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Using an eye-tracker as an assessment tool for concussion diagnosis and fitness to drive in teens

Atefeh Katrahmani
Western New England University

USING AN EYE-TRACKER AS AN ASSESSMENT TOOL FOR CONCUSSION DIAGNOSIS AND FITNESS TO DRIVE IN TEENS

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ATEFEH KATRAHMANI

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A Dissertation Presented by:

ATEFEH KATRAHMANI

Approved as to style and content by

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Dr. Matthew Romoser, Assistant Professor of IE/EM Date

____ ________

Dr. Christian Salmon, Chair and Associate Professor of IE/EM Date

____ ________

Dr. Seyed Ahmad Niknam, Assistant Professor of IE/EM Date

____ ________

Dr. Robert Gettens, Associate Professor of Biomedical Engineering Date

ABSTRACT

Yearly, more than 1 million concussions are diagnosed in the United States. Although there are many cognitive tests that are beneficial for concussion diagnosis, there is no single test that claims it can diagnose concussions with a high degree of confidence. Moreover, because a diagnosis of concussion often comes with a prescribed moratorium on driving, concussed patients are also motivated to know when they are ready to be cleared to drive again. Lacking accurate diagnosis tests for concussions, physicians often have to rely on subjective assessments to decide when it is acceptable for a patient to resume driving.

The primary purpose of this research project was to provide a diagnostic tool for concussion using an eye-tracker. The eye-tracker was used to assess eye movement patterns of the patients with a concussion. The visual cognitive tests results showed that concussions can affect the ability to focus on a moving object and keep the eyes concentrated on the objects. Concussions also cause patients to be less able to establish and maintain focus on fixation points and they demonstrate longer reaction times. A diagnosis method for concussion has been created.

The second goal of the study was to assess whether or not a patient should be restricted from driving after a concussion. Drivers with concussion symptoms tended to drive relatively faster and spend more time looking at their environment. They had more undeliberate eye movements. With regard to hazard anticipation skills, in general, the results demonstrate that when encountering a

potential hazard, a healthy teen driver was more likely to be able to control the situation. They were more able to scan for the hazard showing greater numbers of fixations.

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LIST OF ACRONYMS

Center for Advanced Training Research, and Naturalistic Studies	ATRANS
Balance Error Scoring System	BESS
Connecticut Children's Medical Center	CCMC
Dorsolateral Prefrontal Cortex	DLPFC
Department of Motor Vehicles	DMV
Functional Assessment Measure	FAM
Functional Independence Measure	FIM
Immediate Post-Concussion Assessment and Cognitive Test	ImPACT
King Devick test	K-D test
Mobile Driver Assessment & Training Simulator	MODATS
Mild Traumatic Brain Injury	mTBI
Post-Concussion Symptom Scale	PCSS
Standardized Assessment of Concussion	SAC
Sport Concussion Assessment Tool, Third Edition	SCAT3
Traumatic Brain Injury	TBI
Vestibular/Ocular Motor Screening	VOMS
Vestibular Ocular Reflex	VOR

LIST OF DEFINITIONS

Smooth pursuit: eye movements allow the eyes to closely follow a moving object. It is one of two ways that visual animals can voluntarily shift gaze, the other being saccadic eye movements.

Target acquisition: is the detection, identification, and location of a target in sufficient detail to permit the effective employment of lethal and non-lethal means. The term is used for a broad area of applications.

Heat map: a representation of data in the form of a map or diagram in which data values are represented as colors.

Gaze plot: Displays movement sequence, order and duration of gaze fixation. Displays gaze motion of each respondent separately.

Anti-saccade: task is a gross estimation of injury or dysfunction of the frontal lobe, by assessing the brain's ability to inhibit the reflexive saccade.

Simulator sickness: Can be described as physical discomfort experienced when "driving" a simulated vehicle that is caused by incompatible signals from visual, auditory, and motion systems.

Austroads: is the Association of Australian and New Zealand Road Transport and Traffic Authorities.

Vergence disorder: The two eyes converge to point to the same object. A convergence disorder is a disorder on the simultaneous movement of both eyes in opposite directions to obtain or maintain single binocular vision.

Saccadic latency: the time taken from the appearance of a target to the beginning of a saccade in response to that target.

Disengaging attention: The failure of disengagement processes is inferred in neurologically damaged patients from their performance on attentional cuing tasks.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Problem

While there are no precise statistics about the number of sports-related concussions, emergency rooms report 1.4 to 3.8 million sports-related mTBI (mild Traumatic Brain Injury) patients in the United States annually (Bazarian, Veazie, Mookerjee, & Lerner, 2006a; Halstead, Walter, & others, 2010; Langlois, Rutland-Brown, & Thomas, 2004; Torres et al., 2013a). Diagnosing concussions can be difficult because many concussion assessment tools are subjective and their results are open to interpretation. Currently, self-reporting is the only way to evaluate concussion in many cases (H Daneshvar, Picano, David, & c McKee, 2014), and studies showed that this evaluation technique is not an accurate method of concussion assessment (Kerr, Marshall, & Guskiewicz, 2012).

Complicating matters is the fact that concussed patients resist a positive diagnosis because they fear the impact such a diagnosis will have on their day to day lives or that it will keep them from preferred activities such as sports (Chrisman, Quitiquit, & Rivara, 2013) or driving. Research shows 43% of athletes with a history of concussions hide symptoms in order to be able to return to playing (Register-Mihalik et al., 2013; Torres et al., 2013a). The cognitive tests that are commonly used for concussion assessment have some issues. One of the main issues is the lack of a baseline test for some test methods.

Since every person's brain function is unique, scientists are not able to use the baseline test to compare one patient to another. In addition, the brain's functionality changes over time (Cartensen, 2007; Kerr et al., 2016). Therefore, before using the baseline, there is a need to ensure sure that the existing baseline test for the individual is valid.

Concentration of both eyes on a single point in space requires complete convergence and research shows that up to 90% of concussed patients show symptoms of convergence disorders (Ciuffreda et al., 2007; Dora Szymanowicz OD et al., 2012; Kapoor & Ciuffreda, 2002; Thiagarajan, Ciuffreda, & Ludlam, 2011). Therefore, the investigation of eye movements can be useful in diagnosing concussions. Eye movements can also be used as a measurement tool for assessing the healing process, evaluating fitness to drive, and assessing whether or not a patient's healing has progressed enough to be able to go back to daily life.

The present research will address a new perspective of using eye-tracking as an assessment tool for concussed teens whose symptoms last for more than two weeks. This will be accomplished by executing simulator based and non- simulator based cognitive tests on concussed and non-concussed patients and comparing the results.

1.2 Statement of the problem

Yearly, more than 1 million concussions are diagnosed in the United States (Bazarian, Veazie, Mookerjee, & Lerner, 2006b; Torres et al., 2013b), with the bulk of them occurring while playing sports. Because of a sports culture that often encourages "walking it off and getting back out there," many concussed athletes prefer to hide their injury (Torres et al., 2013b) in order to return to a game sooner. Although there are many cognitive tests that are beneficial for diagnosing concussions, there is no single test that can diagnose concussions with a high degree of confidence.

More than returning to play, because a diagnosis of concussion often comes with a prescribed moratorium on driving, concussed patients are also motivated to know when they are ready to be cleared to drive again. Lacking accurate diagnosis tests for concussions, physicians often have to rely on subjective assessments to decide when it is acceptable for a patient to resume driving.

Specifically, this study attempted to answer the following questions:

1. Is it possible to use a driving simulator to assess concussed patients, or will they experience high rates of simulator sickness?
2. From a diagnostic aspect, do non-simulator based assessments show a significant difference between the concussed and non-concussed participants?
3. Do simulator based assessment tools demonstrate a significant decline in driving performance of teen drivers after a concussion?

1.3 Purpose

The primary purpose of the present research was to use a device that tracks and records eye movement to develop an objective method to assess concussions' impact on brain function. Moreover, the method enables documentation of patients' progress in healing. In the end, the goal was to have a device that therapists and physicians can use to assist in the assessment of fitness to drive following a concussion. The research allowed the Connecticut Children's Medical Center (CCMC) to set up eye-tracking test equipment and to provide an accurate method to diagnose and treat a concussion.

1.4 Hypotheses

The primary hypotheses tested as a part of this research include the following:

1. **Hazard Anticipation**:

   Concussed teens will be able to accurately anticipate significantly fewer hazards than non-concussed teens.

2. **Eye movement patterns**

   a. Concussed participants will have a significantly more random pattern of eye movement in comparison with non-concussed participants

   b. Concussed teens will perform significantly worse on visual cognitive tests than non-concussed teens

1.5 Significance of the Project

The primary beneficiaries of this research are concussed patients. It is very important for patients and their families to have a clear understanding of their injury and its potential implications on safety so they will be more willing to cooperate with treatment. Another group that benefits from this research is medical doctors and occupational therapists that specialize in concussions. This research provides them with a relatively accurate diagnostic method for assessing fitness-to-drive following a concussion. Until now, concussion diagnosis was based upon doctor's judgment and a few physical and cognitive tests. These tests cannot directly prove if the patient is concussed, or not.

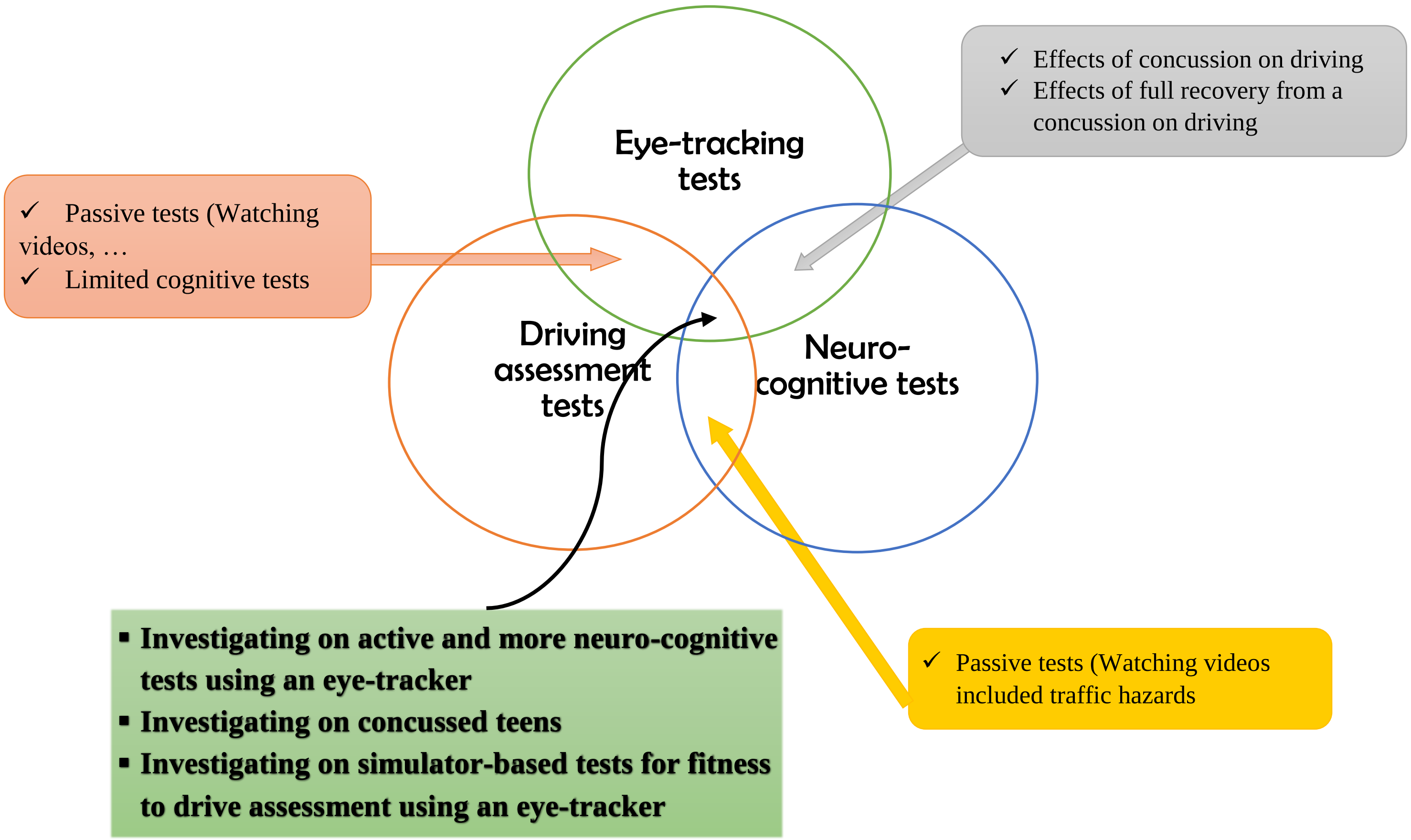

Figure 1- Venn diagram of the research gaps

CHAPTER 2

LITERATURE REVIEW

2.1. Definitions and Symptoms

In the United States, between 1.6 to 3.8 million sports-related concussive injuries occur yearly (Langlois, Rutland-Brown, & Wald, 2006; McCrory et al., 2013). Concussion is known to be a type of Mild Traumatic Brain Injury (mTBI). This type of brain injury occurs from a sudden biomechanical force on the brain, which causes the brain to hit the inside wall of the skull. In the United States, the term mild traumatic brain injury has been used interchangeably with concussion in various literatures (Carroll et al., 2004, McCrory et al., 2009), but in sports medicine, concussion is a subset of mild traumatic brain injury. This dissertation used the term concussion as it is used in sports medicine.

The very first definition of concussion considered it as a long-lasting injury with severe symptoms. In 1965, scientists characterized it as an injury with loss of consciousness fewer than five minutes (Cook et al., 1996). In 1986, Cantu suggested post-traumatic amnesia as an indication of concussion. However in 1991, Kelly and colleagues revised Cantu's idea and suggested loss of consciousness to be a potential symptom instead of a mandatory symptom (Kelly et al., 1991). In 2008, the Third international Conference on Concussion in sports (McCrory et al., 2009) submitted a wide range of symptoms as potential symptoms. The symptoms included headaches, nausea, dizziness, sleep and visual disturbance, and amnesia. The Centers for Disease Control released a consensus statement on sports-related concussion making it the official definition of concussion at the Third International Conference on Concussion in Sport held in Zurich, Switzerland (McCrory et al., 2009). However, in spite of great efforts to set up an appropriate definition, there are still a lot of undefined gaps in the current definition. For instance, patients do not necessarily show all the symptoms, and most of the diagnoses are dependent on patients' self-reports rather than having a measurable, reliable diagnosis tool. This study used the current definition of concussion (H Daneshvar et al., 2014, p. 3) and emphasize visual disturbance symptoms to accomplish its goal. "Some people have the misconception that concussion only happens when you black out after a hit to the head or when the symptoms last for a while. However, in reality, a concussion has occurred anytime you have had a blow to the head that caused you to have symptoms for any amount of time. These include: blurred or double vision, seeing stars, sensitivity to light or noise, headache, dizziness or balance problems, nausea, vomiting, trouble sleeping, fatigue, confusion, difficulty remembering, difficulty concentrating, or loss of consciousness. Whenever anyone gets a ding or their bell rung that too is a concussion." However, there is still a serious lack of knowledge about the definition of concussion among athletes. McDonald and colleagues state that only 66% percent of student athletes receive prior concussion education (McDonald, Burghart, & Nazir, 2016). Moreover, parents need to have more knowledge about concussions and familiarity with concussion symptoms. Sometimes the concussion shows itself a few hours after it occurred, which is the time that student athletes are at home with their parents.

Normally, concussion symptoms mostly disappear within 24 hours post-injury and will improve significantly after two weeks. Studies show that the majority of concussed patients will recover within four weeks of injury (Meehan, d'Hemecourt, Collins, & Comstock, 2011; Meehan, d'Hemecourt, & Comstock, 2010), while other studies show that concussion will completely disappear after three months (Guskiewicz et al., 2003; Michael McCrea et al., 2003, 2009; Meehan et al., 2011). But sometimes symptoms such as vision issues, hearing problems, headache, fatigue, dizziness, forgetfulness, neck pain, and sleep disturbances last for almost a year after the injury (Gordon, Dooley, & Wood, 2006; Hartvigsen, Boyle, Cassidy, & Carroll, 2014; Lau, Collins, & Lovell, 2012; Weiss, Stern, & Goldberg, 1991).

2.2. Diagnosis

While there is a functional disturbance and trauma to the brain due to the concussive event, follow up neuroimaging typically shows no structural impairment to the brain. Therefore, it is difficult to diagnose concussions because neuro-images of the brain usually do not show signs of any physical brain damage. Concussion diagnosis has always been a challenge; it does not necessarily include a loss of consciousness (Carroll et al., 2004). However, while physical damage usually is not found, there are certain psychological and physiological symptoms and signs that manifest themselves. Among these are vision-related symptoms, which can be measured easily (McCrory et al., 2009; Register-Mihalik et al., 2012). One of the signs of healthy vision is object motion anticipation based on past experience (Barnes, 2008). Anticipating motion needs attention, anticipation skills, and memory (Ventura, Jancuska, Balcer, & Galetta, 2015). This dissertation used knowledge about visual deficits in concussed patients to introduce a new tool for diagnosis.

For a more accurate diagnosis of an mTBI, a patient’s fluids such as blood, saliva, CSF, serum, and urine may be examine for the presence of glial fibrillary acidic protein (GFAP) and ubiquitin C-terminal hydrolase-L1. The level of sensitivity and specificity of these biomarkers shows whether someone has a concussion.

Measuring concussion recovery time is still a challenge (Kerr et al., 2016). Some studies attempted to identify a prediction method for concussion recovery time based on factors such as age, history of previous concussion, coma duration and existing symptoms such as headache (Babcock et al., 2013; Chrisman, Rivara, Schiff, Zhou, & Comstock, 2013; Lau et al., 2012). Chrisman and colleagues showed that patients with symptoms such as loss of consciousness, history of previous concussion, amnesia, and dizziness are more likely to have a recovery duration of more than seven days. They also showed that patients with four or more symptoms were twice as likely to have prolonged concussion duration (longer than seven days). Amnesia, subjective fogginess, and dizziness at the time of injury are other factors that make concussion recovery time longer (Iverson, Gaetz, Lovell, & Collins, 2004; Lau, Collins, & Lovell, 2011; Michael McCrea et al., 2013). Patients who return to work following recovery from an mTBI reported that they need greater effort and experience more fatigue compared to before their injury (Wrightson & Gronwall, 1981).

Generally speaking, greater symptom severity at the time of concussion will prolong the duration of the concussion (Meehan, O'Brien, Geminiani, & Mannix, 2015). Research shows that there is no correlation between the number of life time TBI's and severity of the injury or number of symptoms (Ivins, Kane, & Schwab, 2009). Almost 30% of the patients with mTBI experienced at least one new post-concussion symptom or intensification of an existing post injury symptom three months after the injury (Levin & Diaz-Arrastia, 2015). There is little evidence that show mTBI cognitive symptoms last longer than six months (Carroll et al., 2014).

