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Vestibular rehabilitation using a virtual environment for driver safety

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VESTIBULAR REHABILITATION USING A VIRTUAL ENVIRONMENT FOR DRIVER SAFETY

by

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Abstract

Vestibular Rehabilitation using a Virtual Environment for Driver Safety

Master of Engineering

Department of Electrical and Computer Engineering

Ryerson University

Driving is a necessity of life, and it requires multi-sensory input and processing. Often vestibular impaired patients suffer from dysfunctional sensory input that impairs their driving. Therefore, driver's attention, and egocentric navigation skills are investigated in this project through the use of a spaceball driving simulator.

This thesis clearly demonstrates and specifies the steps of implementation of a driving simulator into the spaceball. Driver attention was tested through the use of computer and audio reflex time and was used to analyze the improvement in reaction time. Seat perturbation reflex time test was used to analyze the driver egomotion awareness on the simulator.

The experimental results illustrate the improvement in the driving rehabilitation field of reaction time which leads to the conclusion that the visual-proprioceptive virtual driving simulator could provide treatment to the vestibular impaired patients.

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List of Abbreviations

2-D	Two dimensional
3-D	Three dimensional
BPPV	Benign paroxysmal positional vertigo
CABIN	Computer Augmented Booth for Image Navigation
CAVE	Cave Automatic Virtual Environment
CNS	Central Nervous System
DHQ	Driving Habit Questionnaire
HMD	Head Mounted Displays
IVY	Immersive Visual environment at York
LCD	Liquid Crystal Displays
MEMS	Micro-Electro-Mechanical Systems
SSQ	Simulation Sickness Questionnaire
VE	Virtual Environment
VOR	Vestibulo–Ocular Reflex
VR	Virtual Reality

Chapter 1

Introduction

For most individuals, driving is a necessity of life and yet individuals with serious medical conditions can put themselves and others at risk while on the road. A Canadian study found that alcohol intoxication, driver inexperience, and falling asleep behind the wheel were the top three human factors contributing to crashes involving a motor vehicle [1,2]. Moreover, attention deficit and medical conditions are also significant driving hazards.

Driving requires dividing driver attention between multiple activities and being able to react quickly to situations that often arise without warning. It has been found that talking on the cell phone, lack of sleep and aging contribute to the reduced attention level [3]. These factors lower concentration rate and diminish mental awareness of the driving environment.

Dizziness is one of the most common vestibular problems at old age, of which 50% of its cases are associated with disorders of the vestibular system. The vestibular system is found in the inner ears and is a sensory organ with receptors that detect head acceleration.

Vestibular signals include angular head velocity signals to the brain which are then converted into position signals. The nervous system then takes part in the following tasks: controlling balance by generating postural reflexes in response to head movement, which keep the body upright during a perturbation; it stabilizes gaze by generating the Vestibulo–Ocular Reflex (VOR), and it helps the individual to see an object in focus instead of shaky images while moving through the environment. One more important function of the nervous system is recognizing the spatial orientation, so that the individual is aware of his/her position with reference to gravity and contributes to egocentric navigation skills [3].

In more detail, the vestibular system is responsible for detecting motion of the head and body in space. The two main functional parts are the otoliths, which are sensitive to linear acceleration including head tilt (based on gravity), and the semicircular canals, which are sensitive to angular acceleration.

Vestibular impaired individuals might be unable to disambiguate the dynamic visual information and have difficulties processing egomotion estimation. Particularly, studies in driving simulation show that absence of vestibular information will increase steering reaction time to external movement perturbation, and decrease safety margin in curve driving [4,5]. Missing or improper signals from the impaired vestibular organs result in inappropriate steering adjustment.

Furthermore, patients with vestibular disorders rely heavily on visual information for spatial orientation, which indicates to them whether they are steering straight or staying upright [3]. They are more easily disoriented from visual complexity or visual noise, especially during visually reduced situations such as night time or in raining conditions. Other conditions such as staying in lane or parking a car are difficult for them because they require good spatial navigation skills. Rapid head rotation and movement while checking for traffic before entering an intersection often elicit vertigo in vestibularly impaired patients, making driving a difficult task for these patients [3].

During the course of life, the vestibular system also undergoes morphological changes which become particularly evident in older age [6]. For example, aging causes loss of cells in the tissues of the inner ears, initiates changes in the organelles within the remaining cells, and reduces capillary size and blood flow to the inner ear. Furthermore, the central nervous system that receives input from the vestibular labyrinths shows degenerative changes with age [3]. All the above symptoms are evidence for decrement in vestibular function that occurs with aging. Vertigo is one of the most common vestibular problems; it gives a sense of self motion, such as spinning or falling. Other symptoms include poor balance, blurred vision, and nausea. These problems cause discomfort and decreased independence in activities of daily living, including driving a car [3].

Consequently, it has been established that driving is a significant problem for individuals troubled by dizziness due to illness and fatigue, and vestibular impaired individuals often find themselves troubled by vertigo while driving. It has been shown that vestibular rehabilitation is often associated with improvements in independent and dynamic visual acuity. Through the rapid advances in recent technology, the field of Virtual Reality (VR) has grown immensely. Research shows that a vast number of medical rehabilitation studies benefit from the technological potential of virtual reality development.

The applications of virtual reality range diversely from entertainment to educational research due to its appeal in cost effectiveness, time saving, safety issues, and most importantly it can be customized to suit particular needs. A Virtual Environment (VE) has the ability to reconstruct the simulation setting that the user would to act upon in real life, and is very often much safer than the real world setting, as it can vary in its environment complexity. It is also typically more cost effective.

In this project the problems of vestibular disorders are closely analyzed with respect to how they affect these patients and their driving. A prototype driver simulator is designed using a spaceball which is immersed in a 3-D VR environment. It is believed that this system will aid and train the patients to improve their driving skills and attention, thereby providing safer driving conditions while on the road. The purpose of this pilot study was to begin examine the benefits offered through VR to investigate the purported relationship between driver's attention and driving performance.

There are many recent studies in the area of rehabilitation through virtual environment simulation; different simulation environments are used for different needs, some even combine alternative exercises with virtual simulation training to improve the overall performance of the rehabilitation. Studies show virtual driving rehabilitation training has great success in improving driving performance and increasing independence in patients' daily routine. [7]

The thesis includes five chapters: Introduction, Background, Experimental Set-Up, Results and Discussion, and Conclusion.

Chapter 2

Background Information

2.1 Vestibular Disorders

The vestibular system senses the position of head and body in space as they move. The inner ear is located within the skull and consists of the cochlea, where sound is transformed to nerve signals for the brain, and the vestibular system consisting of three semi-circular canals that function like a gyroscope, relaying information about head rotation to the brain. The vestibular system also contains the utricle and saccule, which relay information about linear acceleration, including the direction of gravity.

Vestibular deficits are very diverse, ranging from complete loss of vestibular motion inputs, to disruption in one or more directions only. Vertigo is a feeling of spinning or whirling when the person is not moving. Alternatively, it can be an exaggerated feeling of motion with small movements. It is the most common form of dizziness. Vertigo is usually caused by problems in the nerves and structures of the vestibular system. Two major vestibular disorders are introduced here in the following sections.

2.1.1 Benign paroxysmal positional vertigo (BPPV)

Benign paroxysmal positional vertigo (BPPV), is one of the most common types of vertigo. About 20% of all dizziness is due to BPPV. The older the person is, the more likely it is that his/her dizziness is due to BPPV, as about 50% of all dizziness in older people is due to BPPV [7]. Dizziness is thought to occur due to loose otoconia (small crystals of calcium carbonate in the utricle and saccule) which can find their way into other parts of the vestibular system as observed in Figure 1.

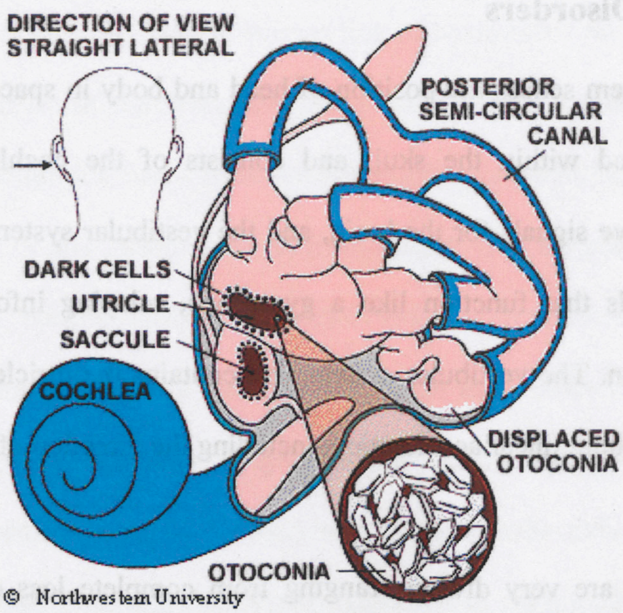


Figure 1: Vestibular system and debris caused BPPV [8].

The semicircular canals contain fluid and special sensors that, when disturbed, inform the brain of a change in head position. Small debris become dislodged within the inner ear and then bounce around when the head moves, triggering faulty signals that the head is still moving even after it stops. This sensation of movement or imbalance when one is not moving is called vertigo, the primary symptom of BPPV [9]. BPPV can trigger sudden sensation of movement or spinning when one moves his/her head or holds it in a certain position [10].

2.1.2 Ménière's disease

Ménière's disease is a disorder that affects the hearing and balance mechanisms in the inner ears, which causes episodes of vertigo, fullness or pressure in the ears and fluctuating hearing loss. Patients suffer from abnormal sensation of pressure or fullness in the ears due to increase in volume and pressure of the endolymph (fluid in the inner ears), causing vertigo, tinnitus (hearing noises) and deafness [11,12].

Ménière's disease affects roughly 0.2% of the population, and it is recurrent and can last between several hours to a day. It is a progressive disease, meaning that it gradually gets worse [12]. Studies show Ménière's disease starts out in only one ear but often extends to both ears [11].

A survey study conducted by Cohen et al (2006) reported patients with vestibular disorders having difficulties driving under reduced visibility conditions such as driving at night or in the rain. They usually have difficulty navigating in visually complex environments and making special maneuvers, in many common situations such as driving on highways and other high traffic roads, changing lanes, staying in lane and fighting the tendency to drift into an adjacent lane [13]. The absence of vestibular information will increase the steering reaction time to external movement perturbation, and decrease safety margin in curve driving [4,5]. Missing or improper signals from the impaired vestibular organs result in inappropriate steering adjustment.

There are many other causes of vertigo that are less common, such as stroke, brain tumor, multiple sclerosis, viral infection, blood pressure and migraine headache. Sometimes even flu medicine, painkillers, depression, anxiety and lack of sleep can cause slight vertigo symptoms.

