realism that have been studied over the years are visual displays and force feedback (Gordon, D.A., 1996). Visual displays provide the user of the simulation with a visual representation of the real world. Force feedback provides those physical cues and responses from the areas of the simulator with which the user directly interacts, such as steering feedback, vibration, and pedal and control response are examples of these types of cues and responses. In order to accurately represent a real world driving scenario, these two elements, along with many others, must be represented in such a way as to convince the user's senses that they are actually in the real world. Studies have been conducted in driving simulators in the areas of force feedback and display types, to determine the effects of each and whether those effects have a significant impact on the performance of the user in the system. There has been no research to date however, which has examined the interaction of these two elements.

II. Procedures

Participants

Eight people (four male, four female) from the Virginia Tech/Blacksburg Virginia area will be recruited at random as participants for this study. The participants will represent a wide range of driving abilities, habits, and preferences. Participants will be over the age of 18 and required to hold a valid United States drivers license. If the participants require the use of eyewear for real world driving, they will be required to use this eyewear during the experiment. All participants will be compensated for their time and effort at a rate of $8/hour. Subjects will be recruited by flyers posted around the Virginia Tech campus, by word of mouth, and postings on the Virginia Tech/Blacksburg USENET newsgroups.

After verifying their age and driver license status, prospective participants will be asked to complete a Participant Screening form and an Immersive Tendencies Questionnaire (ITQ) (attached). The Participant Screening form collects general information regarding the potential participant's health and well-being pertinent to simulator usage. The ITQ measures the propensity of individuals to be involved or immersed in a virtual environment. The prospective participant must then undergo and successfully pass a subjective screening process. This screening process is designed to assist the experimenter in determining a potential participant's susceptibility to simulator-induced sickness. The process will use the Mental Rotation test questionnaire (attached). Once the prospective participant passes the simulator-induced sickness screening, he or she will be considered an active participant in the experiment. Prospective participants will be compensated for their time. No personal information will be collected at any time. No other exclusions will be used in selecting participants.

Apparatus

The fixed-base driving simulator developed for this study is a modified Advanced Therapy Products, Inc. (ATP) Driving Console WT-2000. The console is equipped with an acoustically driven, vibrating seat, which allows for the simulation of vehicle frequency and bounce dynamics. The seat will produce vibrations from 5-120Hz based on a voltage signal output from the controlling computer, which is proportional to vehicle speed. The console is also equipped with feedback steering, optical encoder position sensing, an automatic transmission floor shifter, a speedometer and tachometer, and latching, self-canceling turn signals with dashboard indicators.

Two different displays will be used with the simulator during different experimental sessions. The first is an NEC PlasmaSync 50MP1 50" flat panel monitor. The PlasmaSync display has a horizontal and vertical viewing angle of 160 degrees, a 57 degree diagonal field of view at 40 inches, and can support a multitude of resolution levels on different computer platforms. The second display is the IO Systems, Inc. i-Glasses SVGA 3-D HMD. The i-Glasses HMD has a 26 degree diagonal FOV, an image size representation of 76 inches at 13 feet, and an SVGA resolution of (800 x 600).

The simulator is controlled by an IBM-compatible personal computer running simulation software developed by Dr. Ronald Mourant at Northeastern University in Boston, Massachusetts. The simulated driving environment, or driving course, is a direct representation of the course used by the Virginia Department of Motor Vehicles (DMV) in Charlottesville, Virginia.

Experimental Procedure

Before conducting any portion of the experiment, including screening and pre-testing, all participants will be required to read and sign Informed Consent form.

Pre-testing

A series of pre-tests will be conducted using volunteers from the graduate student community at Virginia Tech. The pre-tests will involve setting up the hardware and software, running the driving scenarios with the various conditions applied, and timing the sessions and setup between each session. This will allow the experimenter to get a better idea of what will be involved in running actual participants, ensure data is being gathered and stored properly, and will allow for problems to present themselves so they may be addressed before the actual experiments begin. These individuals are subject to the same screening procedures as the actual participants and must also sign the Informed Consent form.