Usually, sports clinicians decide on the optimal rest period based on the symptoms' severity and the patients' self-reports. Therefore, there is no specified rest period for concussed patients. Studies show that not only does long rest and avoiding all daily activities not facilitate the recovery time, but it also may make the recovery time longer (Andreassen, Bach-Nielsen, Hechscher, & Lindeneg, 1957; Buckley, Munkasy, & Clouse, 2015; Craton & Leslie, 2014; De Kruijk, Leffers, Meerhoff, Rutten, & Twijnstra, 2002; DiFazio, Silverberg, Kirkwood, Bernier, & Iverson, 2016; Gibson, Nigrovic, O'Brien, & Meehan III, 2013; Majerske et al., 2008; Moor et al., 2015; Silverberg & Iverson, 2013; Thomas, Apps, Hoffmann, McCrea, & Hammeke, 2015). On the other hand, demanding physical or mental activity such as returning to school after partial fading of concussion symptoms may cause the re-emergence of concussion symptoms (Aubry et al., 2002; Balasundaram, Sullivan, Schneiders, & Athens, 2013; Brown et al., 2014; Covassin, Crutcher, & Wallace, 2013; DeMatteo, Volterman, et al., 2015; Leddy, Baker, Kozlowski, Bisson, & Willer, 2011; Symonds, 1928). Some experiments suggest that the optimal length of post-concussive rest varies by patient age. Children, in comparison with adults, need more rest and have a prolonged recovery time (DeMatteo, Stazyk, et al., 2015; McCrory et al., 2013). Student patients who decide to attend school full time and engage in daily academic activities experience a higher risk of symptom spikes on the following day (Silverberg et al., 2016). Recovery time from an mTBI for athletes is shorter than for the general population (Levin & Diaz-Arrastia, 2015). Eighty to ninety percent of the post-concussion symptoms in adult athletes who receive a concussion for the first time normally disappear within the first seven to ten days of the injury (McCrory et al., 2013).

Evidence suggests that in comparison with male student athletes, female student athletes have a longer recovery period and need more post-injury treatment (Kostyun & Hafeez, 2015). Female athletes are also reported to sustain concussions or be re-concussed at higher rates than male athletes (Dick, 2009; Marar, McIlvain, Fields, & Comstock, 2012).

Receiving a concussion, the brain metabolism will be affected negatively because of the changes in ionic gradients, malfunction of sodium, potassium, and calcium channels, imbalance and inflammation of neurotransmitters (Giza & Hovda, 2001). However, studies using other techniques such as susceptibility-weighted imaging and diffusion tensor imaging (DTI) have found structural abnormalities in white matter and cerebral microvasculature (McAllister et al., 1999; Slobounov et al., 2011; Yuh et al., 2014). Some of the concussed patients show tract lesions as post-concussive symptoms (Maruta, Lee, Jacobs, & Ghajar, 2010). The magnetic resonance imaging (MRI) technique of diffusion tensor imaging (DTI) can detect these injuries (Arfanakis et al., 2002; Huisman et al., 2004; Kraus et al., 2007; Ptak et al., 2003).

DTI can provide quantitative representation of basic features of tissue microstructure and micro-dynamics (Basser & Pierpaoli, 2011). It can also detect diffuse axonal injury (DAI) and other microstructural changes in white matter caused by a mTBI (Arfanakis et al., 2002; Huisman et al., 2004; Kraus et al., 2007; Ptak et al., 2003). Visual tracking performance tests can also provide a useful means for assessing functional and structural impairments in mTBI (Maruta, Suh, Niogi, Mukherjee, & Ghajar, 2010).

Research shows that smooth pursuit ability decreases after a mTBI (Suh et al., 2006). Suh and colleagues have found that people with mTBI show symptoms such as decreased target prediction, greater eye position error, and variability of eye position in a circular tracking test.

In addition to causing lack of smooth pursuit, concussions have other visual impairment symptoms such as convergence abnormalities which occur in 47% to 64% of concussed patients (Brahm et al., 2009). Vertigo and light sensitivity are other symptoms of concussion (Singman, 2013).

Predictive visual tracking needs the person's attention and working memory (Barnes, 2008). These functions, which is controlled by the prefrontal cortex (Miller & Cohen, 2001), will be involved in mTBI most of the times (Alexander, 1995; Bigler, 2008; Kushner, 1998; McAllister et al., 2001; Ptito, Chen, & Johnston, 2007). Research shows that there is no significant difference between concussed and non-concussed groups in terms of the predictive visual tracking performance unless they were tested immediately after an attention demanding task (Maruta et al., 2016). The gaze positions around the target were more variable in concussed participants in comparison with the control group.

Almost fifty percent of brain circuits are dedicated to vision (Felleman & Van Essen, 1991). Many of these circuits, which are fronto-parietal and responsible for eye movement (White & Fielding, 2012), are those most frequently involved in concussion (Galetta et al., 2015). Since ocular impairment presents in up to ninety percent of concussed patients (Samadani et al., 2015), investigation of visual processing can be very helpful for concussion diagnosis.

Diagnosing concussions based on eye movements is critical and clinicians should add it to their skill set of clinical expertise (Ventura et al., 2015). Utilizing eye-tracking assessment to diagnose concussion would decrease the need for sideline tests, where athletic trainers are responsible for baseline concussion assessment. In developing a tool for sideline concussion assessment, one should also pay attention to other factors like cost, standardization, accessibility, and reliability.

In contrast, other research shows patients with traumatic brain injury have delays in information processing and show some issues in perception of spatial relationships and inattentiveness to a series of multiple simultaneous events (Brouwer, Ponds, Van Wolffelaar, & Van Zomeren, 1989; Singman, 2013). Response delay duration depends on the severity of the injury, post-injury duration and the tests' complexity (Brouwer, Withaar, Tant, & van Zomeren, 2002).

Two other diagnostic tests for TBI are the Functional Independence Measure (FIM) and the Functional Assessment Measure (FAM). The FIM is an eighteen item, seven level ordinal scale test. It can measure and analyze disability and rehabilitation data. It is sensitive to individual change in the comprehensive inpatient medical rehabilitation program. The FAM focuses on other aspects of functional measurement like cognitive, behavioral, communication, and community functioning measures. The FAM consists of twelve items. Adding FIM and FAM, the total thirty item scale combination is referred to as the FIM+FAM. The time required to administer the FIM+FAM is approximately thirty-five minutes.

Participants with mTBI struggle in some cognitive tests such as the Neuro-Behavioral Test (NBT) (Bazarian et al., 1999), the Attentional and Impairment Model Test (Brewer, Metzger, & Therrien, 2002), the Immediate Memory, Orientation and Delayed Recall Test (Comerford, Geffen, May, Medland, & Geffen, 2002), the Digit Symbol Substitution Test (Monte & Geffen, 2005), and Non-word Repetition Test (NWR) (Voller et al., 1999). However, their performance was consistent with the control group on the Digit Symbol Substitution Test (W, Horswill, & Geffen, 2010). This implies that mTBI patients show neurological impairments in many tests, while they do not show any impairment in neuro-images.

Usually mTBI patients show some visual impairments, such as issues in anti-saccades, prolonged saccadic latencies, higher directional errors, poorer spatial accuracy, and impaired memory guided saccades (Heitger et al., 2004; Heitger, Anderson, & Jones, 2002), even after ten days. Almost thirty percent of mTBI impaired cases show saccadic dysfunction (Capó-Aponte, Urosevich, Temme, Tarbett, & Sanghera, 2012).

Heitger et al. (Heitger et al., 2009) implemented a study in which they asked mTBI patients after three to five months to do saccade tests and compared the results with mTBI patients who recovered well. They show that the second group performed significantly better than the first group in anti-saccade testing, memory-guided saccades, and a self-paced saccade test.

Drew et al. implemented a gap saccade test in which they asked the participants to fixate on a target for a specific amount of time and then on a peripheral target (Drew et al., 2007). When there was a short temporal gap between the central and peripheral targets, acute mTBI patients showed longer saccadic reaction time, but in a longer temporal gap, they had difficulties in disengaging attention. Concussed people were also diagnosed with saccadic function impairments in attention and memory (Drew et al., 2007; Heitger et al., 2004, 2009, 2002; Kraus et al., 2007). Cognitive impairment symptoms affecting attention, processing speed, and memory often exist during the first week to a month (Carroll et al., 2014).

Mucha and colleagues implemented a Vestibular/Ocular Motor Screening Assessment Test in which they stimulated their subjects with vestibular and ocular stimulation (Mucha et al., 2014). They found that the concussed group reported symptoms after researchers stimulated the underlying vestibular–ocular reflex or visual motion sensitivity.

The Standardized Assessment of Concussion (SAC) is another concussion assessment tool that measures concentration, orientation, immediate memory and delayed recall. In a study, they showed that the SAC diagnosed fifty percent of concussed collegiate athletes (Marinides et al., 2015; M. McCrea, Kelly, Kluge, Ackley, & Randolph, 1997). However, there are some validation issues because athletes might memorize test words from their baseline test (Dziemianowicz et al., 2012).

Another concussion test is the Balance Error Scoring System, (BESS, Riemann & Guskiewicz, 2000) which is a low-technology balance assessment tool. Patients usually were asked to stand with their feet together and put their hands on their hips with their eyes closed. They should try to stand still for twenty seconds. If they open their eyes, take their hands off the hips, stumble, fall, or move their hips more than thirty degrees, lift the forefoot or heel, or remain out of testing position for more than five seconds, it is an error. They should repeat the test with a single-leg stance using the non-dominant foot, and then use a heel-toe stance with the non-dominant foot in the rear, which is called the tandem stance (Furman et al., 2013).

King-Devick (K-D) is a vision-based concussion sideline test in which the subject reads numbers on three test cards aloud. The total time of reading is calculated and after a concussion, a new test is taken. The timing is compared with the baseline. The K-D test requires activity of the dorsolateral prefrontal cortex (DLPFC) which is responsible for anticipatory saccades (Pierrot-Deseilligny et al., 2003; White & Fielding, 2012).

Sport Concussion Assessment Tool, Third Edition (SCAT3) is a combination of SAC, modified BESS and other tests like the symptom checklist, Glasgow coma scale, and Maddocks' questions. It takes fifteen to twenty minutes to complete and build a consensus committee based on the best available measures (Guskiewicz et al., 2013; McCrory et al., 2009). However, Ventura et al. showed that even using SAC and BESS at the same time was not successful in showing abnormalities in ten percent of concussed patients in the study (Ventura et al., 2015).

Although the SCAT3 test provides supportive information for concussion diagnosis, it does not test vision and is not an exact and reliable test method (Luoto et al., 2014). In reality, seventeen percent of concussed patients do not show any cognitive impairment (Van Kampen, Lovell, Pardini, Collins, & Fu, 2006), whereas between twenty percent to forty percent of non-concussed athletes show cognitive abnormality (Maerlender et al., 2010).

In 2000, Lovell et al. developed a neuro-psychological test which could help assess concussed athletes (Lovell et al., 2000; Maroon et al., 2000). Immediate Post-concussion Assessment and Cognitive Testing (ImPACT) consists of three steps. The first step is compiling the demographic data, the second step is a neuro-psychological test, and the last step is the Post-Concussion Symptom Scale (PCSS). These three steps together make it the most accurate recent testing tool for diagnosing a concussion. One limitation is the fact that ImPACT needs a baseline test (Echemendia et al., 2012; Gardner, Shores, Batchelor, & Honan, 2012).

2.3. Eye-tracking

Recently, eye-tracking methods have been used in concussion-related research (Caplan et al., 2015a; Cifu & Gitchel, 2014; Heitger et al., 2009). The quality of a patient's eye movement can demonstrate healing progress. The eye-tracking measures how well the patient's eyes are capable of moving, rather than the subject of focus (Samadani, 2015).

Saccadic tests are very helpful in checking whether patients return to normal saccadic functions or not. Little research has been performed by using video-oculography to record visual tracking of a moving target in a circular trajectory (Maruta, Lee, Jacobs, & Ghajar, 2010). These tests are not used in clinics because of the lack of necessary tools and equipment (Dziemianowicz et al., 2012). Dziemianowicz also addressed other saccadic test issues in their research such as absence of baseline tests, calibration issues, poor attention, and medication effects.

There is limited research using the eye-tracking devices to find eye movement impairments in concussed patients. In one experiment, scientists used a portable head-mounted video-based eye-tracker on sixty military participants with a history of concussion and compared them with twenty-six participants in the control group (Caplan et al., 2015a). The result shows larger saccadic position errors, smaller saccadic amplitudes, smaller predicted peak velocities, smaller peak accelerations, and abnormalities in pursuit velocities in military soldiers.

Samadani et al. (Samadani, 2015) assessed the physiological function of cranial nerves by recording eye movements of participants who were watching a movie. Cranial nerve palsies happen in a variety of diseases such as traumas. Researchers assessed all pathological processes that affect the functioning of the crania nerves. In this way, they were able to assess physiological function of the central nervous system. In another study, eye pupil positions were mapped over time and researchers assessed changes in eye movement while the participants were watching a video (Lau et al., 2011). They developed an algorithm that interprets eye-tracking data and concluded that if "concussion" is defined based on criteria such as history, physical examination, radiographic, and the SCAT3, it would be possible to detect a concussion based on a generalized, eye-tracking-based biomarker.

2.4. Legislation

In some states, legislation was enacted to regulate school athletics in the event of potential head injury. For example, in Washington and Kansas, coaches, parents, and teen athletes to read and sign the "Concussion and head injury information sheet," and the legislation also obliges any athlete with suspected concussion symptoms to leave the field of play and see a medical doctor before returning (McDonald et al., 2016; Shenouda, Hendrickson, Davenport, Barber, & Bell, 2012).

Governmental agencies that regulate driving have issued guidelines to limit driving by drivers who have suffered a mTBI. In 2013, Departments of Motor Vehicles (DMV's) in the United States issued guidelines for fitness required to drive following a mTBI. Guidelines also were issued in 2012 by Austroads, the Australian equivalent of United States DMV's, and in 2009 in Europe. In the clinical practice guidelines released in Canada in 2012, they suggested mTBI patients should not drive in the first twenty-four hours after injury (Marshall, Bayley, McCullagh, Velikonja, & Berrigan, 2012). This means that none of these guidelines mandates that patients wait until a full recovery, nor do guidelines suggest a way to assess if a patient is fit to drive twenty-four hours after injury, and if not, when a patient is fit to drive.

2.5. Driving after a Concussion

Driving is a complex task that needs physical and cognitive skills functioning together. It needs the ability to receive sensory information, process the information, and to make proper, timely judgments and responses (Gregory, 1981). Any malfunctioning in physical or cognitive skills may reduce driving performance (Brouwer & Withaar, 1997; Galski, Bruno, & Ehle, 1992; Shenouda et al., 2012; Sivak, Olson, Kewman, Won, & Henson, 1981; Stokx & Gaillard, 1986; Van Zomeren, Brouwer, & Minderhoud, 1987; Webster, Rapport, Godlewski, & Abadee, 1994), slow reaction time (Stokx & Gaillard, 1986), reduce driving skill (Stokx & Gaillard, 1986), and increase crash risk. Research shows that many cognitive processes which are necessary for driving will be affected by concussion (Bottari, Lamothe, Gosselin, Gélinas, & Ptito, 2012; Preece, Horswill, & Geffen, 2011; Stokx & Gaillard, 1986). Not only would concussion affect driving performance, but it also may exacerbate concussion symptoms (Rose, Weber, Collen, & Heyer, 2015).

However, a study shows that if young drivers recover from their brain injury, they will not have residual impairment in driving (Schneider & Gouvier, 2005a). Since diagnosis of concussion and healing length is controversial, there has not been a particular method used to assess whether the patient is fit to drive. Many clinicians, patients and parents do not know that driving while having a concussion would be potentially dangerous (Preece, Geffen, & Horswill, 2013). Clinicians decide whether a patient is healed enough for re-drive or not and recommend limiting driving after injury. This decision depends on the interpretation by the primary care physician of the patient's progress. They might take a risk and let the patient drive or might be conservative and recommend the patient not drive even when the patient is partially safe to drive. Moreover, the law is not the same state to state and the doctors might not be aware of their state guidelines for assessing driving competency (Drickamer & Marottoli, 1993). The medical evaluation, psychological assessment, simulated driving tests, and brief on-the-road driving assessments are the current tests to evaluate patients' fitness to drive (Lings & Jensen, 1991).

Brouwer et al. showed that between forty and sixty percent of brain injured patients will return to driving (Shore, Gurgold, & Robbins, 1980; Van Zomeren et al., 1987; Van Zomeren, Brouwer, Rothengatter, & Snoek, 1988). The driving ability of brain impaired patients has been measured on closed courses (Sivak et al., 1981). While differences between the error scores in turning the steering wheel for the injured and non-injured groups were not significant, the quality of errors in the head injured group was significantly more serious (Van Zomeren et al., 1988). However, the author suggests more complicated tasks need to be examined for validating closed course assessment. In another study, the experimenters show mTBI and TBI patients drive less safely in comparison with non-patients (Hawley, 2001; Novack et al., 2006)

In a study, a group of participants watched films of driving which included traffic hazards (Graydon et al., 2004; Hirth, Davis, Fridriksson, Rorden, & Bonilha, 2007). The neuro-images show activated brain regions including the frontal lobe in patients watching these films. Authors concluded that mTBI might affect driving performance, since the frontal lobe will be impaired as the result of a mTBI.

Literature shows that among the existing diagnosis methods, such as physical examinations, clinical interviews, and neuro cognitive and balance testing, there is no accurate method which can determine if a patient is concussed or not, particularly if the patient attempts to hide the symptoms. However, one of the symptoms, which the patient is unable to conceal, is the eye movement and convergence disorders. Until now, there is no accurate objective method to determine if the patient recovered from a concussion or not.

Using an eye-tracker in executing cognitive tests as an objective assessment tool for concussion diagnosis and healing progress can be beneficial. There are not many research studies implemented on concussed patients. The existing research has been performed while the patients were not engaged in doing a cognitive task, instead, they were sitting and watching a movie or a video game (Lau et al., 2011; Samadani et al., 2015). Caplan et al. (Caplan et al., 2015b) and Suh et al. (Suh et al., 2006) implemented research on concussed military participants and TBI patient, respectively, with limited saccadic cognitive tests. In the case of the fitness-to-drive assessment, no research has been done. Most existing research tests the driving ability and driving performance after a concussion (Bottari et al., 2012; Novack et al., 2006; Preece et al., 2011; Sivak et al., 1981; Stokx & Gaillard, 1986), or they discussed possible residual impairments after a concussion recovery (Schneider & Gouvier, 2005a). None of them assessed if a patient is fit to drive.