2.2 Driving and attention

Vestibular impairment can also result in range of cognitive, behavioral and physical dysfunctions that reduce the ability to carry out everyday activities. Like driving, this is critical in maintaining independence. Cognitive skills such as visual scanning, attention, information processing speed, visuospatial skills (visual perception of spatial relationships among objects), and various executive functions can result in impaired driving performance. Attention is an indication of the ability of the individual to process information from the environment or the capability of receiving and processing stimuli [14]. Divided attention in particular is required to simultaneously conduct more than one task at a time, as driving demands the driver to pay attention to multiple tasks, including monitoring road conditions, environment and the information on the dashboard.

Motor vehicle accidents are categorized into three factor groups: human factors, vehicle-related factors, and environmental factors. Out of these three factors, human factors are considered to be the most common cause of automobile accidents which includes the action taken by or the condition of the driver, such as speeding, violating traffic laws, drug or alcohol use, errors in decision making, age and inattention [15].

Driving is a multidimensional activity that involves at least three hierarchically organization levels of competency: operational, tactical, and strategic (see Figure 2). Deficits in lower levels of the hierarchy may have profound effects on higher levels of competency required for driving; however, deficits at higher levels may have little or no influence on lower level competencies and may be undetected by methods aimed at assessing only those lower levels [15]. Figure 2 shows the association of driving with the three hierarchical levels of competency, coordination is often required across all three of the operational, tactical, and strategic levels. For driving, models that coordinate the levels of cognitive processing along with operational control are needed to capture the overall behavior of the driver for sensible decision making and information processing.

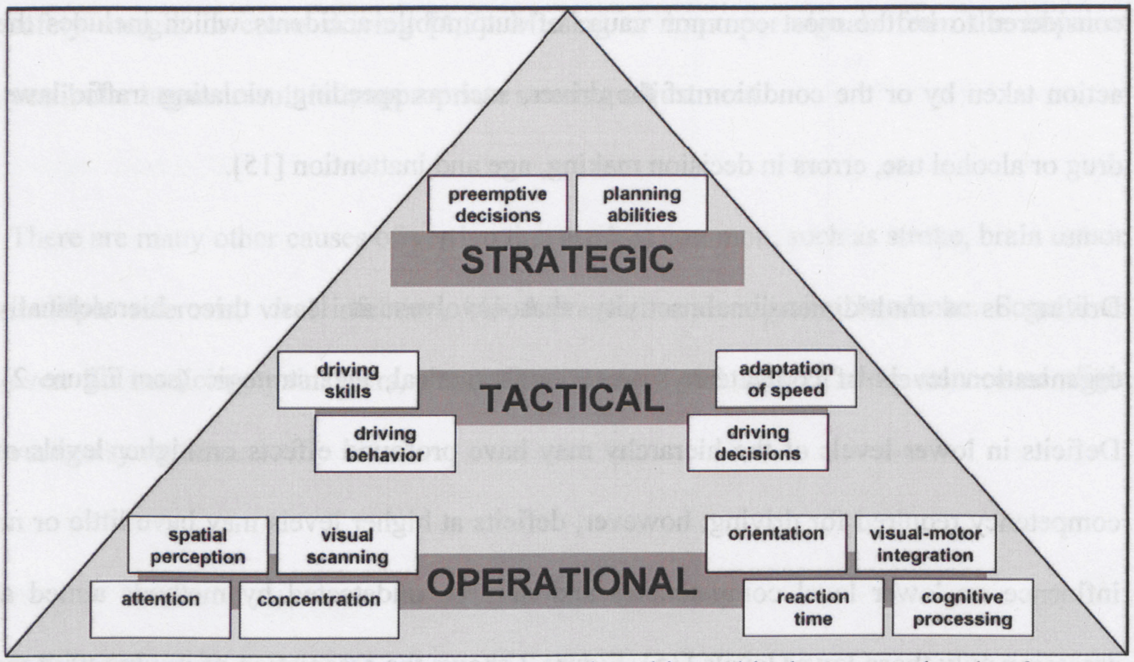


Figure 2: Association of driving with the 3 hierarchical structure levels of competency — operational, tactical, and strategic [15].

"Operational competency (level 1) comprises elementary mental functions, such as attention and concentration, reaction time, visual scanning, spatial perception and orientation, visual-motor integration, speed of cognitive processing, motor coordination, and other basic neuropsychological abilities that are inherent in driving. Tactical competency (level 2) includes those behaviors, skills, and decisions that are associated with driving in traffic, such as adaptation of speed to driving conditions, use of headlights to improve visibility, and decisions about whether to pass other vehicles. Strategic competency (level 3) involves decisions and planning abilities that pertain to the reasons the vehicle is being used at a particular time. It includes the goal(s) for the particular driving session, as well as choices regarding the best route, time of day, and trip sequence (subgoals), along with evaluation of general risks (e.g., traffic conditions, density, and climate) that pertain to the excursion. A disorder that affects driving skills at any of these three levels would produce secondary adverse effects on the various domains of daily adaptive functioning that driving supports, while possibly putting the driver and others on the road at risk [15]. "

2.3 Simulator based rehabilitation

Virtual reality is a simulation of the real world environment that is generated through computer software, providing a coherent multi-sensory environment for subjects to perceive and control virtual objects. In a driving simulator, most but not all of the multi-sensory cues are presented due to the cost and complexity. The user inputs are monitored and used to update the virtual environment displays that provide the realistic feedback to the user.

Studies show that patients with vestibular disorders often avoid highway and rush hour driving to increase safety due to their reduced driving skills. Roles of vestibular function and driving are considered highly correlated, including self motion perception during linear motion, and roll tilt motion during turns or curves. When driving around a curve, accurate detection of vehicle acceleration is required, involving the use of vestibular input.[13] "For example, when a car starts to turn, vestibular input may be important in alerting the driver to correct the car's trajectory, as vestibular input is essential in egocentric spatial orientation during passive stationary and active translation tasks [13]. "

VR is an emerging technology that allows individuals to "interact" with and become immersed in a three-dimensional computer-generated environment. Through its capacity to create dynamic, multisensory, "real-life" stimulus environments, within which all behavioral responding can be recorded, VR potentially offers clinical tools that are not available while using traditional neuropsychological methods.

To date, VR has been successfully integrated into several aspects of medicine, and rehabilitation medicine. Clinicians and researchers are also beginning to recognize VR's potential as a new tool for the study, assessment, and rehabilitation of cognitive processes [7]. In addition, a number of researchers have advocated using VR for the evaluation and retraining of functional activities of daily living, such as the use of public transportation, meal preparation, and driving an automobile. Results from these initial studies indicate that the use of VR has several advantages over traditional neuropsychological assessment and retraining protocols, including the direct evaluation of complex behaviors in ecologically valid environments, objective evaluation of complex behaviors, and the opportunity to present challenging conditions while maintaining the safety of both the clinician and patient. Given these advantages, VR can provide a new mechanism for objectively quantifying driving skills and more directly examining the impact of specific cognitive functions (i.e. divided attention) on driving performance [14].

A typical setup of a multi-sensory driving simulator consists of a driver sitting in a cockpit and triggering actions through a steering wheel and foot pedals, thereby maneuvering the virtual vehicle through the virtual environment. The control of these movements is determined through a vehicle dynamics model. Motion cues can be modeled by placing the driving cockpit on a moving platform which is controlled by a set of six electro-mechanical linear actuators mounted in a hexapod configuration also known as Stewart Platform [16]. The platform creates linear acceleration in the longitudinal, lateral and vertical direction (shown in Figure 3) as surge, sway and heave respectively. It can also create angular acceleration in the directions of roll, pitch and yaw. Thus, it has all six possible degrees of freedom. These motions are controlled in synchronization with the vehicle model, user inputs, and scenario and traffic control.

Figure 3: Driving simulator at the Drive Safety research laboratory with the display of six perturbation possibilities. Adapted from Drive Safety [17].

Several commercially available driving simulators are widely popular amongst occupational therapists, clinicians and researchers due to their flexibility to create virtual driving scenarios, driver safety and data recording capabilities. One of the most popular simulator is the STISIM from System Technology Inc. STISIM can monitor driver behavior, performance and attention including reaction time, driving and visual accuracy, form and color perception, memory recognition, and it also has the capability to extend the monitoring of head and eye movement tracking as the software is incorporated into actual car hardware. DriveSafety, Sim-Drive Canada, DriVR driving simulators are also widely used for off road driver training.

2.4 Immersive Virtual Reality

Large displays usually give more realism to the virtual environment compared to smaller displays. This is presumably because the immersive nature of large displays result in greater feeling of presence. Researches have proven that it does give more presence when they are watching movies from a larger display especially action movies [18,19]. It has been found that performance for egocentric (viewer-centered frame of reference) cognitive tasks on a large display is comparatively better than the small display. It was suggested that the large display tends to bias participants into developing egocentric strategies and therefore presents more immersiveness to the user [20].

Visual abilities are not uniform across the entire filed of view vision. For example, binocular vision, which is important for depth perception only covers 140° of field of view in humans due to the coverage of the overlaps of the images from either eye. Color vision and ability to perceive shape and motion vary across the field of vision also; color vision are concentrated in the center of the visual field and the cognition for shapes and motion are more acute in the periphery. There is much higher concentration of color sensitive cone cells in the fovea (central region of the retina), as compared to the higher concentration of motion sensitive rod cells in the periphery [21].

With today's advanced technology, a variety of products are available to create complex virtual environments for different purposes. High resolution visual displays produce an illusion of a more real surrounding to the user; and the quality of this immersion illusion is referred to as presence. Although an immersive display is important for the sense of presence, it is not necessary and may even be counterproductive for some training purposes [22].

An example of a less immersive visual device is a desktop computer monitor, using a 2-D graphics display. Even though desktop monitors do not provide the sense of realistic immersion as a true stereo 3-D display, the sense of depth can be enhanced through the use of depth cues such as perspective, relative motion, occlusion and aerial perspective [21,23]. Large wall screens and Liquid Crystal Displays (LCD) improve the quality of the sense of depth and therefore the user feels more presence [24]. More advanced virtual environments that display true 3-D stereo are also being used. Shutter glasses, which display alternating left and right views of a scene, trick the visual system to perceive a 3-D scene. Head Mounted Displays (HMDs) enable stereo viewing by displaying the image on small screens worn as eyeglasses. Some HMDs also incorporate a head tracking system, which is capable of changing the virtual views with the user's head movement thus providing more realism to the virtual environment. Advanced immersive displays like the large single wall projections, and multi-wall displays provide even more immersiveness that allow the user to be surrounded by an immersive environment.

As discussed here, the virtual display can be of different form and complexity. However, research has found that although the field of view is usually limited, a horizontal field of view of at least 120° is needed for correct speed perception [16,21].

Drivers need multi-sensory cues for a sense of immersion, as vestibular and proprioceptive inputs play an important role. Research has found that steering and speed control are partly a response to vestibular cues, as the driver in the vehicle perceives orientation of the car through more than visual cues alone.