Participant Familiarization

The participant will be allowed to drive the simulated driving course (using the appropriate display type for the particular treatment condition) to become familiar with the vehicle handling characteristics, display, route, and procedures. After the participant is sufficiently familiar with the VE and relevant hardware components of the simulator, he or she will be given a three-minute break, based on previous research, before the experimental sessions begin.

Experimental Sessions

There will be four different treatment administered to each participant. In order to reduce the effects of practice on the outcome of the data, the treatments have been randomized using a standard Balanced Latin Square. Treatment 'A' will have the participant driving the course using the direct-view display with steering force feedback enabled. Treatment 'B' will have the participant driving the course using the direct-view display with steering force feedback disabled. Treatment 'C' will have the participant driving the course using the head mounted display with steering force feedback enabled. Treatment 'D' will have the participant driving the course using the head mounted display with steering force feedback disabled.

Participants will be asked to fill out the post-treatment Presence Questionnaire after each driving scenario is completed. The data from each participant's driving scenario will be collected by the simulation software and written to a local file on the simulator computer for later analysis. A multivariate analysis of variance (MANOVA) will be used to determine statistical significance between the factors being studied.

III. Risks and Benefits

Potential Risks

The likelihood and seriousness of potential risks associated with this experiment are based on previous research in virtual environments and simulators. Potential, minor simulator-induced sickness could occur during the experiment or could develop within 24 hours after the experiment. The symptoms range from mild to moderate headache, dizziness, disorientation, equilibrium disruption, and slight nausea. The symptoms, if they occur at all, typically last no longer than 24 hours. In very rare cases, intense nausea can be experienced during or shortly after the experiment, again usually lasting no longer than 24 hours. If simulator-induced sickness becomes manifest, at any level, the experiment will be stopped and the participant's needs will be attended to.

Minimizing Risks

The literature shows little evidence to support a clear method of preventing or adequately predicting simulator-induced sickness. A subjective questionnaire called the Mental Rotation Test (MRT) has been shown to predict susceptibility to simulator-induced sickness in some people. The MRT will be used to screen participants before they are allowed to participate in the experiment. The experiment will also allow for at least a 24-hour rest period between each session to allow for any latent effects to dissipate before continuing with the experiment. Participants will be asked not to drive a vehicle or operate heavy machinery for a period of 24 hours after each experimental session.

Benefits

The proposed research will help engineers and researchers build more effective (realistic) low-cost driving simulators for use in studying the effects of "humans in the loop" in virtual environments. The benefits to the participants are a better understanding of driving simulators and the essential components necessary to create a realistic virtual driving environment.

V. Consent Form

See the attached consent form.

IV. Confidentiality

The data from this study will be kept strictly confidential. No information of a personal nature will be collected that could link the participant with the experimental results. Each participant will be assigned a number that will identify that participant through to the conclusion of the research. No data will be released to anyone but the principal investigator and graduate students involved in the project without written consent of the participant.

APPENDIX E - Informed Consent for Participants of Investigative Projects

Informed Consent for Participants
in Research Projects Involving Human Subjects

Title of Project: Effects of Display Type and Force Feedback on Performance in a Medium-Fidelity Driving Simulator

Investigator(s): Dr. John G. Casali, John Grado Professor, ISE Department Head

Dr. Gary S. Robinson, Research Associate Professor, ISE

Mr. Chuck H. Perala, Graduate Candidate, ISE

Grado Department of Industrial and Systems Engineering

Virginia Polytechnic Institute and State University

I. Purpose of this Research/Project

This is an experiment to investigate the effects of display type and steering force feedback on driver performance in a medium-fidelity, fixed-base driving simulator. The objective of this experiment is to capture performance data of individuals while driving a simulated road course. Data collected will include lane deviation, speed control, steering wheel angle, and time to complete the course.