By utilizing the assessment method in this study, doctors will be able to assess the progress of healing in a concussed patient without any need to have a baseline test on record. After the rest period, doctors will be able to use the eye-tracker and repeat the cognitive tests to decide whether or not a patient is healed enough to return to regular daily activities, especially driving, which needs more complex cognitive skills. The focus of this research was to develop cognitive tests that utilized an eye-tracker and an assessment index to measure patients' healing. Figure 1 shows the previous research executed for diagnosis of concussion and assessment of fitness-to-drive after a concussion with the existing gaps and the contribution of this study.

CHAPTER 3

METHODOLOGY

The present research seeks to provide a method to diagnose and assess concussion in patients with concussion symptoms. Cognitive and driving simulated tests were designed to assess whether or not a participant is concussed. More than diagnosing a concussion, these tests provided a means of assessing the difference between driving performance of teen drivers who received a concussion and healthy teen drivers.

1.6 <u>Instruments and Methods</u>

1.6.1 Participants

A total of twenty-four participants were recruited for this study, the concussed driver cohort (twelve concussed) and the non-concussed driver cohort (twelve non-concussed). All participants held a driver's license at the time of the study. Participants with history of other neurological or eye disorders like Parkinson's or colorblindness were excluded from the study. The concussed driver cohort participants were among patients referred to Connecticut Children's Medical Center (CCMC) in Farmington, Connecticut. Drivers in the non-concussed cohort were selected from healthy volunteers from the Farmington area. Drivers in the non-concussed driver group (control group) were recruited to match the gender and age of the first group.

1.6.2 Apparatus

1.6.2.1 Driving simulator

Scenarios have been developed on the ATRANS STISIM V3 Mobile Driver Assessment & Training Simulator (MODATS). MODATS is a portable 3-screen simulator developed for field research in places such as driving schools, research centers and medical facilities (Figure 2). The simulator consists of a gaming chair and high-end plate steel and cast-iron steering and pedal controls. Three 24" LCD monitors are mounted in front of the driver providing an approximately 150 degree field of view.

Figure 2- Mobile Driver Assessment & Training Simulator (MODATS)

1.6.2.2 Eye-tracker

Drivers' scanning were recorded using a Tobii Pro-II mobile eye-tracker (Figure 3). The eye-tracker consists of a lightweight pair of glasses with the scene camera and eye cameras integrated into the frame. The system was calibrated via a wireless connection to the analysis laptop and videos were recorded on a 3”x5”x0.5” video recording unit clipped to the participant’s belt. The driver’s point of gaze, represented as a red circle, was superimposed upon the scene camera video image. The eye-tracker used in this study is shown in Figure 3.

Figure 3- Tobii Pro-II mobile eye-tracker.

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1.6.2.3 Simulator Scenarios

1.6.2.3.1 Low Fidelity Scenarios

The study administrator fitted the participants for the eye-tracker and had them operate the driving simulator. The participants were told to keep their speed from thirty to thirty-five miles per hour (mph) during their drive. They executed a low fidelity drive taking three minutes to finish. The driving scenario environments consisted of: (1) an empty two-lane road, with dashed yellow lines in the middle, and without any upcoming, ongoing or cross traffic, (2) an empty two-lane road, with dashed yellow lines in the middle, in windy weather and without any upcoming, ongoing or cross traffic and (3) an empty two-lane road, with dashed yellow lines in the middle, having curves with different radii and without any upcoming, ongoing or cross traffic. Table 1 shows the low fidelity scenarios.

Table 1- Low Fidelity Scenarios

Scenario number	Scenario name	Description
1	Empty two-lane road	an empty two-lane road, with dashed yellow lines in the middle, and without any upcoming, ongoing or cross traffic
2	Windy weather	an empty two-lane road, with dashed yellow lines in the middle, in windy weather and without any upcoming, ongoing or cross traffic
3	Curves	an empty two-lane road, with dashed yellow lines in the middle, having curves with different radii and without any upcoming, ongoing or cross traffic

The participants were asked to drive and try to maintain their lane. The main goal of this test was evaluating whether the participants were able to tolerate driving and to maintain the right of way (Figure 4).

Figure 4- Driving simulator environment in low fidelity scenario

The Tobii Pro-II glasses recorded the participants' eye movement during driving. For the empty road scenarios in which the participant was driving in a straight lane with and without a windy weather, the percentage of fixations each participant had on the roadway, at the speedometer, at the rear, left or right mirrors, and the percentage of the fixations they had by looking at the non-critical areas like trees and sky (referred to herein as "area of distraction"), was calculated. Moreover, the participant's average speed and the percentage of the time that their speed was out of range (30-35 mph) was also calculated.

For the scenario which included multiple curves, the number of times each participant deviated off the road, their average speed, the percentage of the time they were looking at an area of distraction, the number of fixations at the speedometer, and the percentage of the time they were driving out of speed range (25-35 mph) was calculated. Statistical tests were performed on each of the measuring metrics to compare the differences in the performance between two groups in each metrics.

This is due to the concussed eye movement impairments (Ciuffreda et al., 2007; Dora Szymanowicz OD et al., 2012; Kapoor & Ciuffreda, 2002; Thiagarajan et al., 2011). For the same reason as with the windy weather test, a higher level of steering wheel control is expected for the non-concussed participants in comparison with the concussed drivers.

1.6.2.3.2 High Fidelity Scenarios

The study administrator asked participants to put on the eye-tracker and sit at the simulator. The study administrator ran a four-minute drive in which participants were expected to anticipate hazards, scan, and fixate at the areas with potential hazards (Figure 5). However, the hazards did not materialize during driving. The participants' points-of-gaze were recorded continuously throughout the drive using the eye-tracker. After the experimental drive, the study administrator helped the participant out of the simulator, removed the eye-tracker and the simulated drive was finished.

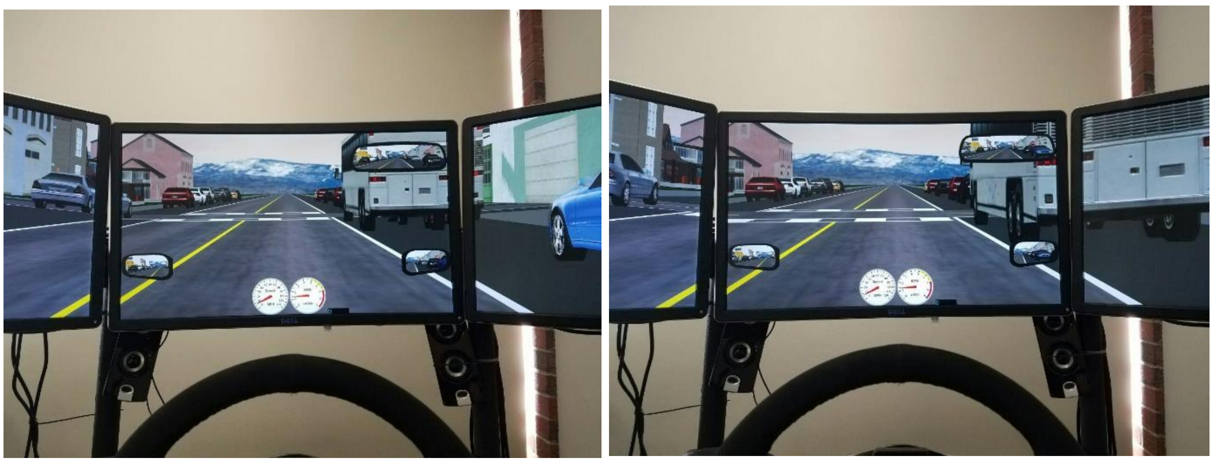

Figure 5- Driving simulator environment in high fidelity test

Table 2 shows a brief description of the scenarios in the high fidelity test section.

Table 2 - High fidelity scenarios

Scenario number	Scenario name	Description
1	*Bus at a midblock crosswalk*	The participant is approaching the crosswalk. A truck is stopped alongside the road in front of the crosswalk. This truck blocks the participant’s view of pedestrians in the crosswalk who may be preparing to cross.
2	*Bicyclist lane encroachment*	The participant is driving in a downtown area with two traffic lanes in each direction. Parking lanes on both sides of the road are heavily filled, with only occasional vacant spaces. On their way, they encounter a parallel-parked truck that is encroaching only very slightly into their lane. There is also a bicyclist traveling between the parked cars and the edge line of the road. The bicyclist will arrive at the back end of the truck only slightly ahead of the participant and, rather than moving to the sidewalk.
3	*Truck blocking a driveway*	The participant is approaching a truck parked along the left side of the road. The view of the front yard and driveway are blocked by hedges and/or trees between the two adjacent houses, as well as by the presence of the truck. There are pedestrians in the driveway. With the view of the driveway obscured, the driver cannot be certain whether or not a vehicle or person might emerge.
4	*Right Turn at Stop sign with a pedestrian*	The participant approaches a two-way stop-controlled intersection and desires to turn right. A household hedge blocks the driver’s view of pedestrians on the sidewalk coming from the right. Once the final car passes through the intersection, clearing the way for their turn, pedestrian steps off the curb from the right, intending to cross from their nearside right corner to the nearside left corner.
5	*Left turn to Side Street*	The participant is approaching an uncontrolled four-way neighborhood intersection. There are sidewalks present on both sides of the roadways in all directions. There is a driveway on the left side of the road prior to the intersection with two bushes near the end of the driveway. The bushes are partially obscuring two pedestrians walking toward the near left corner of the intersection. The participants desire to turn left. An oncoming vehicle (V1) is approaching which requires the participants to yield for the left turn. As V1 is traversing the intersection, the PEDS begin crossing from the near left to the far-left corner of the intersection
6	*Oncoming truck left turn*	The drivers are approaching a four-way, stop controlled intersection. The stop signs only apply to the side roads, which are two-way roads. They are driving on the four-lane road with two lanes in each direction, and they have the right-of-way through the intersection. The driver desires to turn left onto the side road. Arriving at the same time, there is a large tractor-trailer (T1) in the oncoming left most lane. T1 has its left turn indicators on. The truck begins to turn but pauses partially into the intersection. T1 is blocking the participant’s view of oncoming traffic from the right-most lane. When they begin the left turn, a previously unseen vehicle (V2), appears in the blind spot created by the truck and drives straight through the intersection, conflicting with their left turn.

1.6.2.3.2.1 Bus at a midblock crosswalk

This is an example of a situation in which a stopped vehicle, such as a bus or truck, can block the driver's view of pedestrians entering a midblock crosswalk. The participant is in the green car approaching the crosswalk. In this case, a truck is stopped alongside the road in front of the crosswalk, possibly for loading or unloading cargo. This truck blocks the participant's view of pedestrians in the crosswalk who may be preparing to cross. The grey area represents that area of the participant's visual field that is blocked by the truck, not allowing them to see clearly if there is a pedestrian in the crosswalk preparing to cross (Figure 6).

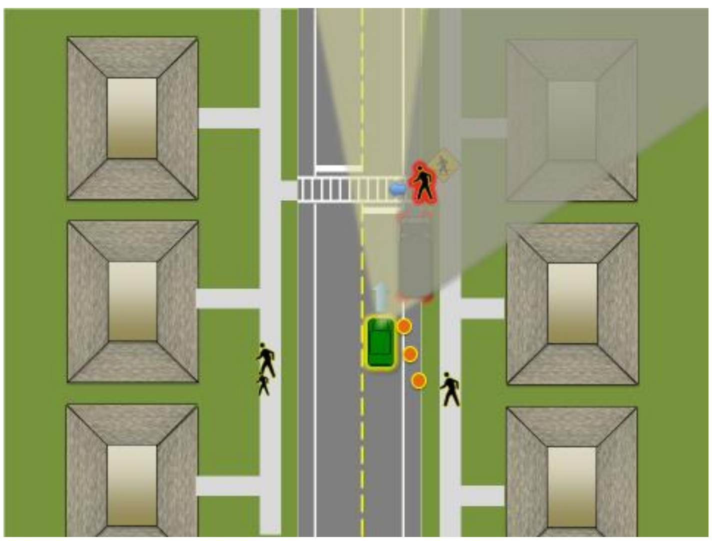

Figure 6- Bus at a midblock crosswalk

There are a few environmental cues that might help the participant determine that there could be pedestrians crossing. First, there are buildings and sidewalks on both sides of the street, meaning that there are destinations pedestrians may be trying to reach on both sides. Second, the presence of pedestrians on the sidewalk should be a cue that added vigilance is required, although it is important to note that a lack of visible pedestrians does not necessarily mean one should be less vigilant. Finally, the pavement markings indicating a crosswalk are a cue that the participant should be prepared for the possibility of crossing pedestrians (Figure 7 and 8).

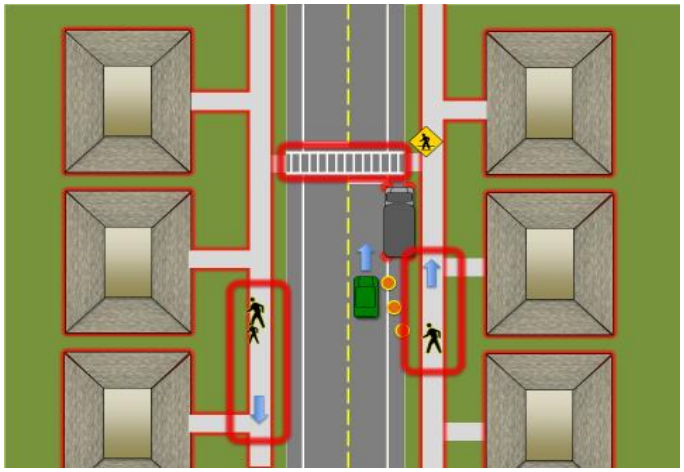

Figure 7- The participant entering the crosswalk

As the participant approaches the obscured crosswalk, they should first slow down, and then monitor the area in the crosswalk just in front of the truck.

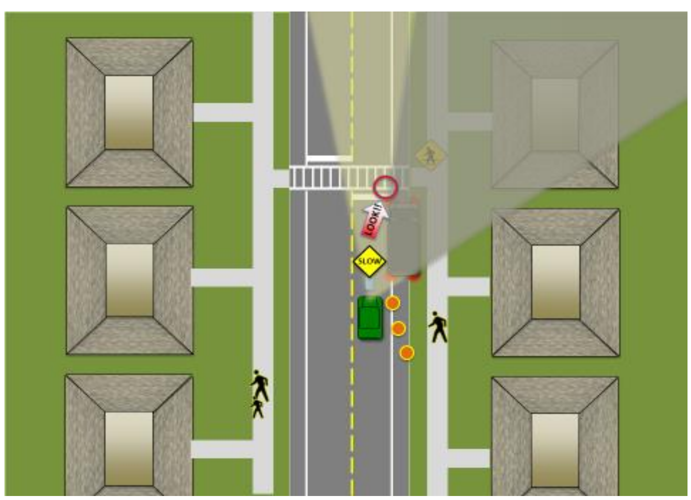

Figure 8- The participant monitoring the crosswalk

Then, as they near the crosswalk, they should continue monitoring the area in front of the truck, in anticipation of the possibility that a pedestrian may unexpectedly appear. Once they are certain there are no pedestrians in or near the crosswalk, or they have yielded to any who were, then they can continue on their way.

1.6.2.3.2.2 Bicyclist lane encroachment

The participant is in the green car driving in a downtown area with two traffic lanes in each direction. There are also parking lanes on both sides of the road, sidewalks, and a variety of buildings and structures. Parking lanes on both sides of the road are heavily filled, with only occasional vacant spaces. On their way, they encounter a parallel-parked truck (T) that is encroaching only very slightly into their lane. There is also a bicyclist (B) traveling between the parked cars and the edge line of the road. The bicyclist will arrive at the back end of the truck only slightly ahead of the participant and, rather than moving to the sidewalk, he will encroach on the participant's travel lane. However, there is an oncoming vehicle (V1) that is preventing the participant from veering to the left to avoid the bicyclist (Figure 9).

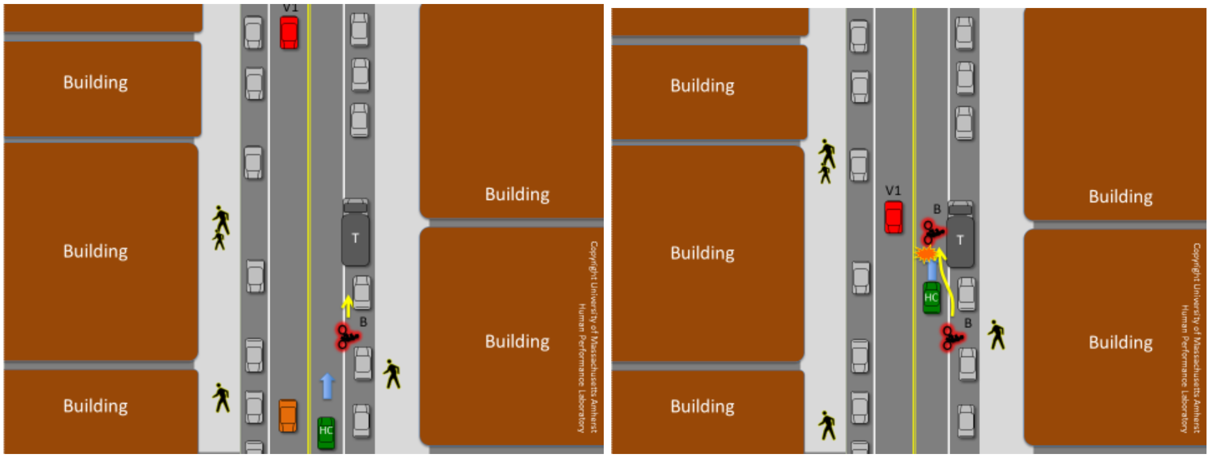

Figure 9- Bicyclist Lane Encroach

1.6.2.3.2.3 Truck blocking a driveway

In this scenario, the participant is driving through an active residential neighborhood. Roadways are unmarked and there are houses on the right and on the left. The participant is in the green car approaching a truck parked along the left side of the road (relative to the participant). The view of the front yard and driveway are blocked by hedges and/or trees between the two adjacent houses, as well as by the presence of the truck. There are pedestrians (a mix of adults and children) in the driveway (moving, loading boxes, kids playing). With the view of the driveway obscured, the driver cannot be certain whether or not a vehicle or person might emerge (Figure 10).

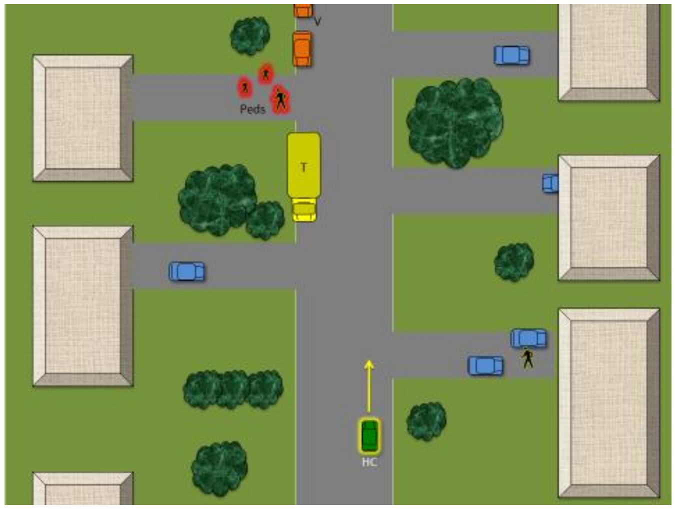

Figure 10- The driver is entering the truck blocking a driveway zone

If they do not slow down and monitor that area behind the truck for emerging pedestrians or vehicles, they might hit them (Figure 11).