Advanced immersive displays range from large single wall projections (e.g. the PowerWall) to multi-wall displays, such as, three-wall displays (e.g. the Immersion Square), four-wall displays (e.g. the CAVE), five-wall displays (e.g. the CABIN), and more recently six-sided displays (e.g. the Immersive Visual environment at York (IVY)). These displays immerse the user into the environment which mimics the human environment interaction in the real world.

Chapter 3

Experimental Set-Up

The purpose of this pilot study was to start examining the benefits offered through carefully designed VR that has the capacity to create dynamic, multi-sensory, real-life simulation environments to investigate the claimed relationship between driver's attention and driving performance.

3.1 Subjects

As this project primarily deals with the system design and implementation of the VR interface, only a few pilot data were collected to verify the accuracy and effectiveness of the designed system. Due to the system being in the development stage, the author is the only test subject of this experiment. The test subject for this pilot data experiment is a healthy 25 year old male, height of 175cm, weighing 70kg and is right hand dominant with prior right-side driving experience, having corrected vision and no medical conditions affecting any of the experimental measurements.

During these experimental sessions, the subject completed various tasks, including a driving training task in the VR environment, computerized reaction time measures, audio reflex time measures and head movement measurements while in training. The subject completed the training protocol over five sessions which lasted approximately half an hour to one hour each.

3.2 Experimental Protocol

During the experiment, the subject underwent both pre-training and post-training tests that consisted of reaction time measurement on a computer and seat perturbation reaction time on the simulator. On the first day, before the training session, a couple of reaction time tests were conducted on the subject, which include the computer reflex test and seat perturbation reaction test; each test was repeated 30 times. A 10 minute tutorial of the virtual environment was provided to familiarize the subject with the driving wheel and the virtual environment. The training session consisted of the subject driving an automobile in a virtual environment through a preset track. The subject completed the track laps three times, after which a five minute break between each laps provided. A randomized audio reaction time test was also given to the subject at any random time during the three runs to avoid any expectancy for the subject. At the end of each session, a repeated computer reflex test was conducted to observe the session training improvement.

A Driving Habit Questionnaire (DHQ) was conducted at the beginning of the experiment to ensure the experimenter is familiar with the subject's driving behaviors and habits. A Simulation Sickness Questionnaire (SSQ) was given to the subject at the end of every training session to ensure the comfort rating before conducting subsequent sessions.

At the end of the last session, a repeated post training seat perturbation reaction time test is performed to see the relationship of the pre-post training improvement.

3.2.1 Environment

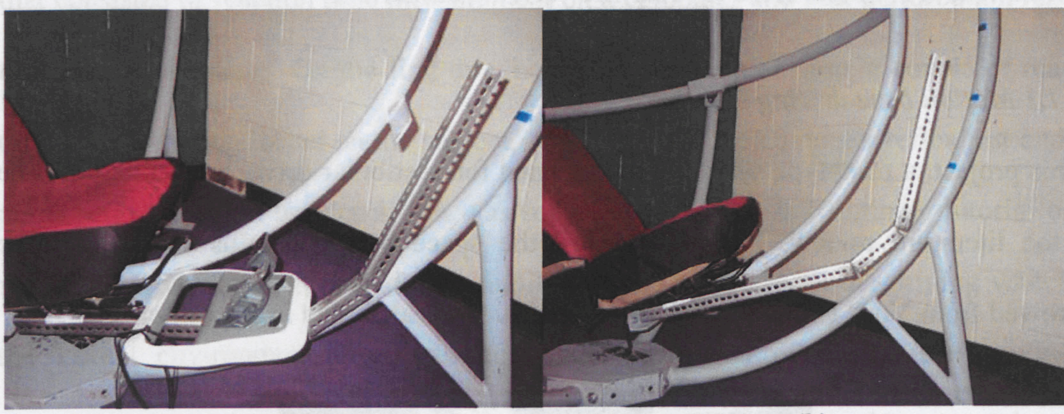
The environment used in this project for the purpose of simulating a driving task was two-fold: the subject was seated in a spherical space ball and immersed in a virtual reality environment to simulate close to “real-life” driving scenarios.

3.2.1.1 Motion base driving simulator

In this project, a prototype system was designed for vestibular driver rehabilitation based on the literature review. Figure 4 shows the space ball apparatus which has been borrowed from York University which has a driver’s seat placed in the center.

Figure 4: Spaceball apparatus for virtual reality training.

Two platforms were specifically designed and mounted on the spaceball to allow the feasibility of steering wheel and the set of gas and break pedals to be mounted on the spaceball to mimic the setup of a driver's cockpit. The length and angle of the foot platform was carefully designed to allow for maximum leg space that can accommodate the average sized adult, while it allows the platform to swing without obstructing other inner rings (see Figure 5).



(a) **(b)**

Figure 5: **(a)** Specially designed platform facilitate the mounting of the gas and break pedals. **(b)** Platform allows maximum leg room while clears the obstruction of the other ring.

The steering wheel platform was designed to angle and extend out to the driver for maximum comfort, providing the realistic feeling of driving a real car. Angles and distance of the steering wheel can be adjusted to accommodate drivers of different height, which allow them to see the full virtual reality view (see Figure 6).

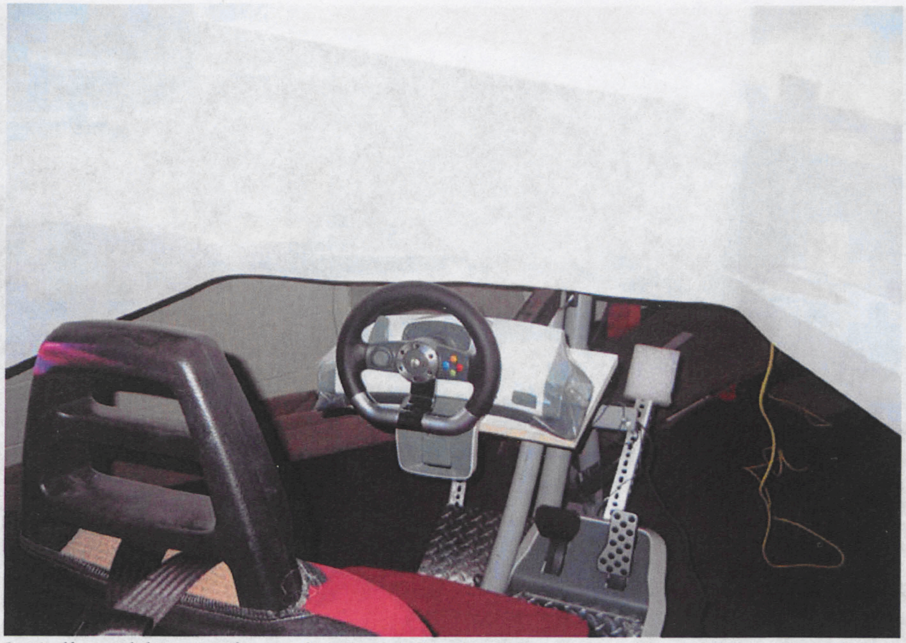


Figure 6: Adjustable steering wheel platform accommodates drivers of different height.

For safety precautions, a safety belt was added to the driver's seat to prevent driver falling off the seat during virtual reality training. The racing seat harness is mounted onto the inner ring where the seat is attached, preventing any sliding of the seat belt (see Figure 7).

Figure 7: Attached seat belt for safety precautions.

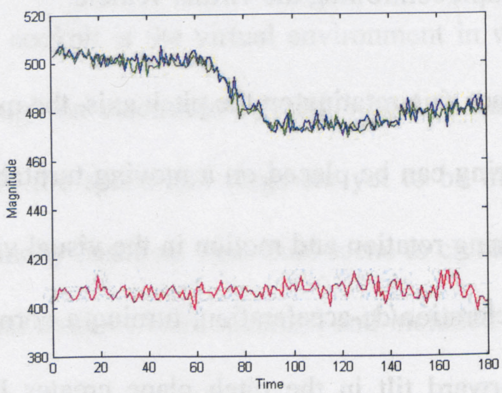
The cockpit is the virtual environment in which the subject controls the virtual vehicle through an electronic steering wheel and a set of gas and brake pedals (see Figure 8). Since the space ball rings are yet to be motorized, the motion of the ring was driven manually based on the visual scene to create the corresponding angular acceleration. The actual motions were recorded and included in the subsequent analysis section in Chapter 4.

Figure 8: Driver sitting in the cockpit controlling the virtual vehicle.

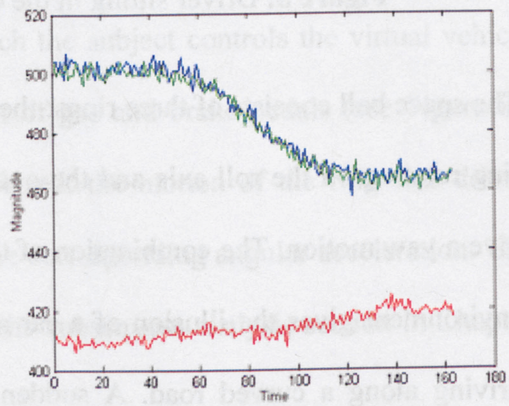
The space ball consists of three rings: the inner ring rotating on the pitch axis, the middle ring rotating on the roll axis and the outer ring can be placed on a moving turntable to give a yaw motion. The combination of the ring rotation and motion in the visual virtual environment gives the illusion of a car acceleration/de-acceleration, turning a corner or driving along a curved road. A sudden forward tilt in the pitch plane creates linear acceleration sensation and backward tilt gives the de-acceleration sensation.

3.2.1.2 Spaceball Actuation

To mimic the driving environment in the spaceball, motion is essential to induce the vestibular and proprioceptive sensations. Prior to the experiment, car dynamic data were collected from placing an accelerometer at the driver's head rest and various actions were performed. The actions performed were forward acceleration, backward acceleration, left and right turns. As observed from Figure 9, the left column figures (a,c,e,g) indicate the car dynamic data, and right column figures (b,d,f,h) indicate the mimicking spaceball data. The spaceball movements in the pitch axis (forward and backward) were moved 20º, the roll axis (left and right) were moved in a magnitude of 15º. Various magnitudes were tested, and 20º in the pitch axis and 15º in the roll axis are the most suitable angles that resembled the car readings.