II. Procedures

The experiment will be conducted at the Virginia Polytechnic Institute and State University's Environmental and Safety Engineering Laboratory located in room 539, Whittemore Hall, Blacksburg, Virginia. The experiment will consist of one pre-experiment screening session and four experimental sessions conducted over several days. Each session will take approximately 30 minutes to complete. The screening session will take approximately 30 minutes in order for you to become familiar with the system and procedures. The experiment will be conducted between April and May, 2002.

As part of the screening process, you will be asked to complete a Participant Screening form. The Participant Screening form collects general information regarding your health and well-being pertinent to simulator usage. You will then be asked to complete a Mental Rotation Test (MRT). The MRT will assist the experimenter in determining a your potential susceptibility to simulator-induced sickness. Once you pass the screening process, you will be considered an active participant in the experiment.

At the beginning of the experimental session, you will be asked to complete an Immersive Tendencies Questionnaire (ITQ). The ITQ, measures your propensity to be involved or immersed in a virtual environment. You will then be asked to sit in a driving simulator and use a head-mounted display (HMD) and a direct-view display (D-V), during different experimental sessions, to view a simulated driving course. The experimenter will explain the functions of the simulator controls and demonstrate how they operate. You will be asked to drive the simulated driving course to become familiar with the vehicle handling characteristics, display, route, and procedures. You will then have any questions answered and be given a three-minute break before proceeding with the driving portion of the session.

The driving portion of the session will require you to drive along the simulated roadway in a centered, right-lane position, obey all traffic signs and laws, and maintain the posted speed limits. During the driving session, the experimenter will verbally present driving task instructions as you operate the vehicle, such as passing cars, maintaining certain speeds, and maintaining lane position. Steering wheel force feedback will be either on or off depending upon which treatment you are given. The driving scenario will end after you have driven the course two complete times.

After you complete each driving scenario, you will be asked to fill out a Presence Questionnaire. This questionnaire will determine the level of presence that you experienced while using the simulator.

III. Risks

Some people experience something called simulator-induced sickness while using virtual environment simulators. Simulator-induced sickness is similar to motion sickness and can occur during the experiment or could develop within 24 hours after the experiment. The symptoms range from mild to moderate headache, dizziness, disorientation, equilibrium disruption, and slight nausea. The symptoms, if they occur at all, typically last no longer than 24 hours. In very rare cases, intense nausea can be experienced during or shortly after the experiment, again usually lasting no longer than 24 hours. For this reason, the experimenter asks that you agree not to drive a motor vehicle or operate heavy machinery for a period of 24 hours after each experimental session. The MRT will be used to determine if you are susceptible to simulator-induced sickness before you participate in the experiment.

If the effects of simulator-induced sickness become too overwhelming for you to continue, the experimental session will be stopped and you will be compensated for your time.

IV. Benefits

You will be given understanding of driving simulators and the essential components necessary to create a realistic virtual driving environment.

The results of this research may help engineers and researchers build more effective (realistic) low-cost driving simulators for use in studying the effects of “humans in the loop” in virtual environments.

V. Extent of Anonymity and Confidentiality

The data from this study will be kept strictly confidential. No information of a personal nature will be collected that could link you with the experimental results You will be assigned a number that will identify you through to the conclusion of the research. No data will be released to anyone but the principal investigator and graduate students involved in the project without written consent of the participant.

VI. Compensation

Monetary compensation will be provided to you at a rate of $8.00 per hour. You will also be compensated for your time during the screening process at the rate of $8.00 per hour. Any fraction of time less than an hour will be pro-rated on an $8.00 per hour basis.

VII. Freedom to Withdraw

You are free to withdraw from this research at any time and for any reason. Circumstances may arise that the experimenter will determine that you should not continue as a participant in the study (an illness for example). You will be compensated for any time you contributed to the research up to that point at the rate specified.

VIII. Approval of Research

This research has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University and by the Grado Department of Industrial and Systems Engineering.