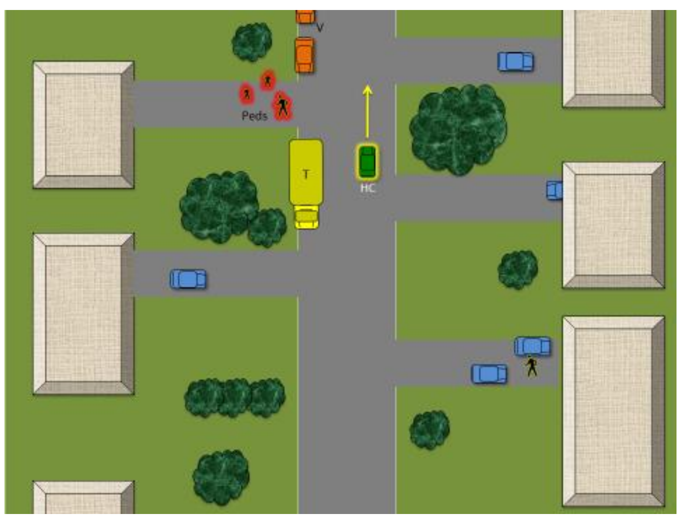

Figure 11- The driver is passing the driveway

1.6.2.3.2.4 Right Turn at Stop sign with a pedestrian

In this scenario, the participant (HC) approaches a two-way stop-controlled intersection and desires to turn right. There are sidewalks on all corners. Buildings, homes and other features are relatively close to the roadway. A household hedge blocks the driver’s view of pedestrians on the sidewalk coming from the right. Cross traffic does not stop, and a line of cars is making its way through the intersection from the left, preventing the participant’s turn. The line of cars forces the driver to wait at least ten seconds. Once the final car passes through the intersection, clearing the way for their turn, pedestrian steps off the curb from the right, intending to cross from their nearside right corner to the nearside left corner. Because their attention is diverted to the left, the participant may not anticipate the presence of the pedestrian and begin to turn right. As a result, they might collide with the pedestrian, who is now in the crosswalk in front of them (Figure 12).

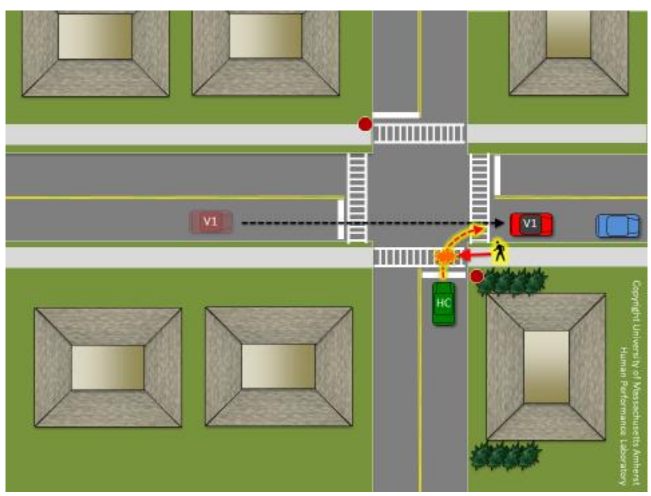

Figure 12- Right Turn at Stop sign with a pedestrian

The participant should take the time to scan the intersection while they wait. A pedestrian could always appear at the very last moment. Scanning continuously for hazards could prevent collisions in these situations (Figure 13).

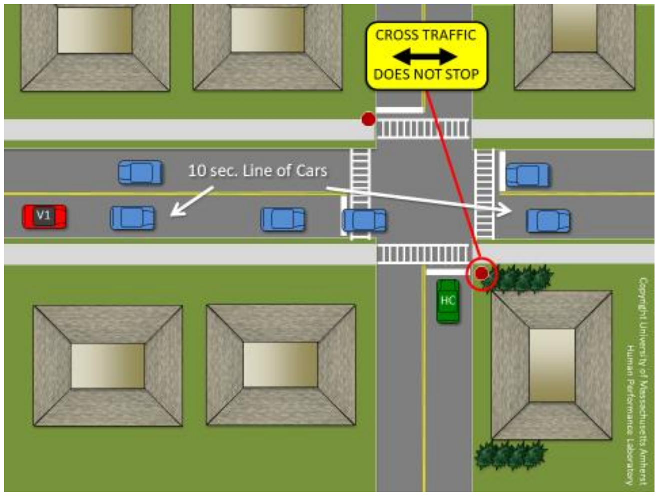

Figure 13- Scanning before a right turn at stop sign with a pedestrian

1.6.2.3.2.5 Left turn to Side Street

The participants (HC) are driving through an active residential neighborhood. Roadways are unmarked and there are houses on the right and on the left. They approach an uncontrolled four-way neighborhood intersection. There are sidewalks present on both sides of the roadways in all directions. There is a driveway on the left side of the road prior to the intersection with two bushes near the end of the driveway. The bushes are partially obscuring two pedestrians (PEDS) walking toward the near left corner of the intersection. The participants desire to turn left. An oncoming vehicle (V1) is approaching which requires the participants to yield for the left turn. As V1 is traversing the intersection, the PEDS begin crossing from the near left to the far-left corner of the intersection (Figure 14).

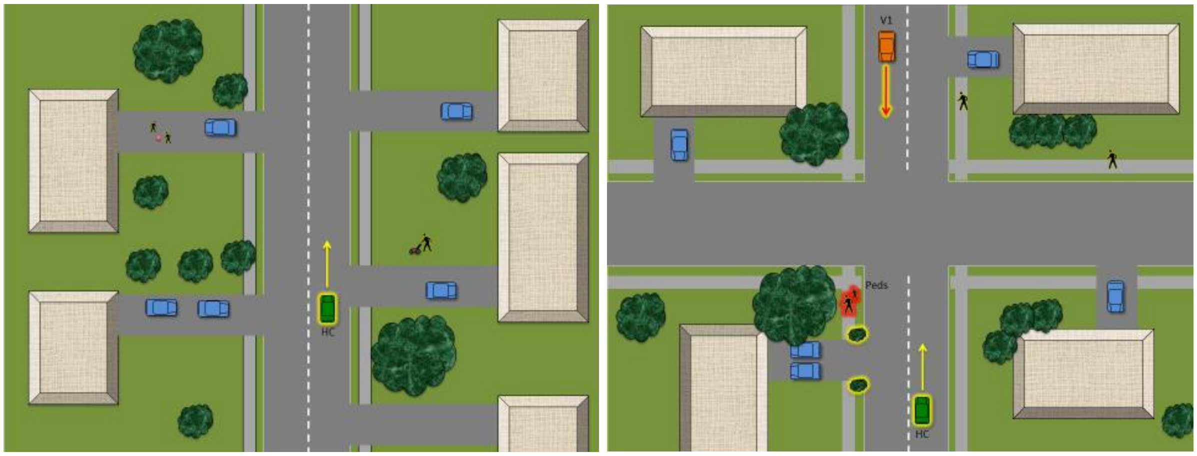

Figure 14- Left turn to Side Street scenario

The drivers are waiting for V1 to clear the intersection. They should continue to scan the environment for potential hazards. They should note the presence of the PEDS prior to turning left and continue to wait to turn until they have safely reached the far-left corner. Only after the PEDS have cleared the intersection should one execute the left turn, or else they will collide with the PEDS. If the drivers begin the turn and stop half way through, they will not hit the PEDs, but maybe the incoming traffic (Figure 15).

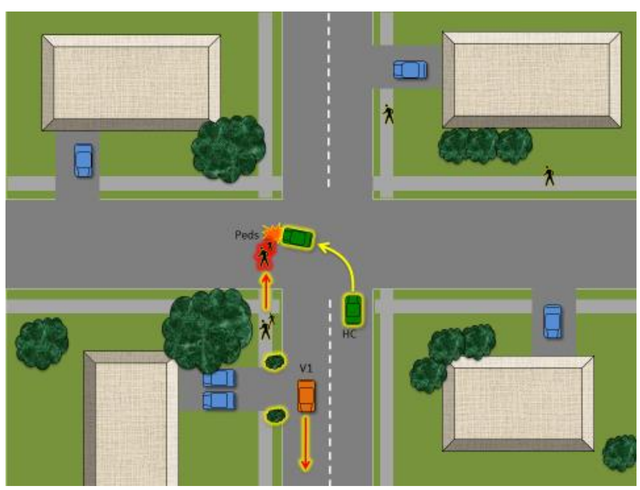

Figure 15- The driver hit the pedestrian turning left to Side Street

1.6.2.3.2.6 Oncoming truck left turn

In this scenario, the drivers are approaching a four-way, stop controlled (two-way) intersection. The stop signs only apply to the side roads, which are two-way roads. They are driving on the four-lane road with two lanes in each direction, and they have the right-of-way through the intersection (Figure 16).

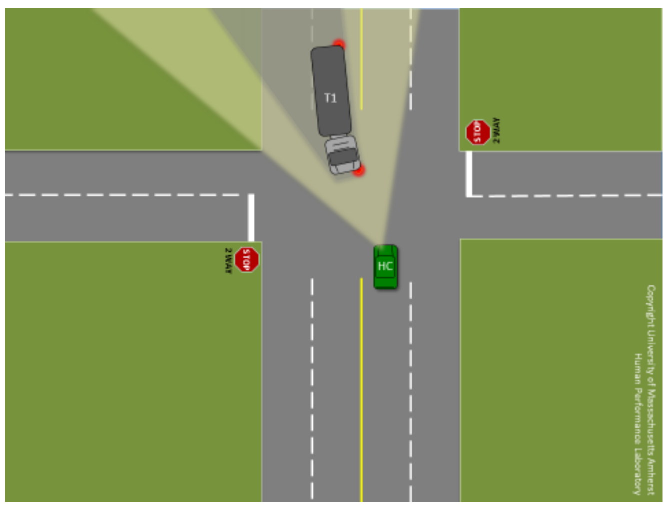

Figure 16- Oncoming truck left turn

The driver desires to turn left onto the side road. Arriving at the same time, there is a large tractor-trailer (T1) in the oncoming left most lane. T1 has its left turn indicators on. The truck begins to turn, but pauses partially into the intersection, presumably to wait for an appropriate gap. T1 is blocking the participant's view of oncoming traffic from the right-most lane. When they begin the left turn, a previously unseen vehicle (V2), appears in the blind spot created by the truck and drives straight through the intersection, conflicting with their left turn.

A good defensive driver assumes that a potentially hidden hazard will materialize and drives as if it will. In this case, at the beginning of their left turn, when they see that the truck prevents a clear view of oncoming traffic, they should slow down and avoid entering the obscured lane (Figure 17).

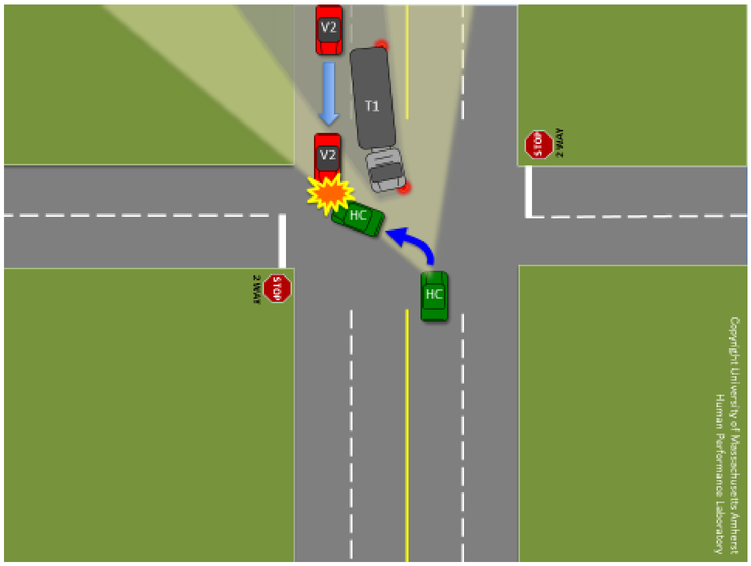

Figure 17- The driver hit the hidden car turning left

1.6.2.4 Pre-study Questionnaire

A pre-study questionnaire was given to the participants. The questionnaire asked for the participants' demographics and driving history. The participants needed to answer to the questions carefully.

1.6.3 Non- Simulator Tests

In this part, a series of ocular tests designed for patients with concussion symptoms were used. Patients put on the eye-tracker and the administrator calibrated the eye-tracker on their eyes. The patient sat on a chair in front of a monitor for ocular tests. The designed ocular tests were a series of tests that examined vestibular/ocular motor screening (VOMS), visual search and scanning ability, and target acquisition. Table 3 shows a brief description of the non-simulator tests.

Table 3-Non- simulator tests

Test number	Test name		Description
1	vestibular/ocular motor screening (VOMS)	smooth pursuit	A solid circle appeared in the monitor and moved horizontally and vertically. The patient was asked to focus on the circle as the circle moved.
2		horizontal saccades	Two single solid circles appeared horizontally on the monitor. The participant needed to move their eyes quickly from one to another for ten seconds.
3		horizontal vestibular ocular reflex (VOR)	A stationary cross appeared in the center of the screen. The participant was asked to fixate on the cross with their eyes and then slowly rotate their head side to side while keeping their eyes focused on the cross for ten seconds.
4	visual search and scanning ability		The participant was asked to sit at a monitor and scan for a target item (like a T) among distractor items (like X's).
5	target acquisition		A folder icon appeared on the upper left-hand side of the screen and twelve balls on the bottom right-hand side of the screen. Each participant was asked to drag the balls, move them toward the basket, and drop them into the basket one by one.

1.6.3.1 Vestibular/Ocular Motor Screening (VOMS)

The VOMS employed in this study consisted of brief assessments in the following three domains: (1) smooth pursuit, (2) horizontal saccades and (3) horizontal vestibular ocular reflex (VOR)

1.6.3.1.1 Smooth pursuit

In this test, the goal was to determine how well the patient is able to follow a moving target. A solid circle appeared in the monitor and moved from left to right and then right to left. The patient was asked to focus on the circle as the circle moved horizontally. Then the circle movement was repeated vertically, and the patient was asked to trace the circle back and forth up and down (Figure 18). These movements repeated for six times.

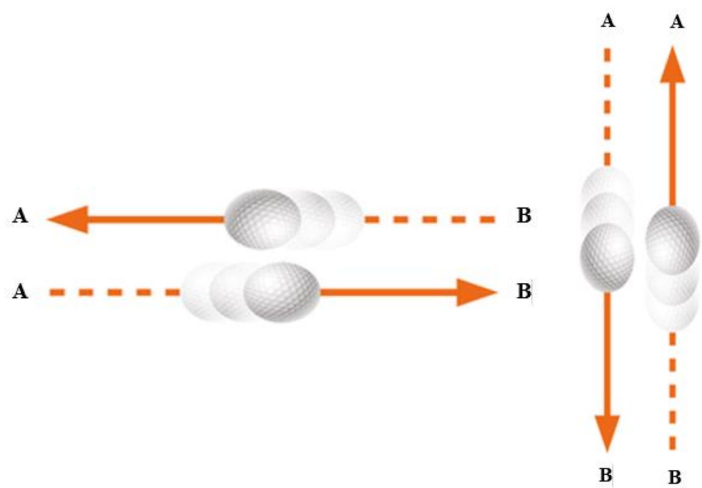

Figure 18- Smooth pursuits test

The participant's fixation points were normalized by considering the start fixation point of each participant (the circle is on the left side of the screen) as the origin and calculating the positions of other fixation points based on the origin. The vertical and horizontal distances of fixation points from the origin were calculated. Since the vertical deviation of the fixation points from the moving circle is important, a one-way ANOVA was applied to this test. A significant difference in vertical/ horizontal deviations of fixation point's values of the concussed and the non-concussed groups was expected. This is because the assumption was that concussed patients struggle with smooth pursuits (Suh et al., 2006, 2006) and that they may show more eye movement impairments and less stability in their eye movements.

1.6.3.1.2 Horizontal saccades

The participant was asked to sit at a desk in front of a monitor. Two single solid circles appeared horizontally on the monitor, one on the left side and the other one on the right. The participant needed to move their eyes quickly from one to another for ten seconds (Figure 19).

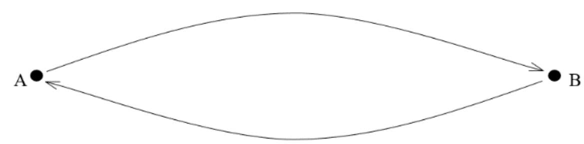

Figure 19- Visual search and scanning ability test

The participant's fixation points were normalized by considering the starting and ending fixation points of each participant (the circles on the left side and right side of the screen) as the origins and calculating the position of other fixation points based on the origins. If the coordinate of the calculated fixation point was closer to point "A", it was compared to point "A". If the coordinate of the calculated point was closer to point "B", it was compared to point "B". The vertical and horizontal distances of fixation points from the origins were calculated. Since the vertical and horizontal deviations of the fixation points from the moving circle are important, a one-way ANOVA was applied to this test. A significant difference in vertical/ horizontal deviations of fixation point's values of the concussed and the non-concussed groups was expected. Due to the saccadic impairments in concussed (Heitger et al., 2009), the non-concussed subjects were able to concentrate at each point more appropriately with fewer distracted gazes, so they showed a greater frequency. A mean center point closer to the zero point (Which is point “A” or “B”) and a smaller standard distance deviation show their level of concentration ability.

1.6.3.1.3 Horizontal vestibular ocular reflex (VOR)

The participant was asked to sit at a desk in front of a monitor. A stationary cross appeared in the center of the screen. The participant was asked to fixate on the cross with their eyes and then slowly rotate their head side to side while keeping their eyes focused on the cross for ten seconds (Figure 20).