(a)



(b)

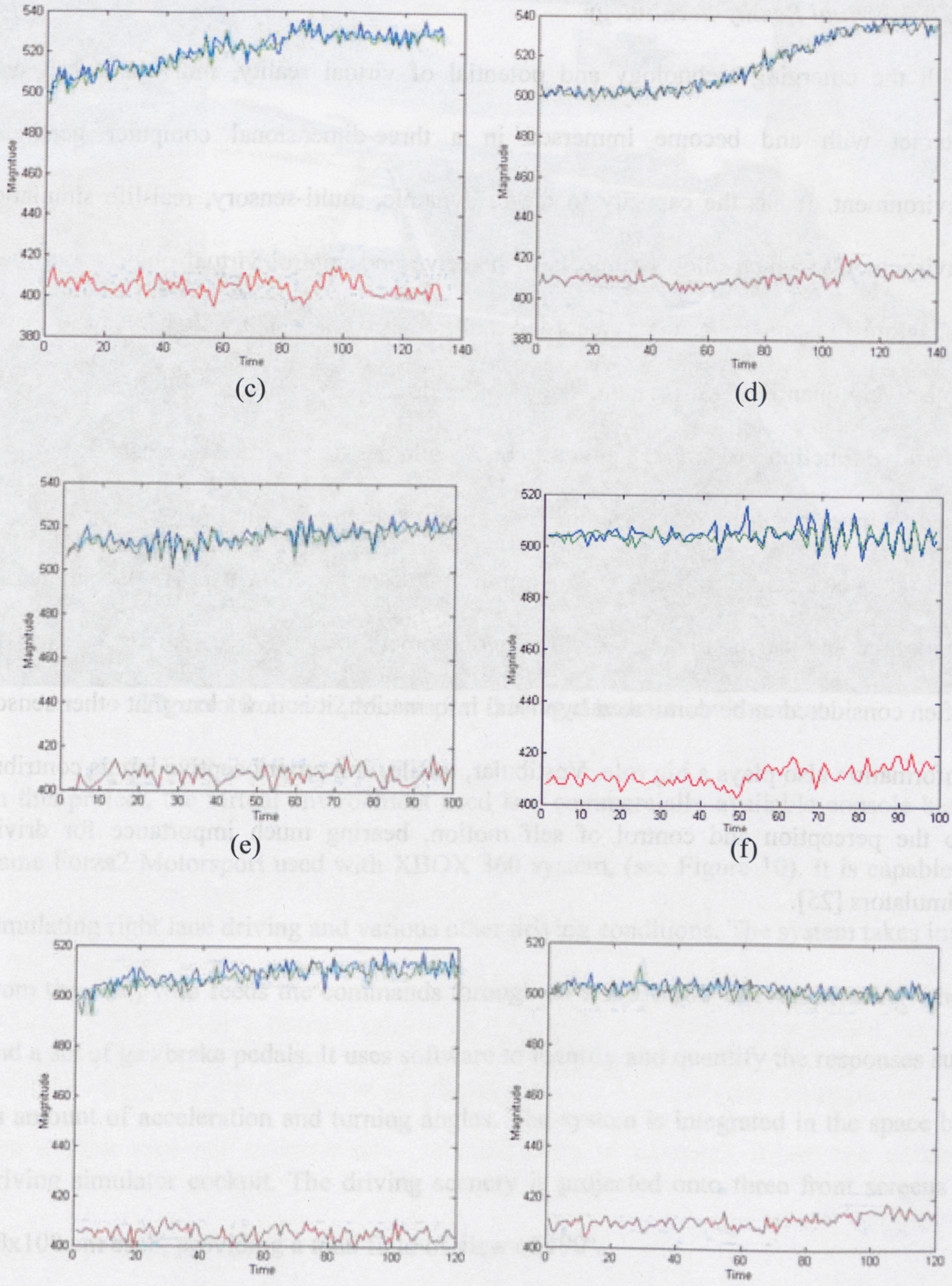


Figure 9: Accelerometer readings: (a) Car forward acceleration, (b) Spaceball forward acceleration (20º), (c) Car backward acceleration, (d) Spaceball backward acceleration (20º), (e) Car left turn, (f) Spaceball left turn(15º), (g) Car right turn, (h) Spaceball right turn(15º).

3.2.1.3 Virtual Reality Technology

With the emerging technology and potential of virtual reality, individuals can now interact with and become immersed in a three-dimensional computer generated environment. It has the capacity to create dynamic, multi-sensory, real-life simulation environments, which allows subjects to perceive and control virtual objects and these behavioral responses can be recorded and analyzed by software. VR allows for objectively quantifying driving skills and more directly examining the impact of specific cognitive functions i.e. divided attention on driving performance. In the past VR has been used to investigate the relationship between divided attention and driving performance, such as speed control, among persons with cognitive impairment [14]. User inputs are monitored and used to update the virtual environment display. As driving is a task that is often considered to be dominated by visual information, it is now clear that other sensory information also plays a big role. Vestibular, tactile, and proprioceptive inputs contribute to the perception and control of self motion, bearing much importance for driving simulators [25].

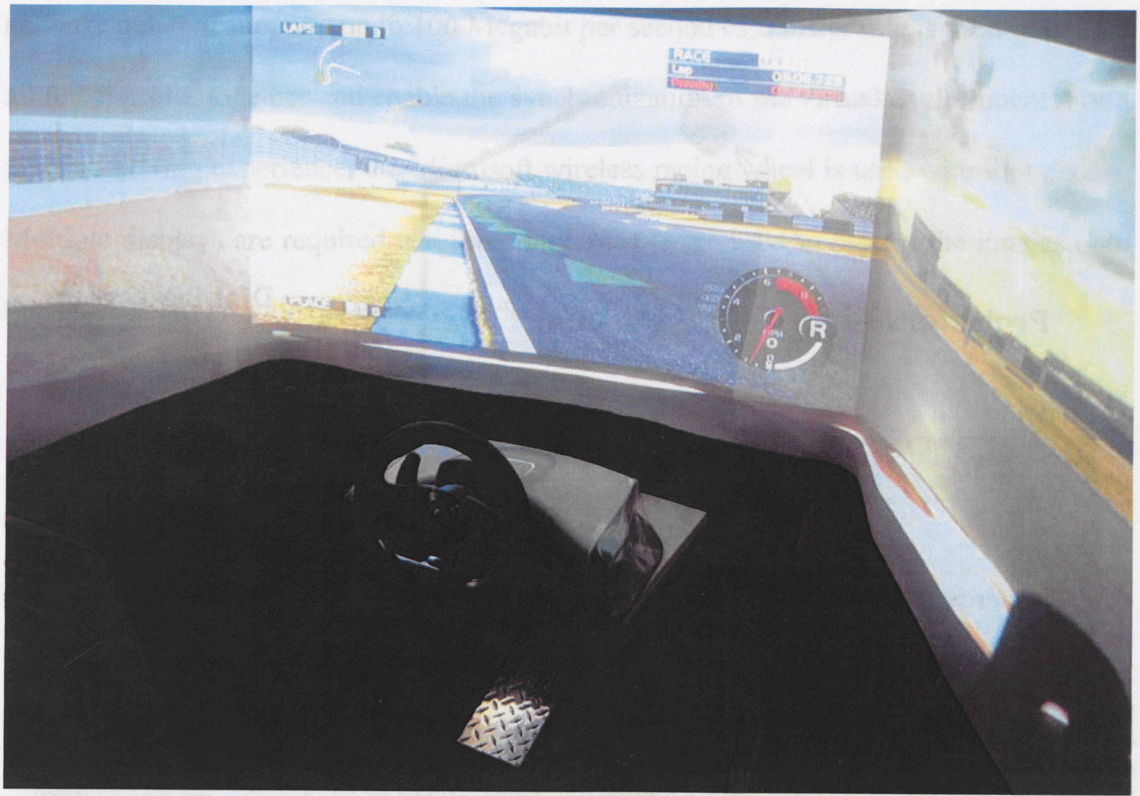


Figure 10: Forza2 Motorsport driving simulator environment.

In this project, the virtual environment used is a commercially available console based game Forza2 Motorsport used with XBOX 360 system, (see Figure 10). It is capable of simulating right lane driving and various other driving conditions. The system takes input from the user, who feeds the commands through an XBOX 360 Wireless Racing wheel and a set of gas/brake pedals. It uses software to identify and quantify the responses such as amount of acceleration and turning angles. The system is integrated in the space ball driving simulator cockpit. The driving scenery is projected onto three front screens of 80x100 cm each, providing a total field of view of 190º.

A three-wall display is used in this experiment, where the two side-view panels are angled outwards at 150° from the front panel as (shown in Figure 11).

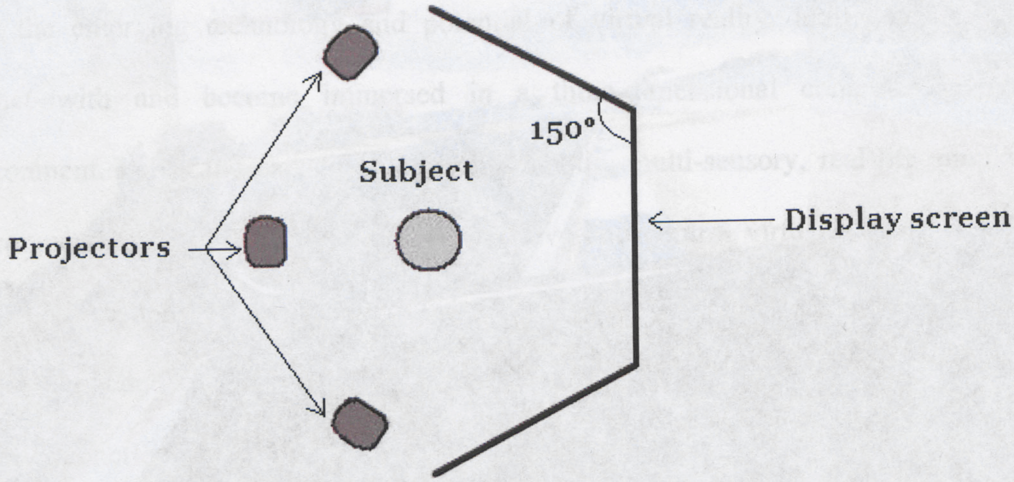


Figure 11: System Setup with side display screens angled at 150° outwards.

3.2.1.3.1 Virtual Environment and Hardware System Setup

Forza2 Motorsport was chosen as the VE to be used in the experiment after evaluating other alternatives, as it offers the most realistic car dynamics. It has been carefully implemented by Microsoft computer programmers and game designers to match the actual engine and real-world physics and can be claimed as a realistic simulator.

Forza2 Motorsport also provides triple screen display support, where the user can setup the environment that includes the two peripheral views. In this region the cognitive motion and shape detection is most sensitive, and provides the user with a more immersive feeling.

For the multi-screen setup, there are several required items, including multiple Xbox 360 consoles and multiple Forza2 Motorsport game program copies, one per display. A network hub that supports up to 100 Megabit per second of transfer rate is used to link up all the consoles together and enable the synchronization of the virtual environment. For a realistic driving experience, the Microsoft wireless racing wheel is used with foot pedals. Multiple displays are required and three projectors were used to project the images onto three screens to provide the realistic peripheral views as (shown in Figure 12).