______________________________ ______________________________

IRB Approval Date Approval Expiration Date

X. Subject's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

____Date__________

Subject signature

____Date __________

Witness (Optional except for certain classes of subjects)

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Chuck H. Perala	(540) 231-9086/cperala@vt.edu
Investigator(s)	Telephone/e-mail
Dr. John G. Casali	(540) 231-9081/jcasali@vt.edu
Faculty Advisor	Telephone/e-mail
Dr. John G. Casali	(540) 231-9081/jcasali@vt.edu
Departmental Reviewer/Department Head	Telephone/e-mail
David M. Moore	540-231-4991/moored@vt.edu
Chair, IRB	Telephone/e-mail
Office of Research Compliance	
Research & Graduate Studies	

Note: You will receive a copy of this form to take with you.

APPENDIX F - Participant Screening Form

Participant Screening Form

Investigator:_______________Date:_______ | Participant #_____

Instructions: Please answer the following questions by filling in the appropriate blanks, placing an “x” in the appropriate locations or circling the appropriate responses.

1. What is your age? _______ years

2. What is your gender? Female ( ) Male ( )

3. Are you currently in your usual state of good fitness? Yes ( ) No ( )

4. How many hours did you sleep last night? _______ hours

5. Do you consider this amount of sleep sufficient? Yes ( ) No ( )

6. Please indicate all medications/substances you have used in the past 24 hours. Circle ALL that apply:

    a. None
    b. Sedatives or tranquilizers
    c. Aspirin, Tylenol, other analgesics
    d. Anti-histamines
    e. Decongestants
    f. Other

7. Do you have a history of seizures? Yes ( ) No ( )

8. Do you have normal or corrected 20/20 or 20/30 vision? Yes ( ) No ( )

9. Are you color-blind? Yes ( ) No ( )

10. How many hours per week do you use a computer? _______ hours

11. My level of confidence in using computers is: 1 2 3 4 5

low average high

12. I enjoy video games (home or arcade): 1 2 3 4 5

agree unsure disagree

13. I am _____ at playing video games: 1 2 3 4 5

bad average good

14. How many hours per week do you play video games? _______ hours per week?

15. How many times in the last year have you experienced a virtual reality game or entertainment? _______ times

16. How many times in the last 48 hours have you experienced a virtual reality game or entertainment? _______ times

Post Experiment Questions

1. Which display type did you prefer most? HMD ( ) D-V ( )
2. Why did you prefer this display type?
3. What did you not like about the other display type?
4. Which level of steering force feedback did you prefer most? Enabled ( ) Disabled ( )
5. Why did you prefer this level of steering force feedback?
6. What did you not like about the other level of steering force feedback?

APPENDIX G - Immersive Tendencies Questionnaire

IMMERSIVE TENDENCIES QUESTIONNAIRE
(Witmer & Singer, Version 3.01, September 1996)

Indicate your preferred answer by marking an "X" in the appropriate box of the seven point scale. Please consider the entire scale when making your responses, as the intermediate levels may apply. For example, if your response is once or twice, the second box from the left should be marked. If your response is many times but not extremely often, then the sixth (or second box from the right) should be marked.

1. Do you easily become deeply involved in movies or tv dramas?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

2. Do you ever become so involved in a television program or book that people have problems getting your attention?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

3. How mentally alert do you feel at the present time?

|________|________|________|________|________|________|________|
NOT ALERT MODERATELY FULLY ALERT

4. Do you ever become so involved in a movie that you are not aware of things happening around you?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

5. How frequently do you find yourself closely identifying with the characters in a story line?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

6. Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

7. What kind of books do you read most frequently? (CIRCLE ONE ITEM ONLY!)

Spy novels	Fantasies	Science fiction
Adventure novels	Romance novels	Historical novels
Westerns	Mysteries	Other fiction
Biographies	Autobiographies	Other non-fiction