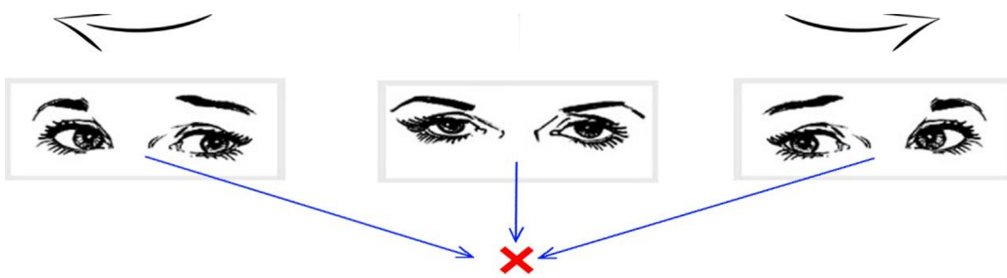

Figure 20- Horizontal vestibular ocular reflex test

The participant’s fixation points were normalized by considering the first fixation point of each participant (the cross in the center of the screen) as the origin and calculating the position of other fixation points based on the origin. The vertical and horizontal distances of fixation points from the origin were calculated. Since the vertical and horizontal deviations of the fixation points from the moving circle are important, a one-way ANOVA was applied to this test. A significant difference was expected in vertical/ horizontal deviations of fixation point’s values between the concussed and the non-concussed groups. The non-concussed subjects were expected to be able to concentrate at each point more appropriately with fewer distracted gazes and to show a greater frequency, with a mean center point closer to the zero point and a smaller standard distance deviation.

1.6.3.2 Visual search and scanning ability

For visual search testing, the study administrator performed a feature search exam. The participant was asked to sit at a monitor and scan for a target item (like a T) among distractor items (like X's) while wearing an eye-tracker. First, they needed to find a T between the Xs in a circular shape. The participant should have clicked on the T as soon as they found it. The participant was asked to find an N among Ms and Ws. Figure 21 shows some sample views of the actual test.

Figure 21- Visual search and scanning ability test

Response time was important in this test. The total response times in which each participant was able to find the specified letters were calculated. As concussion affects visual search and scanning abilities, longer response times for concussed patients were predicted.

1.6.3.3 Target acquisition

This test was performed using a monitor, the eye-tracker and a mouse. A folder icon appeared on the upper left-hand side of the screen and twelve balls on the bottom right-hand side of the screen. Each participant was asked to drag the balls, move them toward the basket, and drop them into the basket one by one (Figure 22).

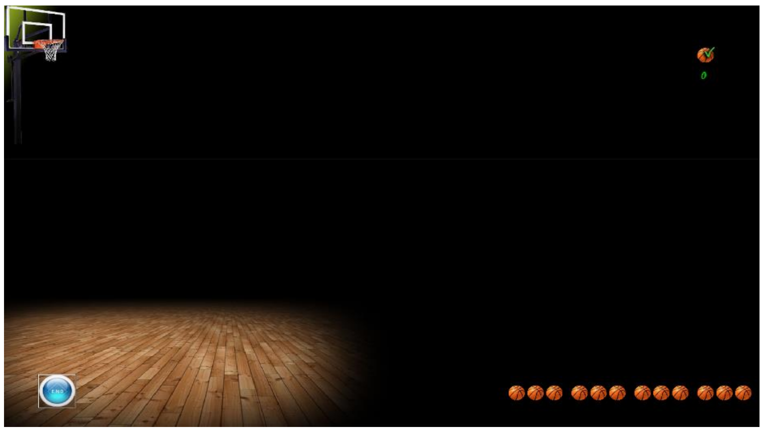

Figure 22- Target acquisition test

Total response time and the total number of successful drops were calculated as dependent variables of this test. Higher rates of successful drops and lower response time rates were anticipated for the non-concussed participants.

1.6.4 Experimental Procedure

The study took place in a single session, lasting half an hour for each participant. During this session, the participant met the study administrator in a laboratory at CCMC. Informed consents were received at this time and the participant was given the opportunity to ask any questions. The participant was also asked to fill out a pre-study questionnaire asking about their demographic data and driving history. The participant then was asked to wear the Tobii pro II eye-tracker and the study administrator calibrated the eye-tracker on their eyes. Figure 23 shows the sequence of the experiment.

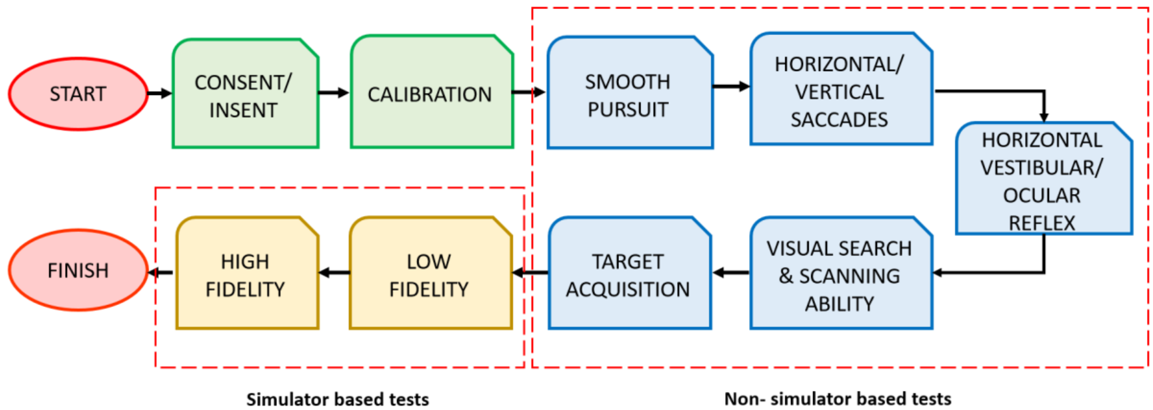

Figure 23- The experiment flowchart

Afterward, the participant was asked to sit in front of a monitor and do the non-simulator tests. As described, the non-simulator tests included five visual cognitive tests, administered in random order (Figure 24).

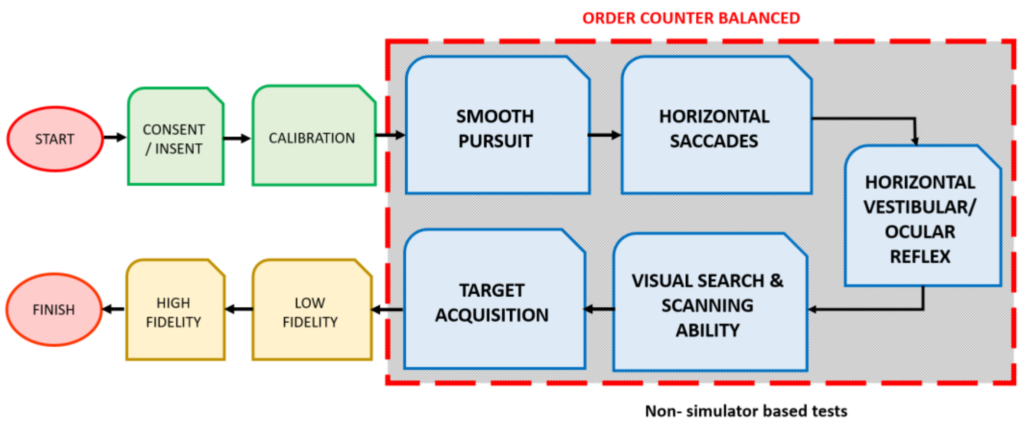

Figure 24- Non-simulator tests

After the non-simulator tests were completed, the study administrator stopped recording the eye-tracker and asked the participant to sit in the driving simulator. The study administrator played a practice drive. After the practice drive, the study administrator asked the participant if they were experiencing simulator-sickness or they were ready to continue. If the participant was ready to continue, the study administrator played the long drive, including low fidelity scenarios and then high-fidelity scenarios (Figure 25). At the end of the long drive, the study administrator stopped recording the eye-tracker and the study was finished.

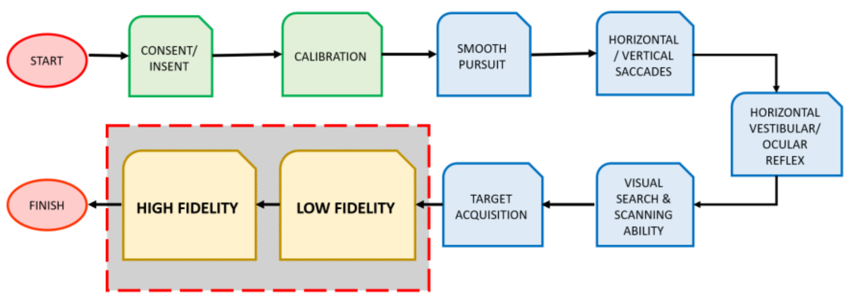

Figure 25- Driving simulator tests

1.6.5 Visual Analysis

In the case of assessing the cognitive test data from the participants, the eye-tracking visual analysis provided a better insight into the information that patients were processing and how they implemented what they were asked to do. Two main methods of quality and visual measurement of the eye-tracking analysis were used: the heat mapping and the gaze plot. One or both of them was used for each of the tests, depending on what outcome of the test was expected. For instance, in the tests where the timing and accuracy were the measurement criteria, the heat map and the gaze plot were useful.

1.6.5.1 Heat map

Heat mapping is one of the best-known visualization techniques for eye-tracking studies. A heat map is a graphical representation of data in which a color-coding system was used to characterize the values driven by variables in a hierarchy. Heat maps help develop an instant feel for an area by showing the data's density visually. The darker the color is, the higher the fixation density is. Heat mapping uses a range of colors, from red to blue showing the most seen to the least seen areas, respectively (Figure 26). The intensity of visualization determines the color of a specific area. If the participants look and fixate at particular areas for longer times and/or with a greater number of fixations, the areas become dark red. The lesser number of times an area is seen, the fainter the red color it is highlighted in. In contrast, the areas they spend the least amount of time or no time on become blue. One can easily understand the participants' area of interest by viewing the image.

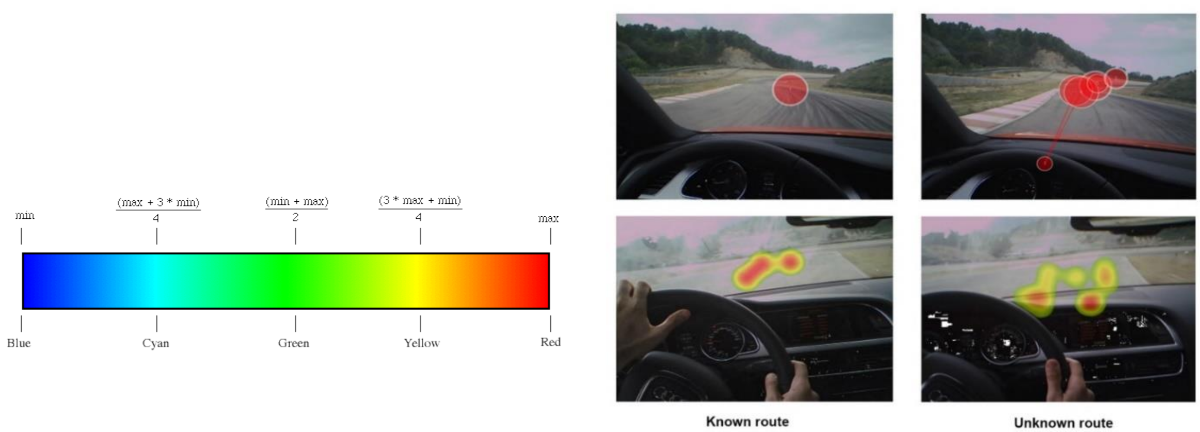

Figure 26- A Sample Heat Map

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In this way, the results showed the areas each participant focused on the most. For the simulator-based low fidelity tests, following the right of way with the minimum number of distractions was expected. The expected heat map schema for each test was described in Table 4. The narrower red areas indicate higher levels of concentration ability.

Table 4-Heat map expectations in experimental tests

Test Type	Test Name	Expectation
Simulator test	Low fidelity scenario	A straight narrow line which shows the right of way with the minimum number of distractions
	High fidelity scenario	More concentration on the hazardous area which is the result of scanning for the hazards
Non-simulator test	Smooth pursuits	A narrow vertical or horizontal straight line
	Horizontal and vertical saccades	Higher concentration of glances on the points A and B
	Horizontal vestibular ocular reflex	Higher glance concentration on the target point
	Cognitive tunneling	Higher glance concentration on the target point
	Visual search and scanning ability	No heat map
	Target acquisition	No heat map

1.6.5.2 Gaze plot

A gaze plot follows people's eye path and shows gaze fixations on a scene with the order of fixation occurrences. It summarizes the eyes' behavior by depicting solid colored dots and scan paths. It also demonstrates the sequences and order of eye movements by numbering each subsequent eye movement. The size of the circle is proportional to the fixation length. Bigger dots show that the participant spent more time looking at a specific area (Figure 27). In terms of these experiments, the gaze plot can help identify the most seen points and the points upon which the participants spent most time. One can understand the difference between the eye movement patterns of the concussed versus the non-concussed participants. It was expected that the non-concussed participants would spend less glance time on distractions and focus more on the target points with a more deliberate scanning pattern and less saccadic impairments.

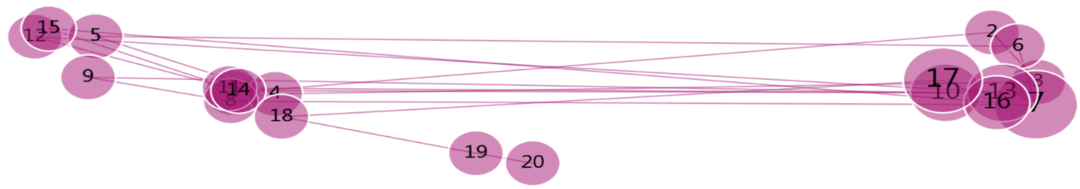

Figure 27- A sample Gaze Plot

Each of the experimental tests followed a specific goal and examined a particular eye movement behavior of the participants. So, not all of the described analysis methods were used in analysis of all tests.

CHAPTER 4

RESULTS

The gender and age of each of the participants, which were verified at the beginning of the study, are shown in figures 28 and 29. The results of other pre-study questionnaire are shown in table 5.

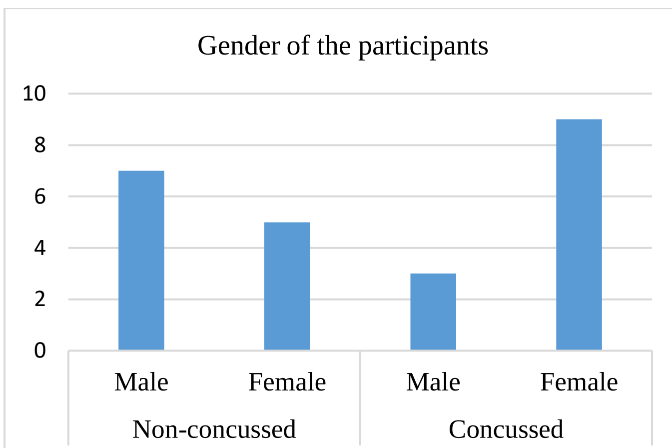

Figure 28- Gender of participants

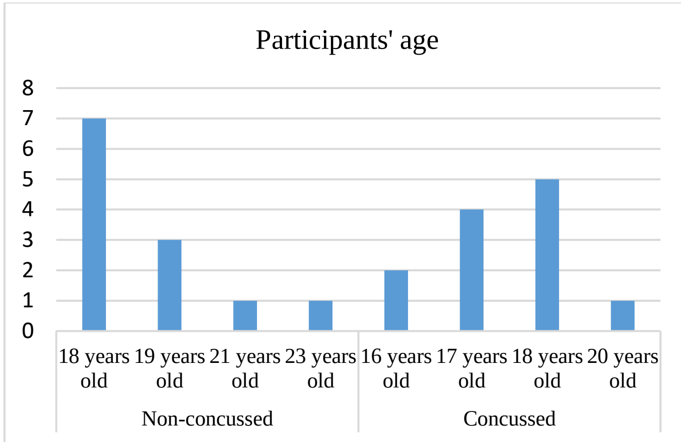

Figure 29- Age distribution of participants

Table 5- Pre-study questionnaire results

	Concussed participants (No.)	Non-concussed participants (No.)
Driver's license	12	12
Restriction	0	0
Violations	0	0
Accident	2	1

1.7 **Driving simulator tests**

1.7.1 Low fidelity test

For this test, the participants were asked to wear an eye-tracker, sit at a driving simulator and drive low fidelity scenarios. The participants' eye-tracking videos were used for the analysis.

The participants were asked to keep their speed between 30 to 35 mph and maintain their right of way. In this test, the Tobii pro II controller software was used for the analysis. The percentage of the time each participant fixated at the roadway, the speedometer, the rear, left or right mirrors, and the percentage of the time they fixated off the road, like trees and sky (distraction areas), was calculated. Moreover, the participant's average speed and the percentage of the time the speed was out of range (30- 35 mph) was also calculated. A two sample t-test has been executed to compare the differences between the times each participant needed to finish the drive. While on average, based on the Table 6 results, the concussed group appeared to finish the drive in shorter time (56.08 seconds) than the non- concussed group (58.42 seconds), the results did not show any significant difference between the two groups (Tables 7). Therefore, there was no significant difference between the two groups in terms of their average speed on a straight empty road.

Table 6- Group statistics result in straight road

	Group ID	N	Mean	Std. Deviation	Std. Error Mean
Average speed	1	12	36.20	7.039	2.032
	2	12	33.70	2.790	0.805

Table 7- Two sample t-test result for the straight road

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig.(2-tailed)	95% Confidence Interval of the Difference	
							Lower	Upper
Scenario duration	Equal variances assumed	3.64	.070	1.148	22	.263	-2.024	7.042
	Equal variances not assumed			1.148	14.37	.270	-2.167	7.186

As shown in figure 30, almost all of the non-concussed participants (Group 2) kept their speed in a reasonable range and they finished the scenario drive in sixty seconds, whereas the concussed participants (Group 1) showed more variability in speed.

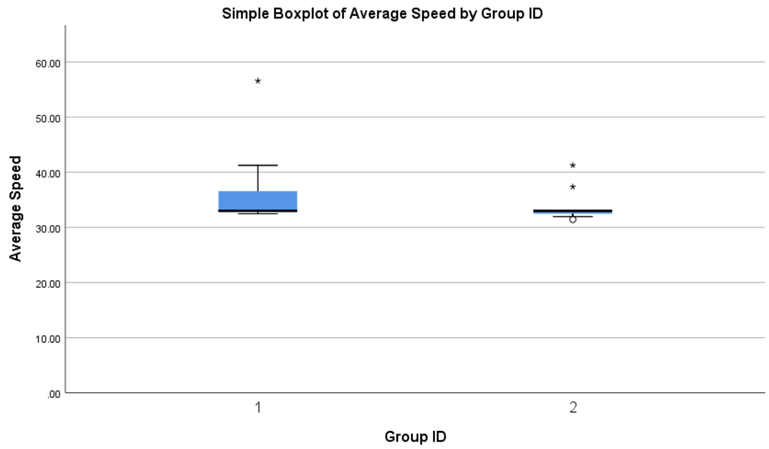

Figure 30- Average speed in straight road scenario

To compare the percentage of the time each participant's speed fell out of the range, a two sample t-test was conducted. The results showed that while there was a relatively significant difference between the mean of the two groups (Table 8), statistical analysis results do not show a significant difference (Table 9).