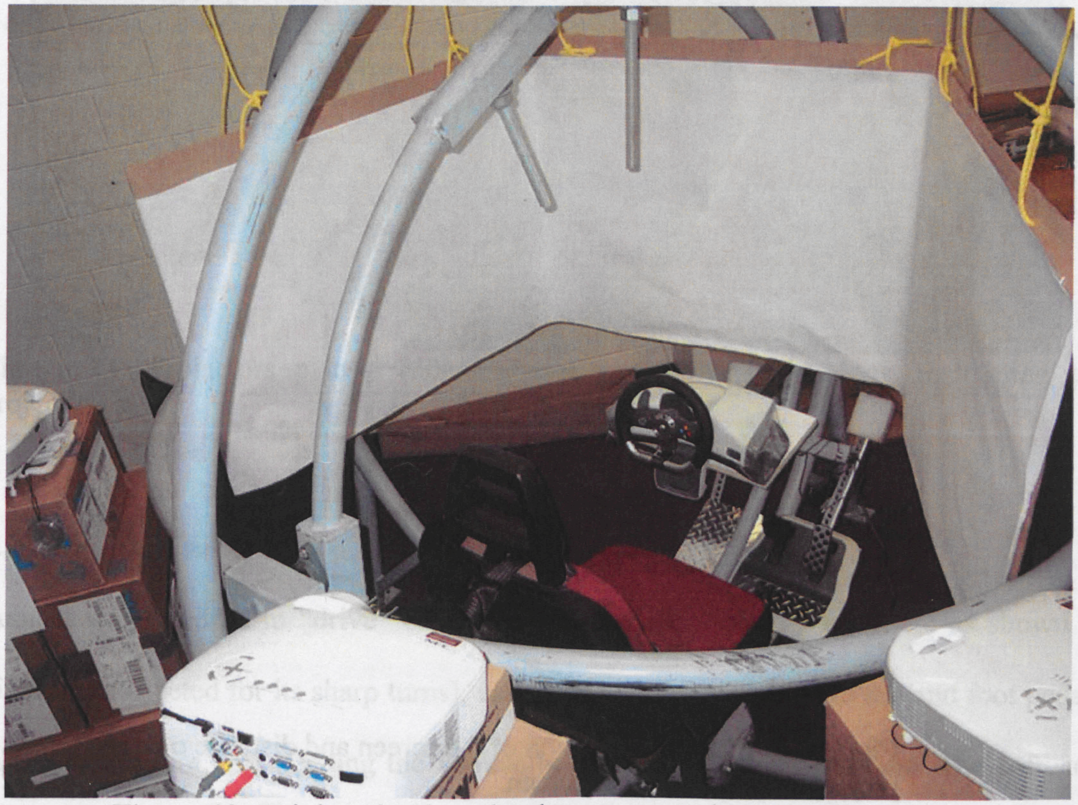


Figure 12: Driving simulator hardware setup with multiple screens.

3.2.1.3.2 Visual Display

The visual display used for this driving simulator was a three-sided or walled large screen with dimension of 80x100cm on each side. One front view and two side views provide frontal field of view of 190° to give the subject the correct depth and speed perception while driving in the simulator. For the three attached screen, three separate identical NEC LT 380 projectors were used which projected three different views of the simulated driving route onto the screens, they were placed 195cm (6.5ft) away from the display screen (see Figure 13), and was placed 150cm above ground to avoid spaceball rings obstructing the projection path during ring movement (see Figure 14). The virtual environment was rendered by the Xbox at 1280x720 pixels and at 60 frames per second with the motion blurs effects and high frame rate that contributes to the realistic sense of speed.

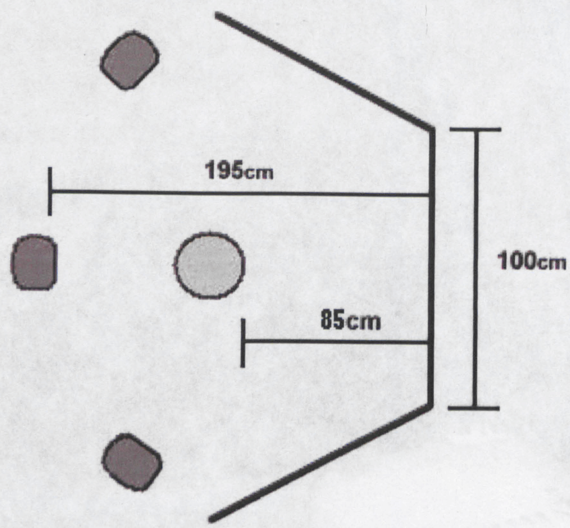


Figure 13: System dimension of the screen and distance of projectors and user from screen.

Figure 14: Projectors placed 150cm above ground to avoid rings obstructing the projection path.

3.2.2 Driving Task

Subject was required to "drive" the vehicle through the VR driving route as shown in Figure 15 (selected for its sharp turns), using the wireless steering wheels and foot pedals mentioned before, and keeping the vehicle in the center of the right lane. The software kept track of the subjects' speed as pressure was applied to the pedals. The space ball was manually moved to match the driver's action. For example, if the subject was accelerating, then the space ball was tilted backwards in its pitch axis to give the subject the feeling of actually accelerating due to inertia. Similarly, if brakes were applied, the space ball was tilted forward. During left and right turns, the space ball was tilted on its roll axis for a more immersive feeling. While the subject was in training, several variables were measured for performance such as head movement, and reaction time as the subject performed the driving task.

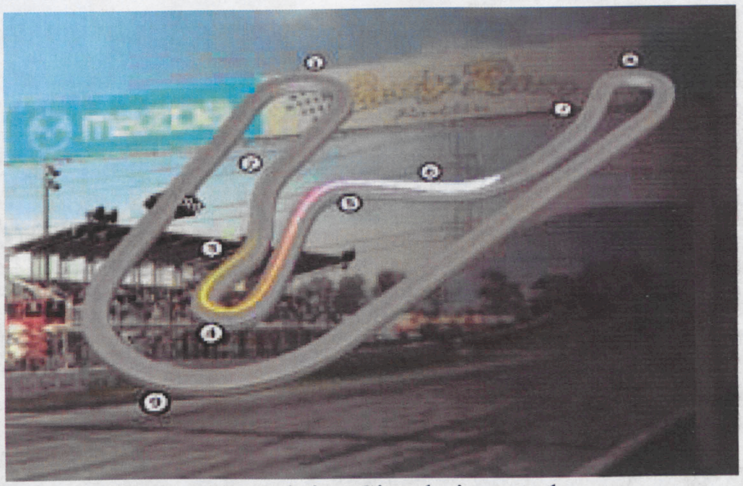


Figure 15: Driving Simulation track route

The training game's activity occurs in a very compelling immersive environment, with sound effects in the game. It provides challenging and unpredictable situations requiring maintenance of attention and cognitive skills at the same time. It combines the learned pattern of visual-vestibular interaction, and is hypothesized to allow for re-learning or re-weighting of the combination of sensory inputs.

3.2.3 Reaction Time

One of the measures to assess the subject's performance was to analyze their reaction time to sudden unexpected physical changes, sound or visual effects before, after and during the VR training. The first exercise included a computer generated reaction time measure where the subject was presented with a test on the computer screen: a quick "click" response with the mouse was required by the subject as soon as the background of a block on the screen changed colors, the time between color change and user's click response is captured through the program and is displayed on the screen. It was hypothesized that during the course of this repeated exercise, the subject's reaction time to sudden cues will be decreased and thereby preparing them for safer driving control (Pre-test). Similarly, this test was also given at the end of every training session to monitor any improvements as a result of the VR training (Post-test). Another exercise was performed on the simulator itself, and these data were only collected twice: on Day one before the training session (Pre-test) and on Day five after the training session. This exercise included measuring the subject's reaction time to sudden external physical changes: while the subject was seated in the simulator, sudden random left/right swings were exerted on the subject and he/she was to steer the driving wheel accordingly (left/right) to compensate for the change of environment. Measurements of the change of seat position and the subjects hand movements were recorded through accelerometers and using MATLAB. The reaction time is extracted to track the improvement of reflex time over the 30 trials in each test.

Additionally, reaction time during training was measured by presenting a sudden sound cue such as a car horn where the subject had to respond by shouting back a number while driving the VR route. This resembles real-life scenario where a sudden car may horn at an intersection to capture ones attention. A stop-watch was used to monitor the subject's response to the stimuli by setting it on at time of sound cue presented and stopping as soon as the subject had made his/her reply. This exercise was believed to help the subject maintain alert attention and help reduce reaction time accordingly to avoid any dangers while on the road.

3.2.4 Head Movements

Furthermore, head movements were recorded in each subject during the VR training. This usually indicates how much an individual is moving when navigating in the virtual environment, in this case the driving route is shown in Figure C1 in Appendix C. To measure head movements, a tri-axis MEMS linear accelerometer was mounted on an adjustable headgear, which was fitted to the subject's head at the beginning of the session.

The data was digitized, amplified, filtered and sampled at 1,000 Hz. Head movement in pitch, yaw and roll are recorded. The data was displayed on a LabVIEW interface and recorded for analysis. Three axes of head movements were recorded as text files and the data was processed and analyzed using MATLAB.

3.2.5 Simulator Sickness Questionnaire

It might seem intuitive that more immersive virtual environments would be best for motor training, but this may not be the case, in part because of the practical difficulty in implementation. Such immersive virtual environments can generate cybersickness [23]. A number of virtual reality studies use a Simulator Sickness Questionnaire (SSQ), given in Appendix A, as an indication of whether the virtual environment is causing discomfort to the subjects [26,27]. The SSQ reports whether the subject encounters any of the simulator sickness symptoms such as headache, fatigue, dizziness, nausea, etc. [28].

Other forms of questionnaires are also used such as the Driving Habits Questionnaire (DHQ), given in Appendix B, to investigate the driving habits such as the amount, distance, condition and experience of driving. This information evaluated together with the simulation data would give more insight into the subject's improvement [29]. The DHQ is used to determine the driver's habits, and it has the potential to be used to classify the performance of different subjects.

Chapter 4

Results and Discussion

During the course of the experiment, driver reflex time data were collected from the VE Forza2 Mortorsport, as the experiment was conducted using the popular 1994 Honda Civic 1.5 VTi, therefore the data results can be used to represent a large population of motor vehicles.

To examine the performance of the designed driving simulator, experimental data were collected over a span of five days. A training session, along with pre- and post tests, was conducted on one subject and specific criteria were analyzed which may assist in examining the common problems encountered by vestibular impaired individuals in a driving scenario; the experimental tests are focused on reaction time tests analysis.