8. How physically fit do you feel today?

|________|________|________|________|________|________|________|
NOT FIT MODERATELY FIT EXTREMELY FIT

9. How good are you at blocking out external distractions when you are involved in something?

|________|________|________|________|________|________|________|
NOT VERY GOOD SOMEWHAT GOOD VERY GOOD

10. When watching sports, do you ever become so involved in the game that you react as if you were one of the players?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

11. Do you ever become so involved in a daydream that you are not aware of things happening around you?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

12. Do you ever have dreams that are so real that you feel disoriented when you awake?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

13. When playing sports, do you become so involved in the game that you lose track of time?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

14. How well do you concentrate on enjoyable activities?

|________|________|________|________|________|________|________|
NOT AT ALL MODERATELY WELL VERY WELL

15. How often do you play arcade or video games? (OFTEN should be taken to mean every day or every two days, on average.)

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

16. Have you ever gotten excited during a chase or fight scene on TV or in the movies?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

17. Have you ever gotten scared by something happening on a TV show or in a movie?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

18. Have you ever remained apprehensive or fearful long after watching a scary movie?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

19. Do you ever become so involved in doing something that you lose all track of time?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

20. On average, how many books do you read for enjoyment in a month?

|________|________|________|________|________|________|________|
NONE ONE TWO THREE FOUR FIVE MORE

21. Do you ever get involved in projects or tasks, to the exclusion of other activities?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

22. How easily can you switch attention from the activity in which you are currently involved to a new and completely different activity?

|________|________|________|________|________|________|________|
NOT SO EASILY   FAIRLY EASILY   QUITE EASILY

23. How often do you try new restaurants or new foods when presented with the opportunity?

|________|________|________|________|________|________|________|
NEVER   OCCASIONALLY   FREQUENTLY

24. How frequently do you volunteer to serve on committees, planning groups, or other civic or social groups?

|________|________|________|________|________|________|________|
NEVER   SOMETIMES   FREQUENTLY

25. How often do you try new things or seek out new experiences?

|________|________|________|________|________|________|________|
NEVER   OCCASIONALLY   OFTEN

26. Given the opportunity, would you travel to a country with a different culture and a different language?

|________|________|________|________|________|________|________|
NEVER   MAYBE   ABSOLUTELY

27. Do you go on carnival rides or participate in other leisure activities (horse back riding, bungee jumping, snow skiing, water sports) for the excitement of thrills that they provide?

|________|________|________|________|________|________|________|
NEVER   OCCASIONALLY   OFTEN

28. How well do you concentrate on disagreeable tasks?

|________|________|________|________|________|________|________|
NOT AT ALL   MODERATELY WELL   VERY WELL

29. How often do you play games on computers?

|________|________|________|________|________|________|________|
NOT AT ALL OCCASIONALLY FREQUENTLY

30. How many different video, computer, or arcade games have you become reasonably good at playing?

|________|________|________|________|________|________|________|
NONE ONE TWO THREE FOUR FIVE SIX OR MORE

31. Have you ever felt completely caught up in an experience, aware of everything going on and completely open to all of it?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY FREQUENTLY

32. Have you ever felt completely focused on something, so wrapped up in that one activity that nothing could distract you?

|________|________|________|________|________|________|________|
NOT AT ALL OCCASIONALLY FREQUENTLY

33. How frequently do you get emotionally involved (angry, sad, or happy) in news stories that you see, read, or hear?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