Table 8- Group Statistics results for falling out of speed range

	Group ID	N	Mean	Std. Deviation	Std. Error Mean
Speed Out of range %	1	12	34.74%	28.43%	8.20%
	2	12	19.75%	14.87%	4.29%

Table 9- Statistical analysis results for out of range speed

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	95% Confidence Interval of the Difference	
							Lower	Upper
Scenario duration	Equal variances assumed	4.88	.038	1.62	22	.120	-4.22%	31.19%
	Equal variances not assumed			1.62	16.60	.124	-4.58%	31.56%

Figure 31 shows that the percentage of the time the concussed participants' speeds (group 1) was out of range was more than the same criteria in non-concussed participants (group 2).

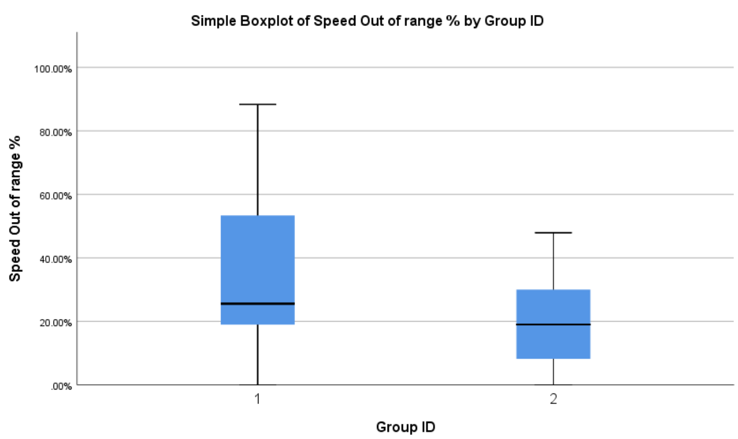

Figure 31- Percentage of the time spent on fixating off the road

With regard to the percentage of the time each participant spent on fixating off the road, the analysis showed a significant difference between the performances of the two groups in some regions. There were significant differences in the percentage of time the participants looked at the road in front of the car (called polygon) and looked at their mirrors (left mirror, right mirror or rear mirror) (Table 10).

Table 10- Independent Samples Test result for drivers' fixating off the road

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	95% Confidence Interval of the Difference	
							Lower	Upper
Road	Equal variances assumed	.08	.76	-2.06	20	.05	-31.55	.15
	Equal variances not assumed			-2.06	19.43	.05	-31.58	.18
Speedometer	Equal variances assumed	.27	.60	-.40	18	.69	-10.98	7.44
	Equal variances not assumed			-.40	17.79	.68	-10.88	7.35
Mirrors	Equal variances assumed	1.56	.24	2.38	9	.04	.069	2.55
	Equal variances not assumed			2.21	5.06	.07	-.20	2.82
total	Equal variances assumed	.00	.99	-1.68	22	.10	-43.73	4.50
	Equal variances not assumed			-1.68	21.56	.10	-43.76	4.53

In the portion of the test in which participants drove down a road with curves of different radii, the analysis results showed a significant difference between the driving performances of the participants in the two groups. The results showed (Tables 11) a significant difference between the times each participant finished the drive. Concussed patients drove at higher speeds.

The results showed a difference in the participants' tendencies to look away from the road. While the participants in control group spent more time focusing at the road and their mirrors, the concussed participants had more distracted eye movement and had a higher number of fixations off the road.

Table 11- Group statistics results for driving on a road with curves

	Group ID	N	Mean	Std. Deviation	Std. Error Mean
Average speed	1	12	32.45	2.53	0.73
	2	12	29.94	3.02	0.87
Off the road fixation (s)	1	12	9.25	10.23	2.95
	2	12	.25	.62	.17
Sp fixation (no.)	1	12	13.33	8.48	2.45
	2	12	18.67	6.44	1.86
No. of deviations	1	12	2.00	1.12	.32
	2	12	1.25	.96	.27
Speed Out of range %	1	12	16.03%	18.99%	5.48%
	2	12	0.41%	1.44%	0.41%

There was a slight difference in terms of the number of fixations while participants checked the speedometer. While the mean of the number of the concussed participants' fixations at the speedometer was relatively less than non-concussed participants' fixations (18.67 vs. 13.33), the statistical result did not show a significant difference between the two groups.

Although the results showed that the concussed participants were less able to control the car and had a greater number of deviations from their driving lane, the statistical analysis results did not demonstrate a significant difference between the two groups.

Table 12- Statistical analysis result for driving in the road with curves

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig.(2-tailed)	95% Confidence Interval of the Difference	
							Lower	Upper
Average speed	Equal variances assumed	1.101	.305	2.21	22	.037	.1622	4.879
	Equal variances not assumed			2.21	21.35	.038	.1581	4.883
Off the road fixation (s)	Equal variances assumed	24.85	.00	3.04	22	.00	2.86	15.13
	Equal variances not assumed			3.04	11.08	.01	2.49	15.50
Sp fixation (no.)	Equal variances assumed	.73	.39	-1.73	22	.09	-11.71	1.04
	Equal variances not assumed			-1.73	20.51	.09	-11.74	1.07
No. of deviations	Equal variances assumed	.01	.89	1.75	22	.09	-.13	1.63
	Equal variances not assumed			1.75	21.48	.09	-.14	1.64
Speed Out of range %	Equal variances assumed	17.32	.00	2.84	22	.01	4.21%	27.02%
	Equal variances not assumed			2.84	11.12	.01	3.53%	27.70%

The results showed that concussed group had a higher incidence of distracted driving, as demonstrated by a greater number of instances looking away from the road. The difference between the percentages of time each participant spent while driving distracted and looking off the road is shown in table 12.

1.7.2 High fidelity test

In the high fidelity driving simulator test, the participants were asked to wear the eye-tracker and drive several scenarios in a driving simulator. The drive consisted of scenarios with potential latent hazards. The participants were asked to drive, scan for the latent hazard and mitigate the hazards. The eye-tracking videos were used for the analysis. The participants' fixation points were recorded with the eye-tracker. The participants' fixation points were mapped and used as the analysis metrics. For instance, if the participants fixated at the hazardous area and slowed down to mitigate the hazard, it was assumed the participant anticipated the hazard and coded as "one". Otherwise, it was coded as "zero". Blind scoring was utilized for each participant. For each of the six scenarios, each participant received a score (zero or one) based on their hazard anticipation behavior. So, by the end of the analysis, 164 binary numbers were extracted (twenty-four participants multiplied by six scenarios). Then a two proportion test analysis was executed to examine if the difference in hazard anticipation skill between the concussed and non-concussed groups is significant.

SPSS two proportion test and chi-squared test results showed a significant difference between the hazard anticipation skills of the participants with concussion symptoms and the participants without concussion symptoms (Tables 13 and 14). The results showed that the concussed patients were less able to recognize and fixate at the hazardous area. On the other hand, the participants without concussions symptoms were more successful in hazard anticipation and they were more able to mitigate the hazard. They also had more fixations and they fixated at the hazardous area more deliberately.

Table 13- Cross tabulation results in SPSS for high fidelity test

		Number of correct anticipation						
		1	2	3	4	5	6	Total
Group No.	1	4	2	2	3	1	0	12
	2	0	2	3	3	3	1	12
Total		4	4	5	6	4	1	24

Table 14- Chi-Square test results in SPSS for high fidelity test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	6.200[a]	5	.287
Likelihood Ratio	8.179	5	.147
Linear-by-Linear Association	4.316	1	.038
N of Valid Cases	24		

a. 12 cells (100.0%) have expected count less than 5. The minimum expected count is .50.

Figure 32 shows that the concussed participants (Group 1) showed a wider range in their ability to anticipate and mitigate hazards, whereas the non-concussed participants (Group 2) were more able to do so.

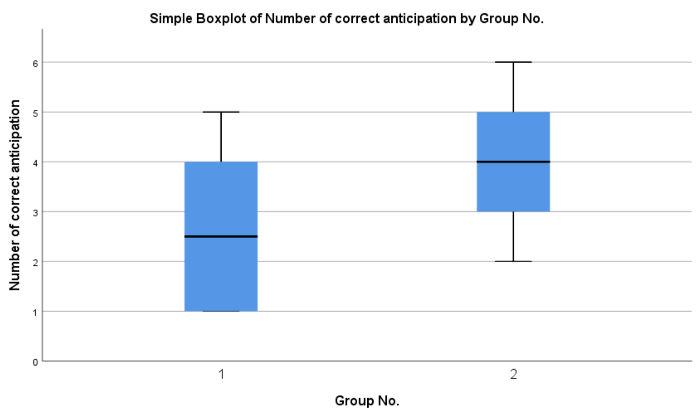

Figure 32- Number of hazard recognition

1.8 Non- simulator tests

1.8.1 Horizontal Saccades

Using SPSS, the results show a significant difference between the eye movement patterns of the concussed versus non-concussed participants. The non-concussed participants had significantly more accurate eye movements from one point to another point. Their fixation points were closer to the target points (A & B). The vertical (X), horizontal (Y) and total distances from the target points (D) were calculated. Significant differences between the fixation points' distances – in horizontal, vertical and total distance – were seen between two groups. Table 15 shows the statistical analysis results.

Table 15- ANOVA statistical analysis of horizontal saccades test

		df	F	Sig.
X	Between Groups	1	4544.959	.000
	Within Groups	27358		
	Total	27359		
Y	Between Groups	1	89836.456	.000
	Within Groups	27358		
	Total	27359		
Distance from zero	Between Groups	1	21487.905	.000
	Within Groups	27358		
	Total	27359		

As shown in figures 33 and 34, the concussed participants attempted to fixate at the two targeted points were less accurate. The non-concussed participants, on the other hand showed more accurate fixations. The concussed participants were unable to fixate accurately on two separate points and instead fixated on random point between the two targets.

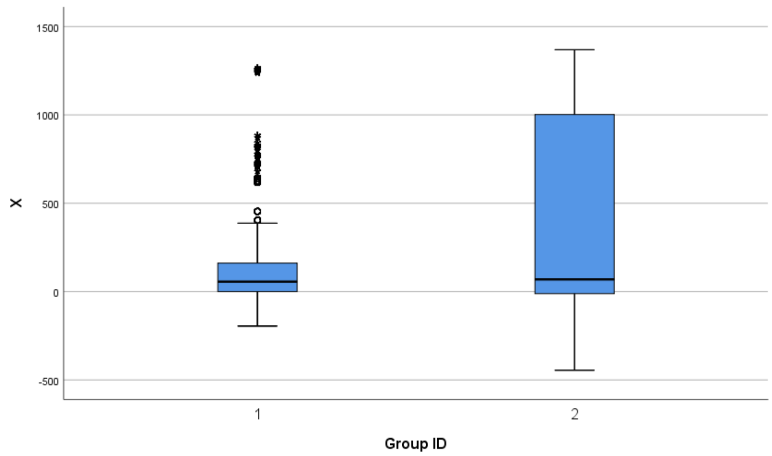

Figure 33- Horizontal distance of fixation points from origin

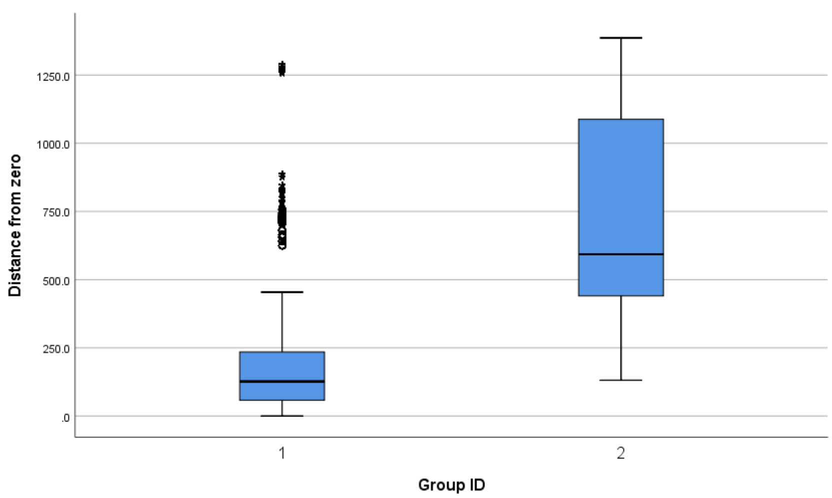

Figure 34- Total distance from origin

Not only were the concussed group less able to fixate at the target points accurately, they showed more undeliberate fixations and gaze points. Figure 35 illustrates the difference in convergence of the fixation points of the concussed and non-concussed participants. As the figure shows, the non-concussed participants' fixation points showed more condensed fixation points while the results express more spread and undeliberate fixation points in concussed participants.

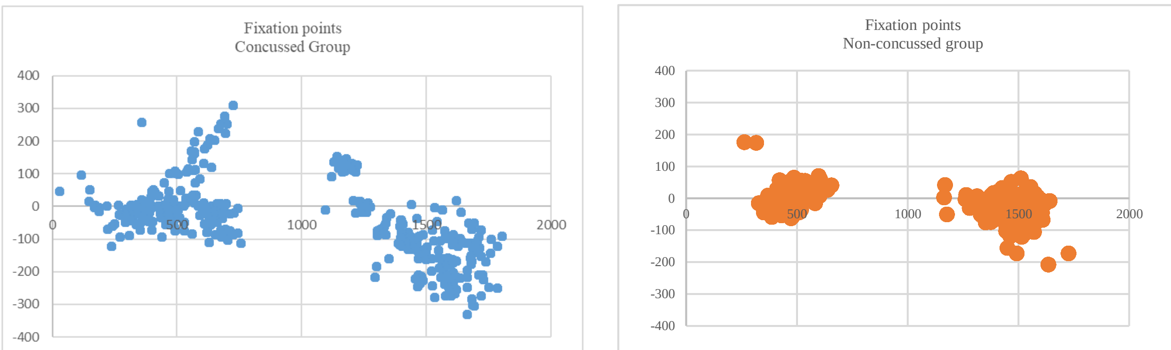

Figure 35- Fixation points of concussed (left) vs. non-concussed (right) participants

In addition to more accurate and more deliberate eye movements, the non-concussed participants showed significantly faster eye movements when moving their eyes back and forth between two target points. The amount of time in which the non-concussed participants were able to look back and forth between two target points in ten seconds was significantly greater in comparison with same amount in concussed patients. This shows a faster cognitive processing in non-concussed participants.

According to Fitt's Law (Fitts, 1954), when moving back and forth between two points with your fingers or looking back and forth, the faster the finger or the eyes move, the less accurate movement is expected. It means that, when one group shows more accurate eye movements it is expected to have a fewer number of unfocused jumps in a specific period of time. However, while the non-concussed group showed less accurate gaze points, they had fewer target hits. This can be a result of their injuries.

In the case of assessing the cognitive test data from the participants, the eye-tracking visual analysis may provide a better insight into the information that patients were processing and how they implemented what they were asked to do. Figure 36 shows a sample heat map of a concussed and a non-concussed participant.

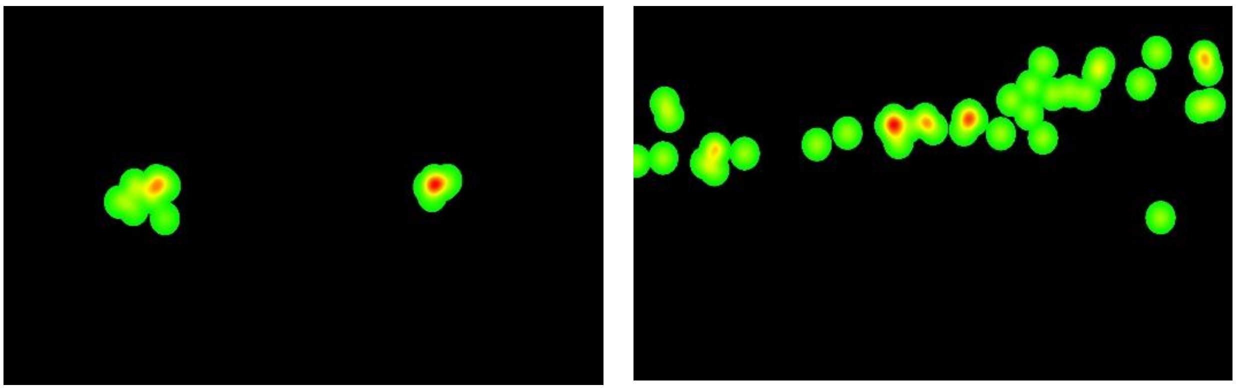

Figure 36- Heat map of the non-concussed (left) and concussed (right) participants

1.8.2 Horizontal Vestibular Ocular Reflex Test

For this experiment, the distances of each participant's fixation points from the target point were calculated. The distances include the longitudinal distance (X), the latitudinal distance (Y) and the total distance from the target point (D). The SPSS results show a significant difference between the fixation point's distances (X, Y and D) of the concussed group and the non-concussed group (Table 16). This means that the participants with concussions symptoms were less able to focus on the target point and more likely to have longitudinal and latitudinal fixation points around the target points.

Table 16- ANOVA Statistical analysis for the Horizontal Vestibular Ocular Reflex Test

		df	F	Sig.
X	Between Groups	1	49.861	.000
	Within Groups	76512		
	Total	76513		
Y	Between Groups	1	8864.298	.000
	Within Groups	76512		
	Total	76513		
Distance from zero	Between Groups	1	1534.590	.000
	Within Groups	76512		
	Total	76513		

As shown in figures 37, 38 and 39, the box plot and the scatter plot for the horizontal vestibular ocular reflex test show that in comparison with the non-concussed participants (Group 2), the concussed participants (Group 1) had more wide-spread fixation points.