During the course of the training the subject was asked to complete DHQ and SSQ. The DHQ showed that the test subject is an active and experienced driver, familiar with both driving on the highway and high traffic roads. The results of SSQ indicate that the test subject experienced slight nausea after the training phase, which subsided after a few minutes of break. The nausea effect could have been caused by the non-synchronous or delay of movement of the rings with the VE. This is consistent with the theory by Lo reporting that scene oscillation is one of the major contributing factors of cybersickness, the scene movement can introduce a sense of self motion illusion (vection), which can then cause symptoms of cybersickness in the absence of appropriate body movement [30]. Due to the immersive nature of a VE, the visual sensors inform the brain that the environment should be moving with the VE and when there is a conflict, the Central Nervous System (CNS) generates a mismatch between the visual-vestibular senses and proprioceptive senses, and thus causes the nauseating sensation. It has been reported by Lo, that in the presence of scene oscillation, both nausea rating and SSQ scores increased at significantly higher rates than with no oscillation [30].

4.1 Computer-based Reaction Time Test

A color differentiation reaction time test was done on the computer. Using a computer mouse, the subject would need to react to the random color changes on the screen and stop the program timer by clicking on the stop button. For each session, the subject was asked to complete the computer reaction time test 60 times, divided into pre- and post training sets. Therefore, prior to the training session the subject would complete 30 computer reflex trials and another 30 computer reflex trials following the training. A five minute break between training and reflex tests was provided to compensate for the fatigue, to avoid any unwanted factors in the data collected. The test was aimed to determine the subject's reaction time to color changes, which further implied the driver's response time to visual input. Many driving scenarios induce sudden changes in the driver's visual environment, such as the incoming red light or a sudden stop from the vehicle ahead, all of which demand the driver to react with fast response.

Table A, shows the results of the pre training and post training reaction time scores for each of the five day test sessions. It can be observed from Figure 16 that the pre training reflex test has an unexpected increase in reaction time in session two and three. However, in session four and five the computer reflex time has a drastic decline, fitting back to the expected decreasing trend. In comparison to the post training test results, the unexpected increase of reflex time only occurred in session two, and the rest of the results show a linear decreasing trend. The decreasing trend indicates the improvement in visually induced reflex time after training on the VE.

Table A: Pre-Post Computer Reflex Time Comparison.

Computer Reflex		
Session	**Pre**	**Post**
1	0.344	0.331
2	0.356	0.344
3	0.367	0.323
4	0.335	0.317
5	0.331	0.315

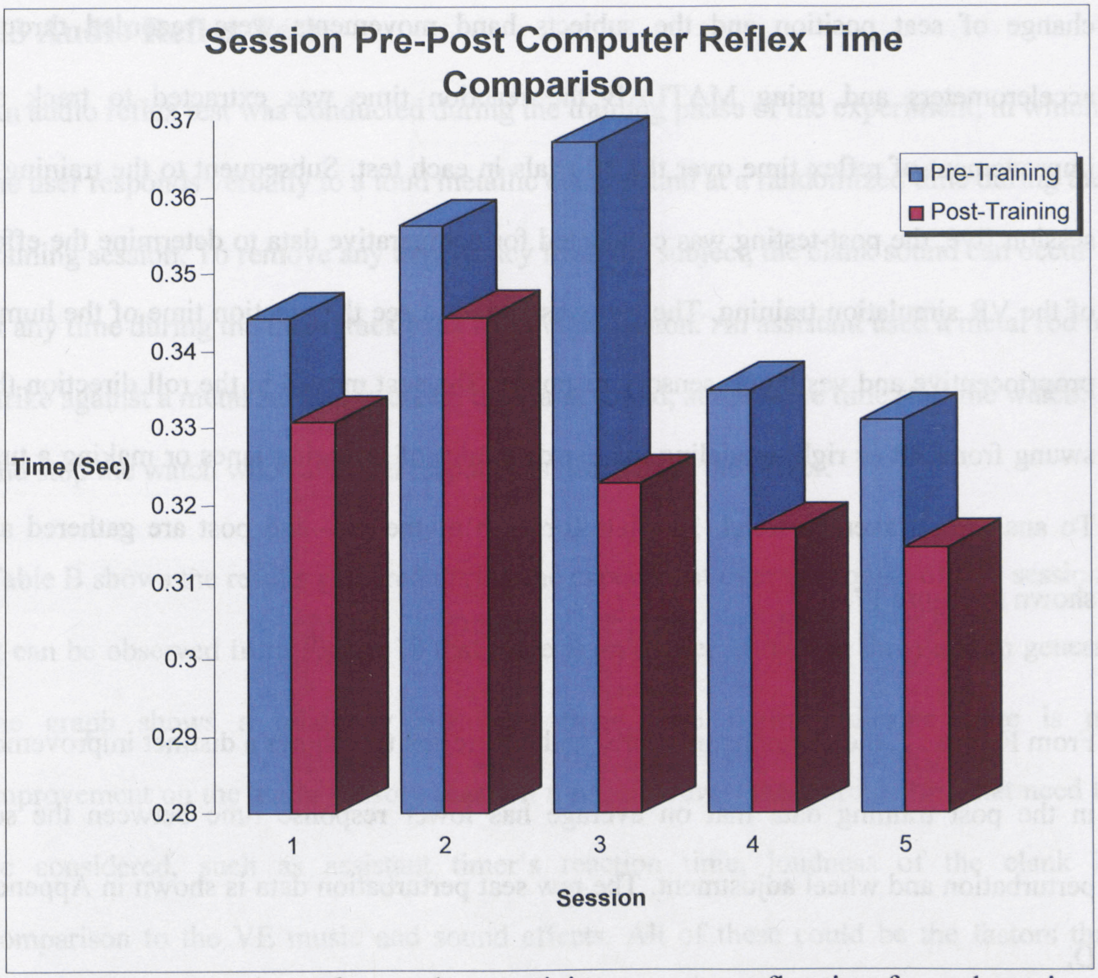


Figure 16: Comparison of pre and post training computer reflex time for each session.

4.2 Seat Perturbation Reaction Time Test

A seat perturbation reaction time pre-testing is taken in session one before the training. In this test the subject was asked to sit in the driver's cockpit during this test with no visual display and the subject is asked to turn the driving wheel to the opposite direction of the seat sway. The movement of the seat moves only in roll axis, therefore to avoid user expectancies, the movement direction was randomly chosen and different in the pre and post sessions. The time between when the seat started to swing and the time of the driving wheel turning is taken as the seat perturbation reaction time. Measurements of the change of seat position and the subjects hand movements were recorded through accelerometers and using MATLAB the reaction time was extracted to track the improvement of reflex time over the 30 trials in each test. Subsequent to the training in session five, the post-testing was conducted for comparative data to determine the effect of the VR simulation training. The test was aimed to see the reaction time of the human proprioceptive and vestibular sensory response. The seat moved in the roll direction that swung from left or right modeling the car dynamics of changing lanes or making a turn. To analyze an average trend, 30 trials for each of the pre- and post are gathered and shown in Figure 17.

From Figure 17, the comparison of pre- and post reflex test shows a distinct improvement in the post training data that on average has lower response time between the seat perturbation and wheel adjustment. The raw seat perturbation data is shown in Appendix D.

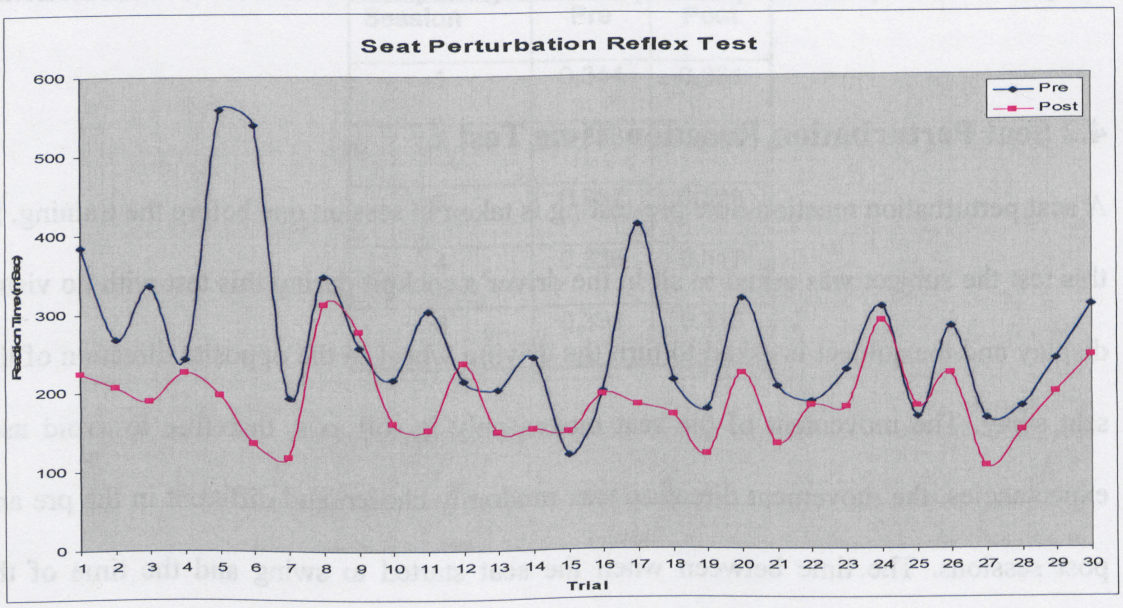


Figure 17: Seat Perturbation Reaction time.

4.3 Audio Reflex Test

An audio reflex test was conducted during the training phase of the experiment, in which the user responds verbally to a loud metallic clank sound at a randomized time during the training session. To remove any expectancy from the subject, the clank sound can occur at any time during the three track runs within the session. An assistant used a metal rod to strike against a metal surface to create the clank sound, at the same time start the watch, and stop the watch when a verbal response is heard from the driver.

Table B shows the results gathered during the experiment over the course of five sessions. It can be observed from Figure 18 that there is an outlier in session three and in general the graph shows a relatively stationary trend. The figure indicates there is no improvement on the audio sensory reaction time. However, there are factors that need to be considered, such as assistant timer's reaction time, loudness of the clank in comparison to the VE music and sound effects. All of these could be the factors that affected the results collected.

Audio reflex time reflects the reaction time that the driver responds to external noise or sound while driving. If this reaction time improves during the training it could be transferred to a real world scenario such as reacting to a car horn to avoid traffic accidents.

Table B: Audio Reflex Time in Sec.