34. Are you easily distracted when involved in an activity or working on a task?

|________|________|________|________|________|________|________|
NEVER OCCASIONALLY OFTEN

APPENDIX H - MS Excel Data Table

sex	subject	display	feedback	trmt	lap	segment	mtimesec	mlndev_l	mnlndev_r	mlndev	msldev	mabsldev	vmph	vstr_angdeg
m	1	D-V	enable	a	1	1	261.5160	0.0000	0.0000	-0.2480	-11.7640	11.7640	173.9819	2327.6074
m	1	D-V	enable	a	1	2	68.5620	0.0286	-0.9084	-0.6853	-4.5164	4.5164	54.9377	148.5837
m	1	D-V	enable	a	1	3	117.3440	0.4422	-0.6716	-0.2046	-9.6544	9.6544	135.2803	137.3937
m	1	D-V	enable	a	1	4	172.6560	-0.0602	-0.5025	-0.3758	-8.7650	8.7650	90.7935	59.2752
m	1	D-V	enable	a	2	1	179.2190	0.0000	0.0000	-0.1994	-3.3393	3.3393	133.4516	1050.3686
m	1	D-V	enable	a	2	2	69.5940	0.3061	-1.0439	-0.5854	-5.1041	5.1041	78.0115	188.4711
m	1	D-V	enable	a	2	3	113.6250	0.1386	-0.7929	-0.3126	-7.9747	7.9747	121.7956	131.6096
m	1	D-V	enable	a	2	4	183.7970	-0.0534	-0.3395	-0.2742	-12.0872	12.0872	109.6235	109.4748
m	1	D-V	disable	b	1	1	189.5940	0.0000	0.0000	-0.1060	-4.9246	4.9246	197.0967	3682.0049
m	1	D-V	disable	b	1	2	67.2030	0.1917	-0.9343	-0.4888	-3.6553	3.6553	63.1686	160.6191
m	1	D-V	disable	b	1	3	111.0620	0.5560	-0.5714	-0.1911	-6.6820	6.6820	150.1979	142.8399
m	1	D-V	disable	b	1	4	168.3440	-0.1993	-0.4955	-0.3871	-7.3614	7.3614	113.3600	64.8200
m	1	D-V	disable	b	2	1	159.1250	0.0000	0.0000	-0.1701	-0.0100	0.0100	163.1369	782.0883
m	1	D-V	disable	b	2	2	68.1400	0.1348	-0.8205	-0.4472	-4.2052	4.2052	51.9787	164.1867
m	1	D-V	disable	b	2	3	112.8900	0.5763	-0.4964	-0.1553	-7.4806	7.4806	100.7029	135.7833
m	1	D-V	disable	b	2	4	166.5940	-0.1495	-0.3078	-0.2595	-6.6540	6.6540	56.7955	54.6364
m	1	hmd	enable	c	1	1	210.7500	0.0000	0.0000	-0.0919	-7.0648	7.0648	254.6111	1746.2330
m	1	hmd	enable	c	1	2	64.6250	0.2383	-0.4173	-0.2513	-2.0858	2.0858	82.7445	174.0355
m	1	hmd	enable	c	1	3	107.0470	0.3227	-0.2094	-0.0211	-4.4310	4.4310	97.4568	135.8312
m	1	hmd	enable	c	1	4	271.7500	0.1894	-0.3201	-0.0922	-1.4560	1.4560	118.5327	75.4309
m	1	hmd	enable	c	2	1	183.5780	0.0000	0.0000	-0.2376	-3.9399	3.9399	154.8128	715.4187
m	1	hmd	enable	c	2	2	69.1720	0.0941	-0.8271	-0.5710	-4.4115	4.4115	199.7208	141.2523
m	1	hmd	enable	c	2	3	114.7500	0.3426	-0.4047	-0.1741	-8.3520	8.3520	196.4062	129.7392
m	1	hmd	enable	c	2	4	157.1250	0.0584	-0.4078	-0.3004	-3.0834	3.0834	144.4843	49.0141
m	1	hmd	disable	d	1	1	302.1410	0.0000	0.0000	-0.0495	-14.0796	14.0796	179.5809	996.6508
m	1	hmd	disable	d	1	2	69.3590	0.2975	-0.6878	-0.4760	-4.6098	4.6098	165.3784	173.0597
m	1	hmd	disable	d	1	3	114.8120	0.4363	0.0269	0.1290	-8.5911	8.5911	207.1149	139.3511
m	1	hmd	disable	d	1	4	159.0310	0.2087	0.0141	0.1189	-3.9164	3.9164	123.3098	66.6866