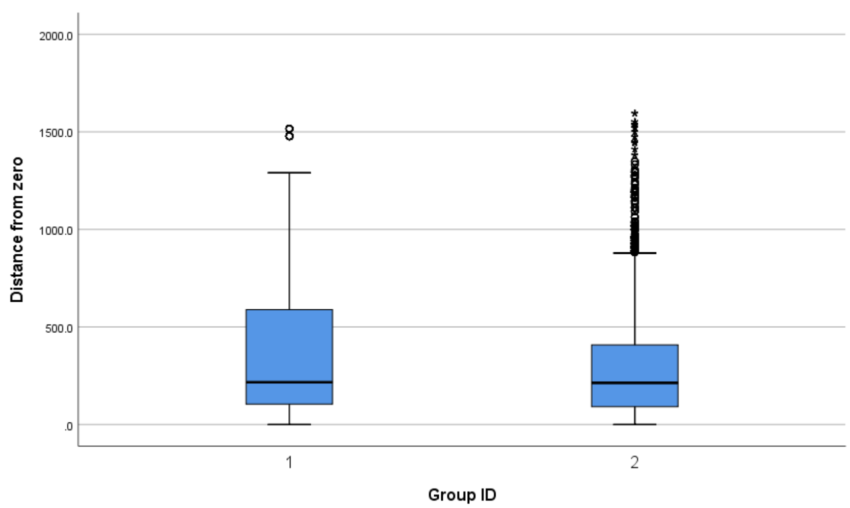

Figure 37- Box plot for the Horizontal Vestibular Ocular Reflex Test

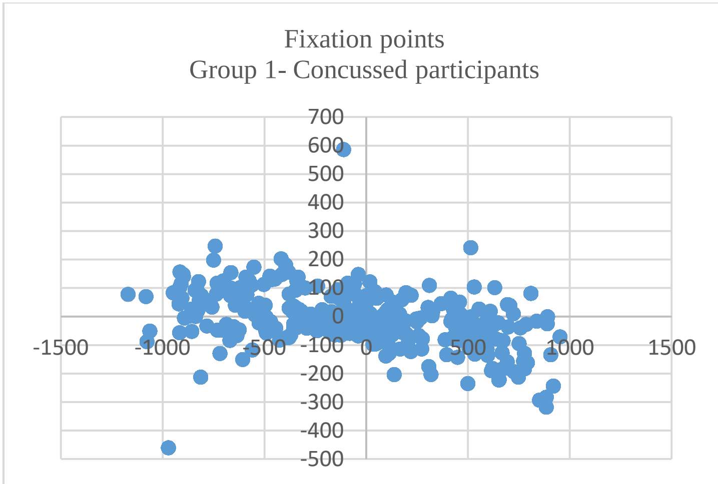

Figure 38- Fixation points for the concussed participants in the Horizontal Vestibular Ocular Reflex Test

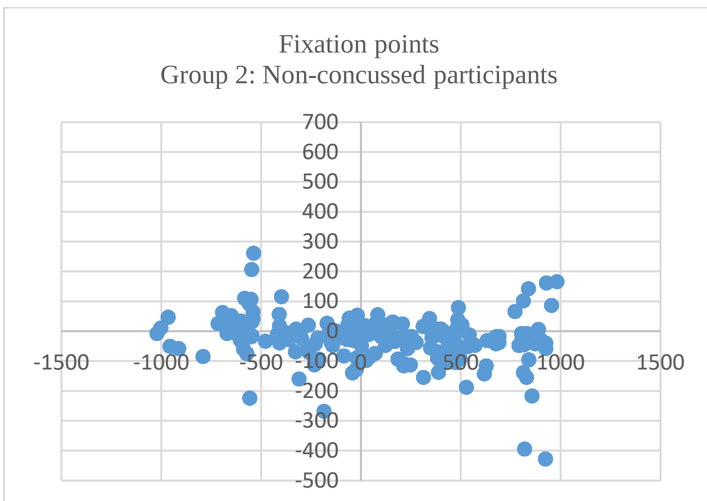

Figure 39- Fixation points for the non-concussed participants in the Horizontal Vestibular Ocular Reflex Test

As visually demonstrated, the heat map and gaze plot of a concussed and a non-concussed participant is shown in Figure 40 and 41. While the concussed patient has more random gaze points and a more wide-spread heat map, the non-concussed participant was able to focus at the target point and had less saccadic eye movements.

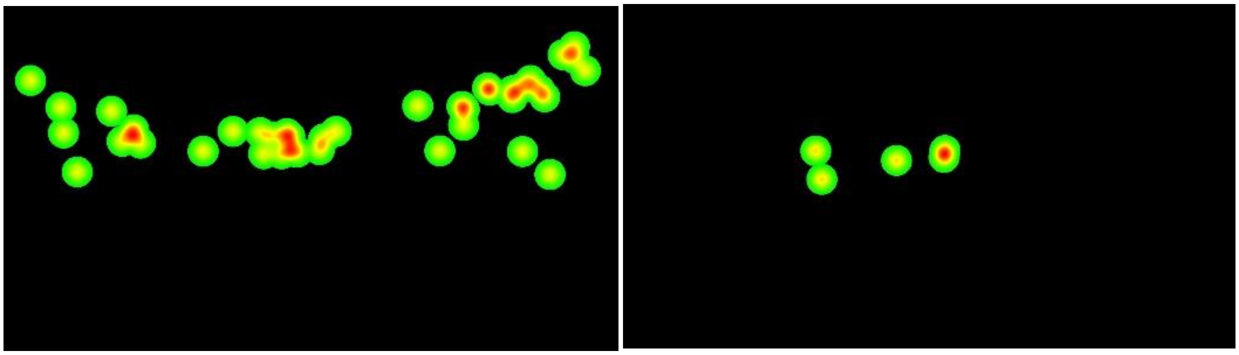

Figure 40- Heat map of the concussed (left) and non-concussed (right) participants for the non-concussed participants in the Horizontal Vestibular Ocular Reflex Test

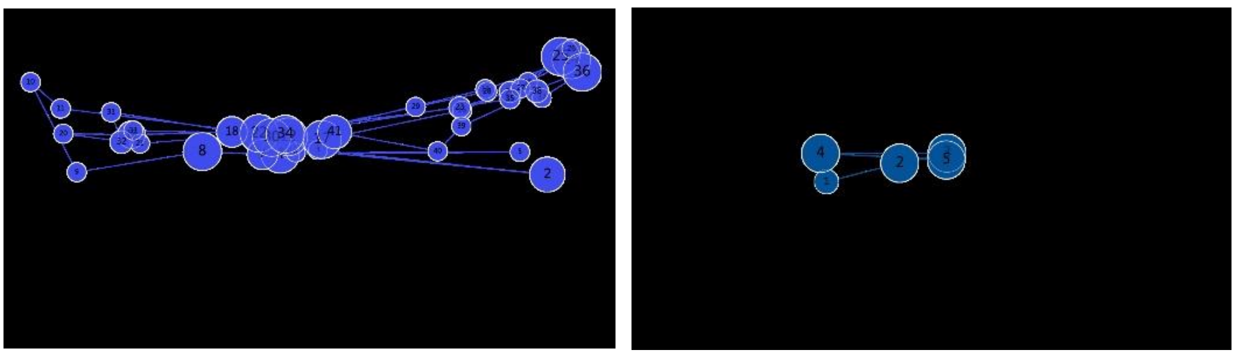

Figure 41- Gaze points of the concussed (left) and non-concussed (right) participants in the Horizontal Vestibular Ocular Reflex Test

The non-concussed subjects were able to concentrate at each point more appropriately with less distracted gazes, so they showed a greater frequency, a mean center point closer to the zero point and a smaller standard distance deviation. This shows the level of their concentration ability because the non- concussed participants are more capable of fixating at a specified point with less eye vibrations. The average of standard deviations for the concussed group was equal to 233.89, which is relatively higher than the average of standard deviations for the non-concussed group, which was 195.06.

1.8.3 Visual search and scanning ability

For this experiment, each participant completed three visual search tests. The first test was a simple visual search test. The second one was a moderate test and the third one was a hard visual search test. The test durations per each participant (find the targeted letter) per test were calculated. The total time for each participant to finish all the three tests was also calculated. A one-way ANOVA test was implemented to investigate whether or not there was a significant difference between the response times for two groups. The SPSS results show a significant difference in response time between the concussed and non-concussed group. This means that the participants with concussions symptoms relatively spent more time to find the target letter in each test. However, the results for each test shows a significant difference between two groups for each test exist for the easy and moderate test (Tables 17 & 18), while for the hard tests, the differences were not significant (Table 19). In total a significant difference between two groups was shown in table 20.

Table 17- Response time ANOVA analysis for the easy visual search test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	8.036	1	8.036	7.299	.014
Within Groups	20.917	19	1.101		
Total	28.952	20			

Table 18- Response time ANOVA analysis for the moderate visual search test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	57.143	1	57.143	5.322	.032
Within Groups	204.000	19	10.737		
Total	261.143	20			

Table 19- Response time ANOVA analysis for the hard visual search test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.683	1	2.683	.379	.546
Within Groups	134.556	19	7.082		
Total	137.238	20			

Table 20- Response time ANOVA analysis for visual search test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	48.255	1	48.255	6.558	.013
Within Groups	448.824	61	7.358		
Total	497.079	62			

As shown in figure 42, in comparison with the non-concussed group (Group 2), the concussed group (Group 1) spent more time finishing the test for all test levels.

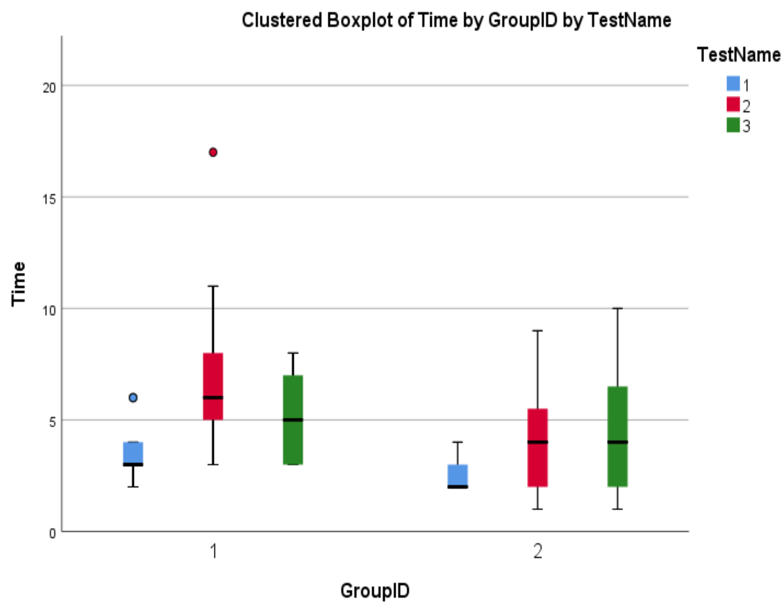

Figure 42 -Box plot for response time of the visual search and scanning ability

As visually shown, the difference between heat map and gaze plot of a concussed and a non-concussed participant is illustrated in Figures 43 to 48. The concussed patient has more random gaze points and a more wide-spread heat map which results in skipping from the target letter while taking a glance at it. The non-concussed participants, on the other hand, were more able to focus at the target letter in their mind and spent less time to click at the target letter.

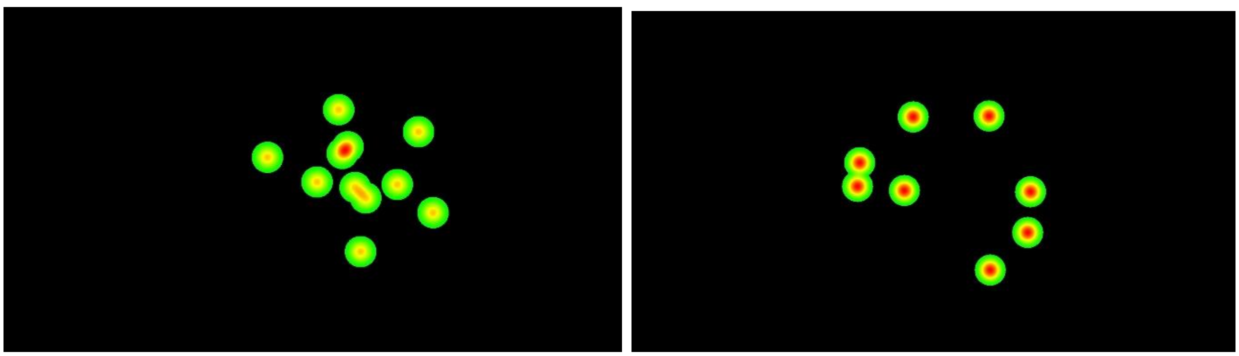

Figure 43 -Heat map of the concussed (left) and non-concussed (right) participants- Easy test

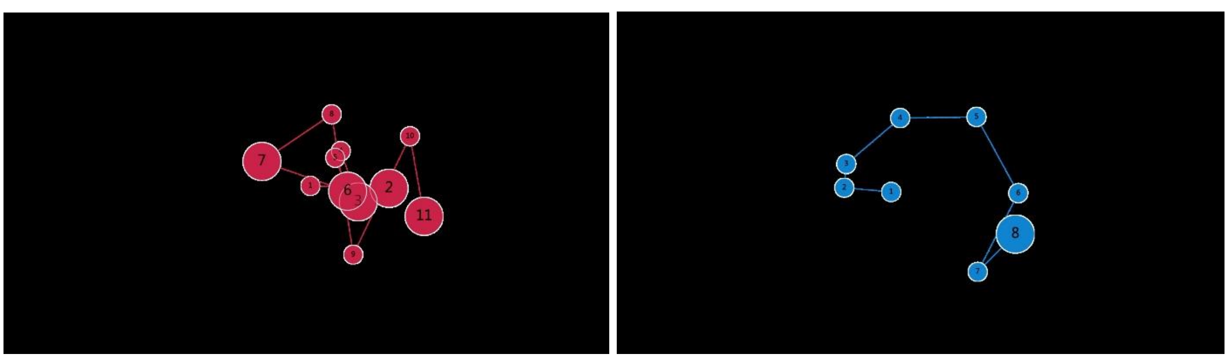

Figure 44 - Gaze points of the concussed (left) and non-concussed (right) participants- Easy test

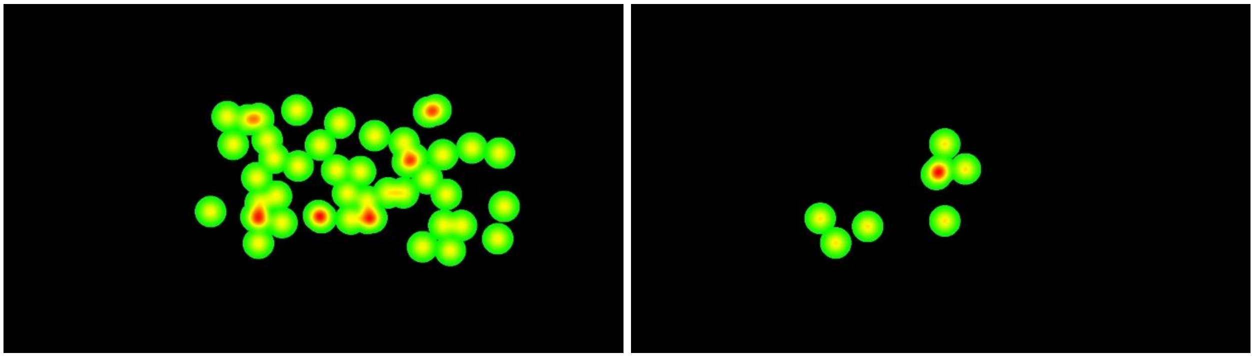

Figure 45 - Heat map of the concussed (left) and non-concussed (right) participants- Moderate test

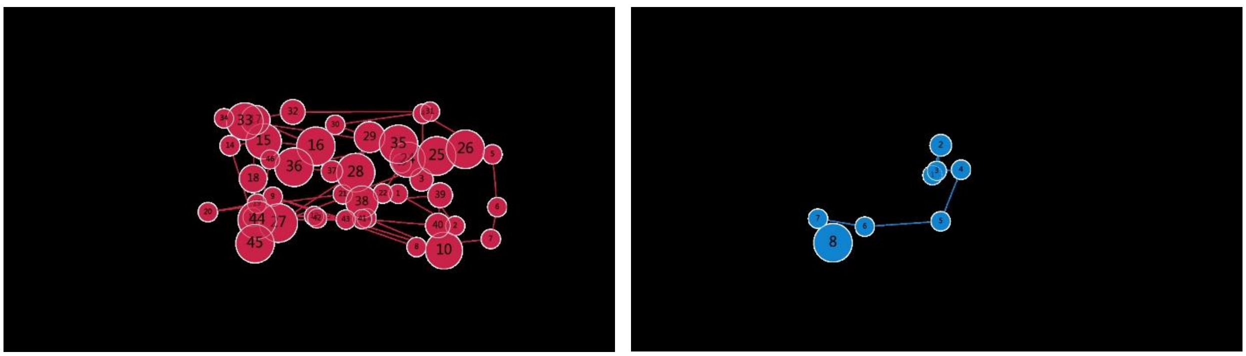

Figure 46- Gaze points of the concussed (left) and non-concussed (right) participants- Moderate test

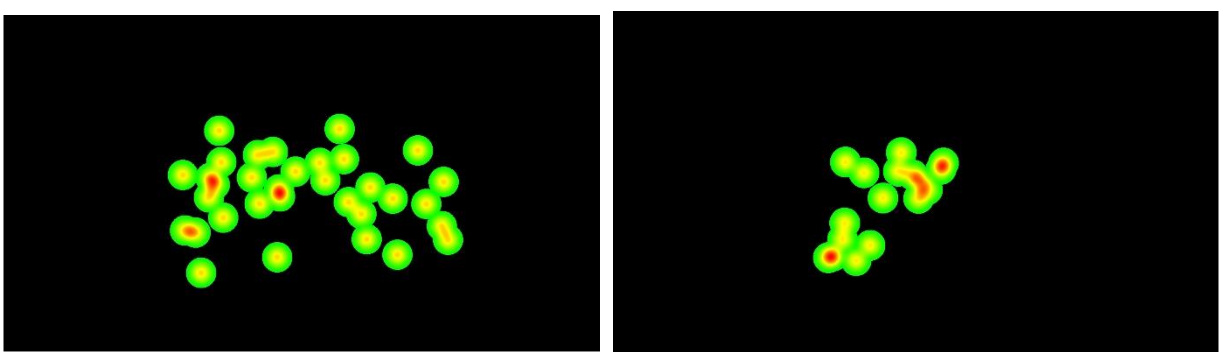

Figure 47- Heat map of the concussed (left) and non-concussed (right) participants- Hard test

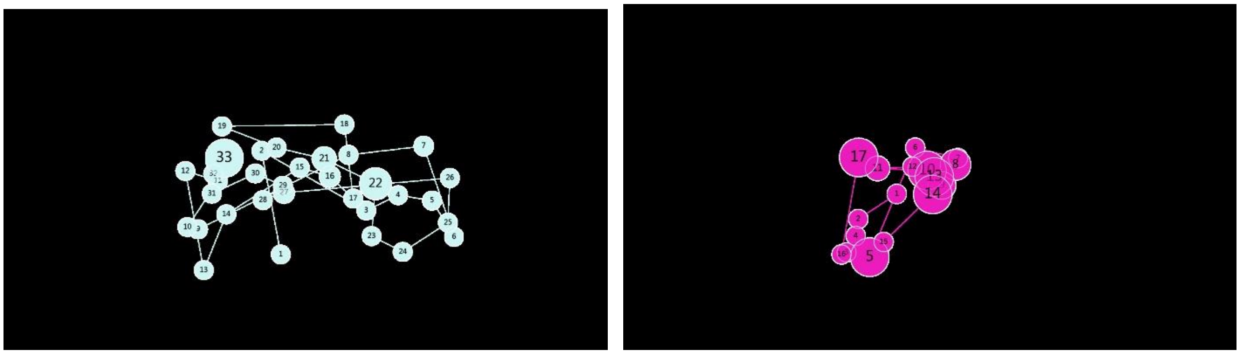

Figure 48- Gaze points of the concussed (left) and non-concussed (right) participants- Hard test

1.8.4 Target Acquisition

For the target acquisition test, the total time that each participant spent to drag and drop the balls to the basket and the number of successful drops were calculated. The statistical analysis showed that, in general, there is no significant difference between the response time and the number of correct drops of the concussed and non-concussed participants (Table 21).