Audio Reflex (Sec.)	
1	1.24
2	1.34
3	1.90
4	1.17
5	1.43

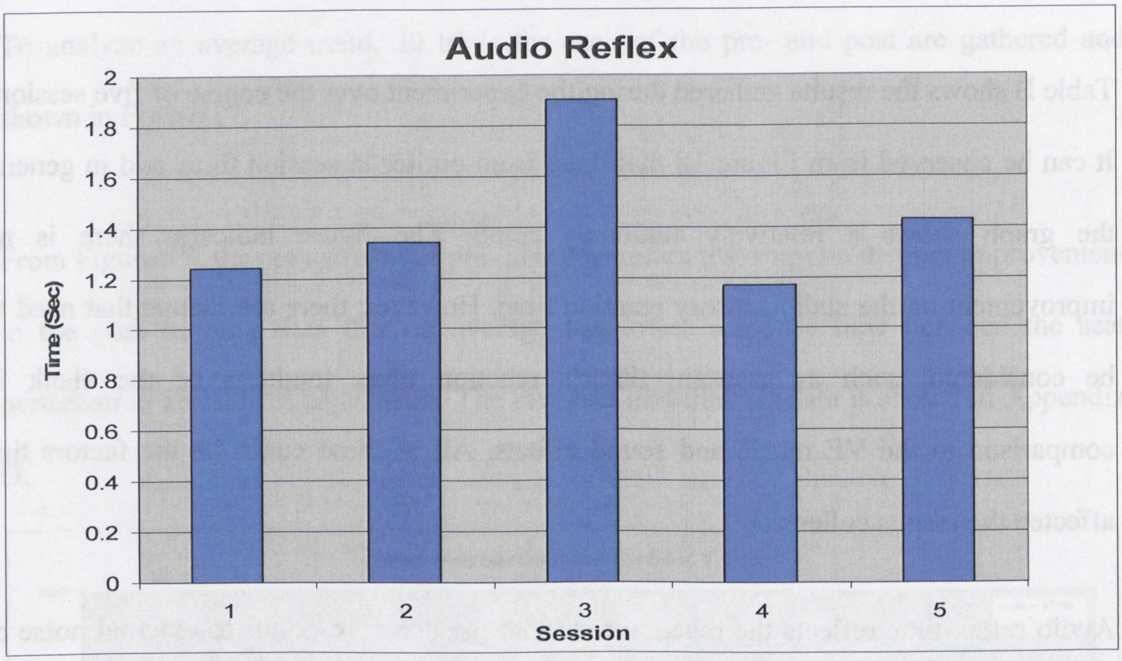


Figure 18: Audio Reflex Time during training sessions.

4.4 Spaceball Driving Simulator assessment

There are several novelties to the spaceball driving simulator in comparison to the existing commercialized driving simulator. One of the most significant differences is the cost; the existing driving simulators range in size and price, from $15,000 non-motion based simulator desktop systems to $3,000,000+ high-fidelity full-vehicle simulators [31].

The break down cost of the non-motorized spaceball moving platform is roughly $10,000, and the cost of other setup equipments mentioned in Chapter 3 is roughly $2,000. Therefore, the total cost of the motion based spaceball driving simulator is $12,000. The primary testing tasks of the spaceball simulator involve psychomotor or cognitive exercises and tests compare to the rule-based testing (whether driver fully stop at stop signs), and thus the spaceball moving dynamic would need to provide the realistic vestibular and proprioceptive senses to the user. The projector based displays generate seamless continuation of virtual environment from front panel to the side panels, creating immersive sensations, a desktop based simulator with seam between screens is show in figure 19.

Figure 19: Desktop driving simulator with seam between screens.

Chapter 5

Conclusion

Driving is an activity that is essential to self sufficiency in our daily life among adolescents and adults. It provides a means of engagement in most of our daily routine, including employment, family care, educational pursuits, social engagement, and entertainment. It would affect the quality of life for a person if the right to drive is taken from him or her. Therefore, research is done and studies are conducted to improve the driving safety such as for those who suffer from vestibular impairments. With virtual reality, there seems to be a solution. The purpose of this project was to see if the proposed driving simulator can improve measures related to driving performance and operational competency of subjects so as to make the driving safer for not only themselves but everyone else on the road.

As mentioned in the previous section, driving requires divided driver attention between multiple activities and being able to react quickly to situations that often arise without warning. It has been found that talking on the cell phone, lack of sleep and aging contribute to reduced attention level [3]. These factors lower concentration and diminish mental awareness of the driving environment.

From the obtained results, indication of the improvement in reaction time in healthy test subject leads to the conclusion that the visual-vestibular-proprioceptive virtual driving simulator could provide treatment for vestibular impaired patients.

The system has been developed with preliminary tests for proof of concept. Further testing will be required to determine the system performance characteristics. Application specific development will be possible after more human testing and user feedback. Additional modification could include a set of motorized ring actuators that will be able to replicate the six degrees of freedom to mimic the realistic driving conditions.

Furthermore, the system can be used to investigate a variety of driving research factors, such as effects of alcohol consumption, lack of sleep, and head-eye coordination, etc. It can also be used as an exposure therapy tool for post-accident patients to alleviate their fear of driving.

Appendix A

Simulator Sickness Questionnaire

Please indicate the degree to which you are experiencing the following symptoms:

General discomfort	None	Slight	Moderate	Severe
Fatigue	None	Slight	Moderate	Severe
Headache	None	Slight	Moderate	Severe
Eyestrain	None	Slight	Moderate	Severe
Difficulty focusing	None	Slight	Moderate	Severe
Increased salivation	None	Slight	Moderate	Severe
Sweating	None	Slight	Moderate	Severe
Nausea	None	Slight	Moderate	Severe
Difficulty concentrating	None	Slight	Moderate	Severe
Fullness of head1	None	Slight	Moderate	Severe
Blurred vision	None	Slight	Moderate	Severe
Dizzy (eyes open)	None	Slight	Moderate	Severe
Dizzy (eyes closed)	None	Slight	Moderate	Severe
Vertigo 2	None	Slight	Moderate	Severe
Stomach awareness	None	Slight	Moderate	Severe
Burping	None	Slight	Moderate	Severe

1 Fullness of head refers to an awareness of pressure in the head.
2 Vertigo refers to a loss of orientation with respect to vertical or upright.

Source: Kennedy et al (1993)

Appendix B

Driving Habits Questionnaire (DHQ)

Source: Owsley et al (1999) [31]

Interviewer: "Now I'm going to ask you some questions about driving."

<u>Current Driving</u>

1. Do you currently drive?

   ______ (1) yes **(go to question #4)**
   ______ (0) no **(go to questions #2 and #3 only)**

1. ☐

2. Why did you stop driving?
   (Wait for the subject's spontaneous reply; write it in space below.)

   ____
   ____
   ____
   ____

2. Copy text

3. When is the last time you drove? ________________ (month/year)
   (If within 1 year, go to question #25)

3. ☐

4. Do you wear glasses or contact lenses when you drive?

   ______ (1) yes
   ______ (0) no

4. ☐

5. Do you wear a seatbelt when you drive? Would you say:

   ______ (1) always
   ______ (2) sometimes
   ______ (3) never

5. ☐

6. Which way do you prefer to get around?

_______(3) drive yourself
_______(2) have someone drive you
_______(1) use public transportation or a taxi

6. ☐

7. How fast do you usually drive compared to the general flow of traffic? Would you say:

_______(5) Much faster
_______(4) Somewhat faster
_______(3) About the same
_______(2) Somewhat slower
_______(1) Much slower

7. ☐

8. Has anyone suggested over the past year that you limit your driving or stop driving?

_______ (1) yes
_______ (0) no

8. ☐

9. How would you rate the quality of your driving? Would you say:

_______(5) Excellent
_______(4) Good
_______(3) Average
_______(2) Fair
_______(1) Poor

9. ☐

10. If you had to go somewhere and didn't want to drive yourself, what would you do? Would you:

_______(1) Ask a friend or relative to drive you
_______(2) Call a taxi or take the bus
_______(3) Drive yourself regardless of how you feel
_______(4) Cancel or postpone your plans and stay home
_______(5) Other (specify):_______________________________________

10. ☐

Exposure

11. In an average week, how many days per week do you normally drive?

_______ number of days per week

11. ☐

12-14. Please pause for a moment and consider all the places you drive in a typical week. (Pause) Now tell me those places.

Place	How many times a week		Estimate Miles from home (one-way)		Total Miles
______Store	______	X	______	=	______
______Church	______	X	______	=	______
______Work	______	X	______	=	______
______Relative's House	______	X	______	=	______
______Friend's House	______	X	______	=	______
______Out to eat	______	X	______	=	______
______Appointments (e.g., doctor, hair)	______	X	______	=	______

Now, are there any other places you go in a typical week?

Others

______	______	X	______	=	______
______	______	X	______	=	______
______	______	X	______	=	______
				subtotal	______
					X 2

(12) ☐ Total # of places traveled to

(13) ☐ Total trips

(14) ☐ Total Miles Driven

15-16. Please list your friends and/or family members that you regularly travel with in a car over the past year.

(1)_________ I am always the driver when I go out in a car.
(add a "0" to #15 and a "1" to #16)

When traveling with this individual, who usually drives?

Relationship	Driving
(A) ______________________	______(1) I am usually the driver ______(3) This person is usually the driver ______(2) About half and half
(B) ______________________	______(1) I am usually the driver ______(3) This person is usually the driver ______(2) About half and half
(C) ______________________	______(1) I am usually the driver ______(3) This person is usually the driver ______(2) About half and half
(D) ______________________	______(1) I am usually the driver ______(3) This person is usually the driver ______(2) About half and half
(E) ______________________	______(1) I am usually the driver ______(3) This person is usually the driver ______(2) About half and half
(F) ______________________	______(1) I am usually the driver ______(3) This person is usually the driver ______(2) About half and half

Please use reverse side for additional people

(15) ☐
Total number of individuals

(a "0" if the person always drives self)

(16) ☐
Total dependency score = Average of numbers above

(a "1" if the person always drives self)

<u>Avoidance</u> "Now I am going to ask you some more questions about your driving."

Interviewer: Use <u>Answer Sheet A</u> for questions <u>17 thru 24</u>

17a) During the past 3 months, have you driven when it is raining?

________Yes **(go to 17b)** ________No **(go to 17c)**

17b) Would you say that you drive when it is raining with:
(Please check only **one** answer)

5______No difficulty at all
4______A little difficulty
3______Moderate difficulty
2______Extreme difficulty

17c) Is it mostly because of your visual problems that you do not drive when it is raining?

1________Yes **(go to 18a)** ________No **(go to 18a)**

17. ☐

18a) During the past 3 months, have you driven alone?

________Yes **(go to 18b)** ________No **(go to 18c)**

18b) Would you say that you drive alone with:
(Please check only **one** answer)

5______No difficulty at all
4______A little difficulty
3______Moderate difficulty
2______Extreme difficulty

18c) Is it mostly because of your visual problems that you do not drive alone?

1________Yes **(go to 19a)** ________No **(go to 19a)**

18. ☐

19a) During the past 3 months, have you parallel parked?

________Yes **(go to 19b)** ________No **(go to 19c)**

19b) Would you say that you parallel park with:
(Please check only **one** answer)

5______No difficulty at all
4______A little difficulty
3______Moderate difficulty
2______Extreme difficulty

19c) Is it mostly because of your visual problems that you do not parallel park?

1________Yes **(go to 20a)** ________No **(go to 20a)**

19. ☐

20a) During the past 3 months, have you made left-hand turns across oncoming traffic?

_________Yes (go to 20b) _________No (go to 20c)

20b) Would you say that you make left-handed turns in traffic with:
(Please check only **one** answer)

5______No difficulty at all
4______A little difficulty
3______Moderate difficulty
2______Extreme difficulty

20c) Is it mostly because of your visual problems that you do not make left-hand turns across oncoming traffic?

1________Yes (go to 21a) _________No (go to 21a)

20. ☐

21a) During the past 3 months, have you driven on interstates or expressways?

_________Yes (go to 21b) _________No (go to 21c)

21b) Would you say that you drive on interstates or expressways with:
(Please check only **one** answer)

5______No difficulty at all
4______A little difficulty
3______Moderate difficulty
2______Extreme difficulty

21c) Is it mostly because of your visual problems that you do not drive on interstates?

1________Yes (go to 22a) _________No (go to 22a)

21. ☐

22a) During the past 3 months, have you driven on high-traffic roads?

_________Yes (go to 22b) _________No (go to 22c)

22b) Would you say that you drive on high-traffic roads with:
(Please check only **one** answer)

5______No difficulty at all
4______A little difficulty
3______Moderate difficulty
2______Extreme difficulty

22c) Is it mostly because of your visual problems that you do not drive on high traffic roads?

1________Yes (go to 23a) _________No (go to 23a)

22. ☐

23a) During the past 3 months, have you driven in rush-hour traffic?

_________Yes (go to 23b)   __________No (go to 23c)

23b) Would you say that you drive in rush hour traffic with:
(Please check only one answer)

5______No difficulty at all
4______A little difficulty
3______Moderate difficulty
2______Extreme difficulty

23c) Is it mostly because of your visual problems that you do not drive in rush-hour traffic?

1________Yes (go to 24a)   _________No (go to 24a)

23. ☐

24a) During the past 3 months, have you driven at night?

_________Yes (go to 24b)   __________No (go to 24c)

24b) Would you say that you drive at night with:
(Please check only one answer)

5______No difficulty at all
4______A little difficulty
3______Moderate difficulty
2______Extreme difficulty

24c) Is it mostly because of your visual problems that you do not drive at night?

1________Yes (go to 25)   _________No (go to 25)

24. ☐

Crashes and Citations

25. How many accidents have you been involved in over the past year when you were the driver? Please tell me the number of all accidents, whether or not you were at fault.

____ accidents

25. ☐

26. How many accidents have you been involved in over the past year when you were the driver where the police were called to the scene?

______ accidents

26. ☐

27. How many times in the past year have you been pulled over by the police, regardless of whether you received a ticket?

______ times

27. ☐

28. How many times in the past year have you received a traffic ticket (other than a parking ticket) where you were found to be guilty, regardless of whether or not you think you were at fault?

______ times

28. ☐

<u>Driving Space</u>

29. During the past year, have you driven in your immediate neighborhood?

(1)_____ yes
(0)_____ no

29. ☐

30. During the past year, have you driven to places beyond your neighborhood?

(1)_____ yes
(0)_____ no

30. ☐

31. During the past year, have you driven to neighboring towns?

(1)_____ yes
(0)_____ no

31. ☐

32. During the past year, have you driven to more distant towns?

(1)_____ yes
(0)_____ no

32. ☐

33. During the past year, have you driven to places outside the state of Alabama?

(1)_____ yes
(0)_____ no

33. ☐

34 During the past year, have you driven to places outside the southeast region?

(1)_____ yes
(0)_____ no

34. ☐

Appendix C

Sample Head-movement Figure

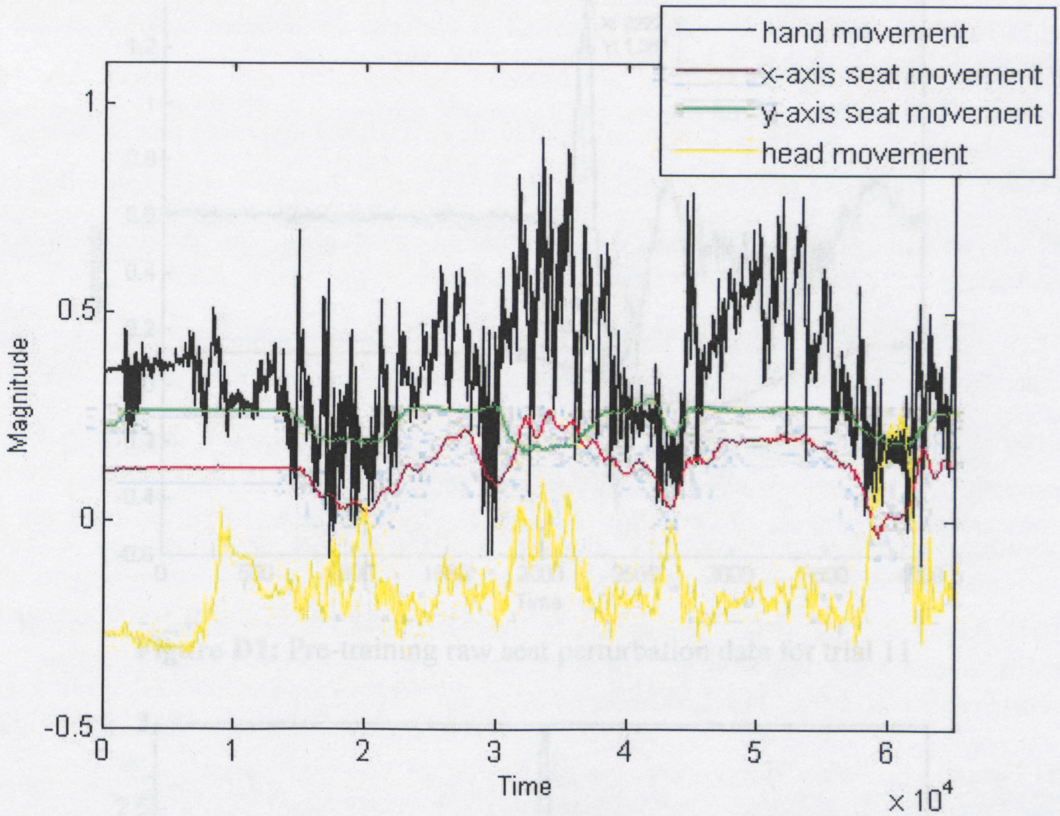


Figure C1: In training sample head-movement with seat movements and hand movement

In Figure C1, a sample of the complete test data taken during the training session. Black line shows the hand movement controlling the steering wheel, a dip in magnitude indicates the hand movement to the right and a rise in the magnitude shows the hand movement to the left. The green line and red line displays the x (roll) and y (pitch) axis of seat perturbation movement respectively, and similarly a dip indicates right movement and left movement is shown by a rise. The head movement is show by the yellow line;

alternatively, a rise shows the head is looking to the right and a dip shows the head moving to the left.

Appendix D

Sample Raw Seat Perturbation Figures

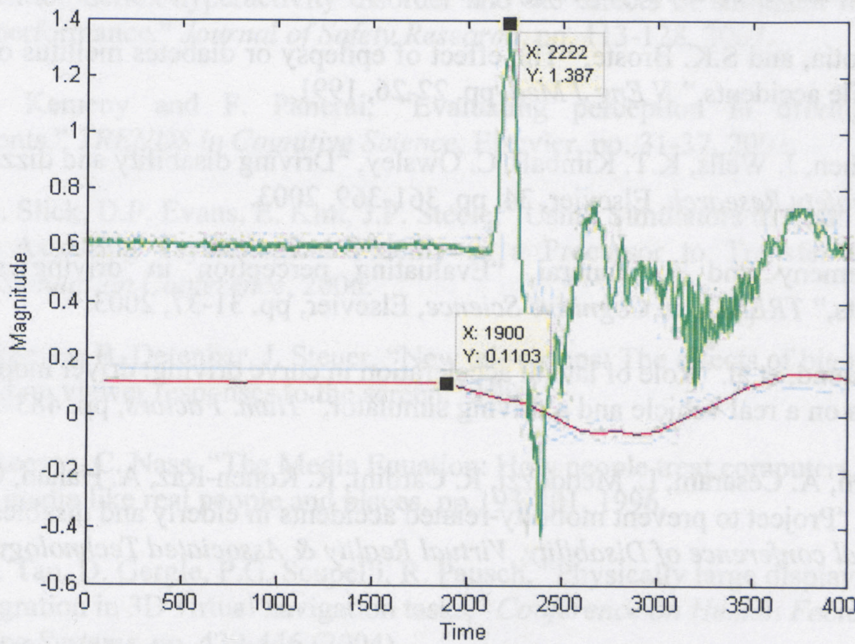


Figure D1: Pre-training raw seat perturbation data for trial 11

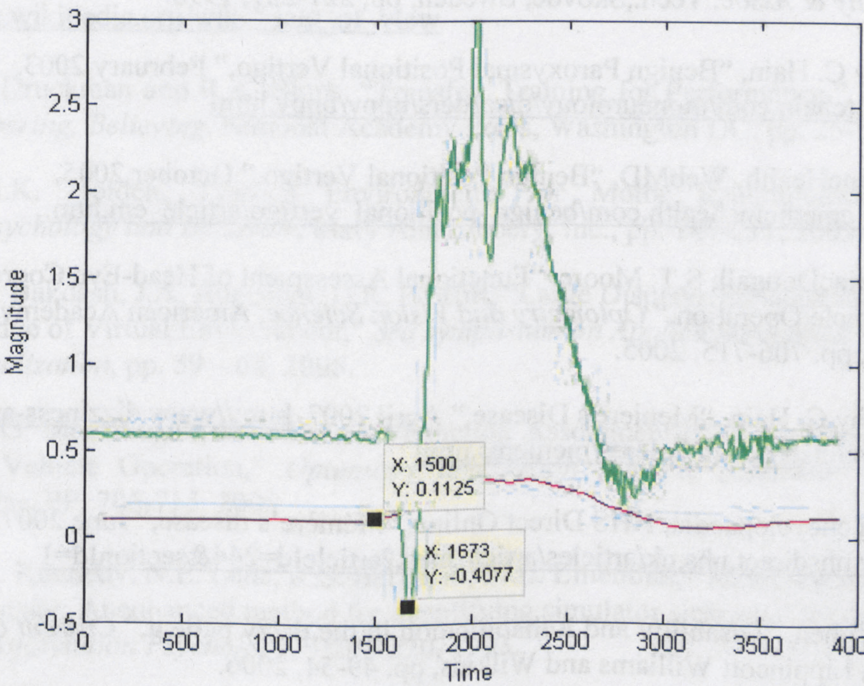


Figure D2: Post-training raw seat perturbation data for trial 11

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