Table 21- ANOVA Statistical analysis for the Target acquisition test

		Sum of Squares	df	Mean Square	F	Sig.
Total time	Between Groups	51.042	1	51.042	.645	.431
	Within Groups	1741.917	22	79.178		
	Total	1792.958	23			
Correct	Between Groups	2.042	1	2.042	.985	.332
	Within Groups	45.583	22	2.072		
	Total	47.625	23			

Figures 49 and 50 show that the differences between the response time and number of correct drops in concussed (Group 1) and non-concussed participants were not significant. However, on average the concussed group had smaller numbers of correct drops and spent more time finishing the test.

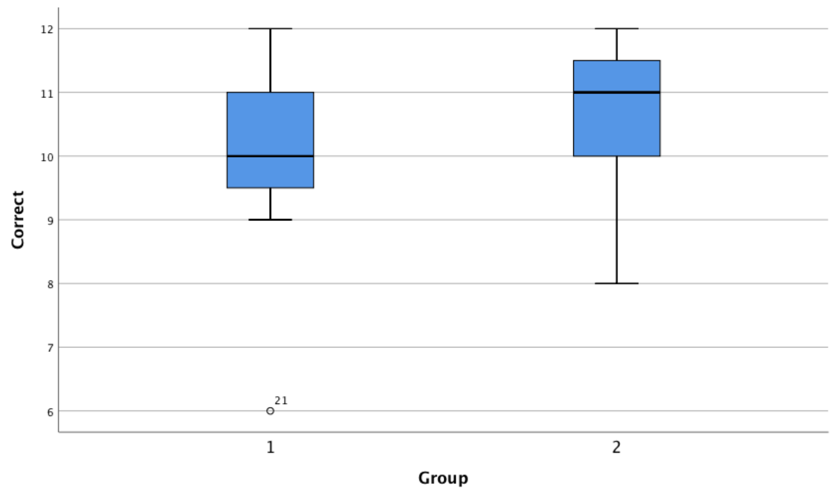

Figure 49- Box plot for number of correct drops in target acquisition test

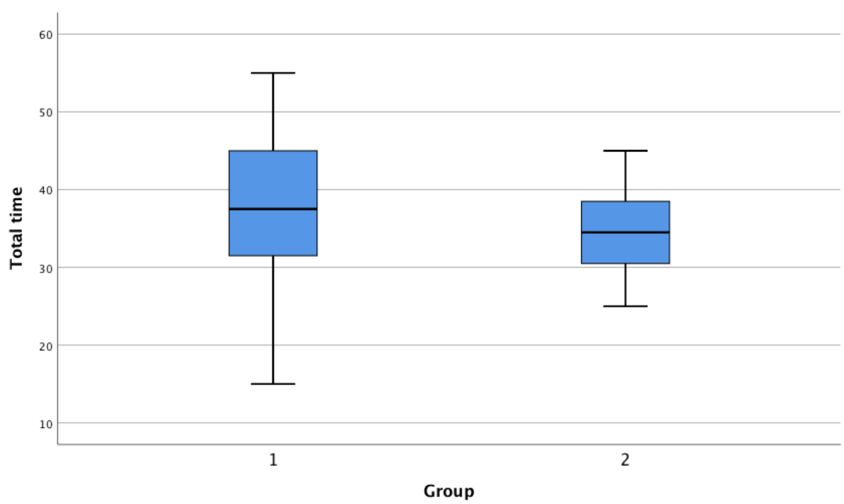

Figure 50- Box plot for response times in target acquisition test

Figures 51 and 52 show the heat map and gaze plot of a concussed and a non-concussed participant. As it is shown in figure 50, while the healthy participant mostly focused on the balls (bottom right hand) and the basket (upper left hand), the non-concussed participant had more random fixations on other areas and they also spent more time on the on areas around the balls and basket.

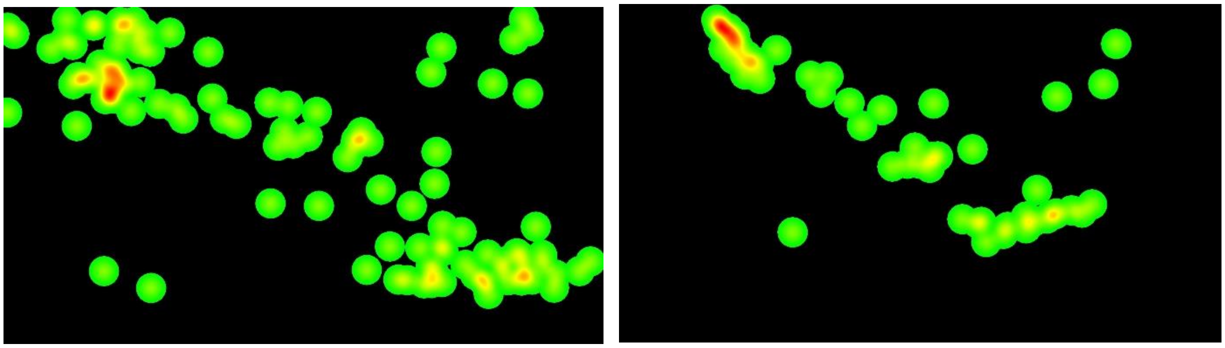

Figure 51- Heat map of the concussed (left) and non-concussed (right) participants for the Target acquisition test

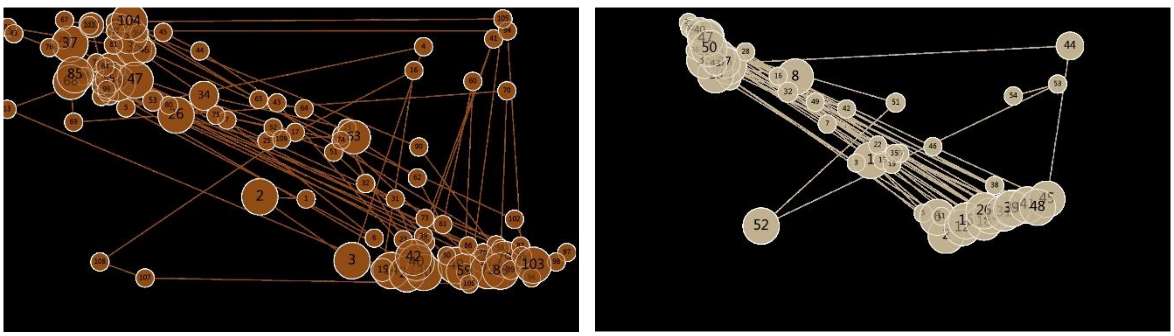

Figure 52- Gaze points of the concussed (left) and non-concussed (right) participants for the Target acquisition test

1.8.5 Horizontal Smooth Pursuits

In the horizontal smooth pursuits test, the participants were asked to follow a solid circle, which moved back and forth horizontally on a monitor in front of them. The participants were asked to follow the circle with their eyes while trying to keep their head fixed. Their eye movements were recorded. Their fixation points were normalized by considering the start fixation point of each participant (the circle is on the left side of the screen) as the origin and calculate the position of other fixation points based on the origin. The vertical and horizontal distances of fixation points from the origin were calculated. Since the vertical deviation of the fixation points from the moving circle is important, a one-way ANOVA was applied to this test. The results show a significant difference between the vertical deviations of fixation points in concussed versus non-concussed group (Table 22). This means that the non-concussed group were more able to follow the moving circle with a lesser deviation and smoother eye movements.

Table 22- ANOVA Statistical analysis for the Horizontal Smooth Pursuits

		df	F	Sig.
Gaze point Y	Between Groups	1	332.68	.000
	Within Groups	26017		
	Total	26018		

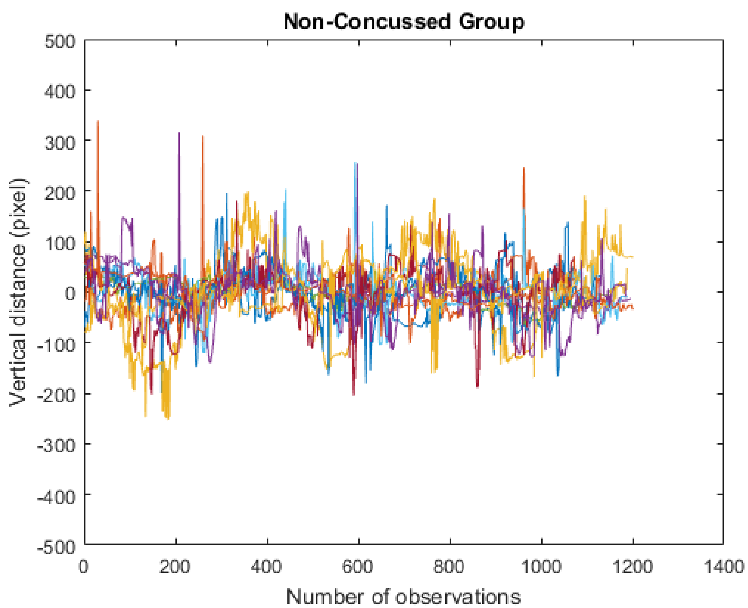

Figure 53- Vertical fixation deviations for the non-concussed participants for the Horizontal Smooth Pursuits

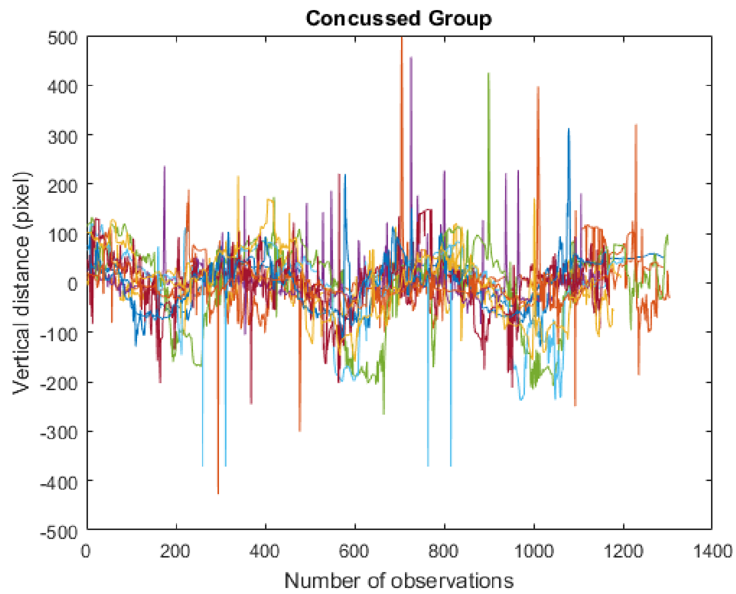

Figure 54- Vertical fixation deviations for the concussed participants for the Horizontal Smooth Pursuits

As illustrated in figures 53 and 54, the non-concussed group in comparison with the concussed group has a smaller standard deviation resulting in a smaller lower and upper control limit, which shows that the concussed group has relatively lesser control on their eye movement pattern and has more eye movement vibrations. Figures 55 and 56 supports the test results. The different between the variances and numbers of fixation points of the participants' in each group is shown on heat maps and gaze plots.

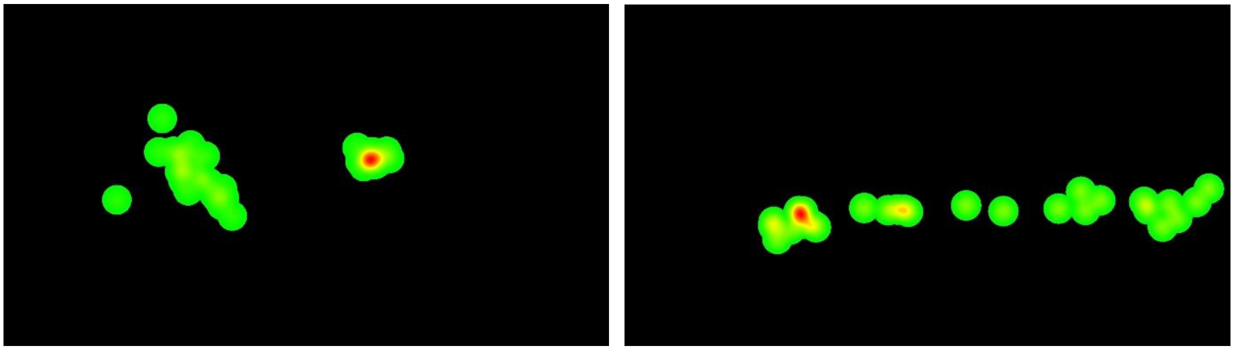

Figure 55- Heat map of the concussed (left) and non-concussed (right) participants for the Horizontal Smooth

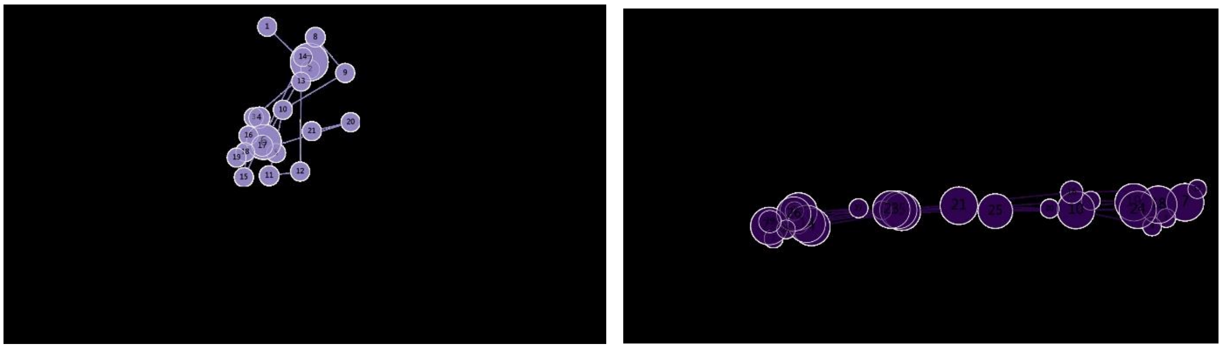

Figure 56- Gaze points of the concussed (left) and non-concussed (right) participants for the Horizontal Smooth

Figures 57 and 58 show histograms of the peaks in fixation points in concussed and non-concussed participants who are doing a horizontal smooth pursuit test using Matlab. An example of Matlab code which was used for the peak analysis is shown in figure 59.

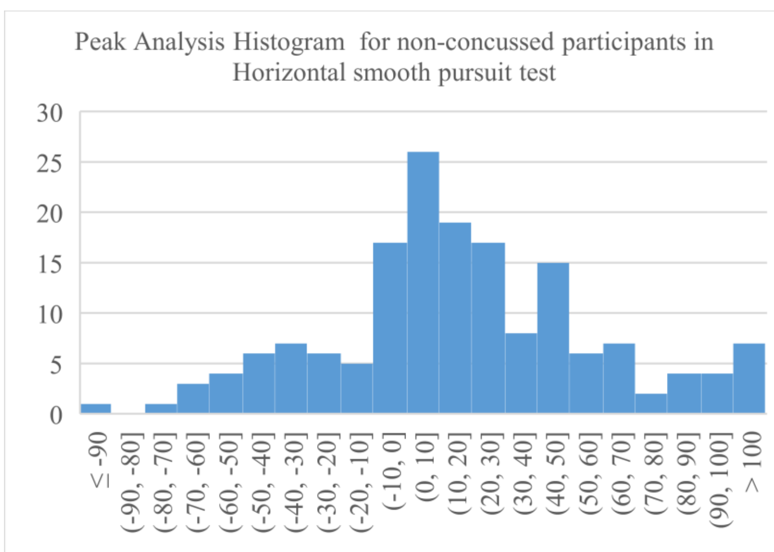

Figure 57- Peak analysis histogram for non-concussed participants in Horizontal smooth pursuit test

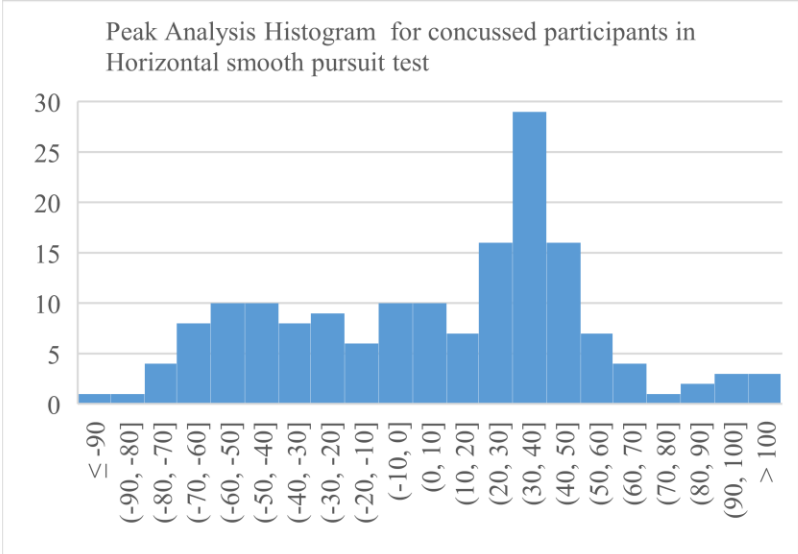

Figure 58- Peak analysis histogram for concussed participants in Horizontal smooth pursuit test

```
HC=xlsread('HSP.xlsx','Control');
nHC=11;

for i=1:nHC
    peak0=findpeaks(HC(:,nHC+i));
    for j=1:length(peak0)
        peak(j,i)=peak0(j);
    end
end
xlswrite('HCPeak.xlsx',peak)
```

Figure 59- Matlab code for peak analysis

1.8.6 Vertical Smooth Pursuits

In this test, the participants were asked to follow a moving circle appeared on a monitor in front of them with their eyes without moving their heads. The circle moved vertically. The participants' eye movements were recorded. The SPSS results show a significant difference between the two groups in terms of eye movements' characteristics (Table 23). While the participants were asked to keep their eyes focus at the moving circle and try not to deviate from it, the concussed group were less able to do so. They showed relatively a higher level of deviation, which means the less smooth vertical eye movements.

Table 23- ANOVA Statistical analysis for the Vertical Smooth Pursuits

X origin			
	df	F	Sig.
Between Groups	1	159.232	.000
Within Groups	22438		
Total	22439		

As illustrated in figures 60 and 61, the non-concussed group in comparison with the concussed group has a smaller standard deviation resulting in a smaller lower and upper control limit, which shows that the concussed group has relatively lesser control on their eye movement pattern and has more eye movement vibrations.

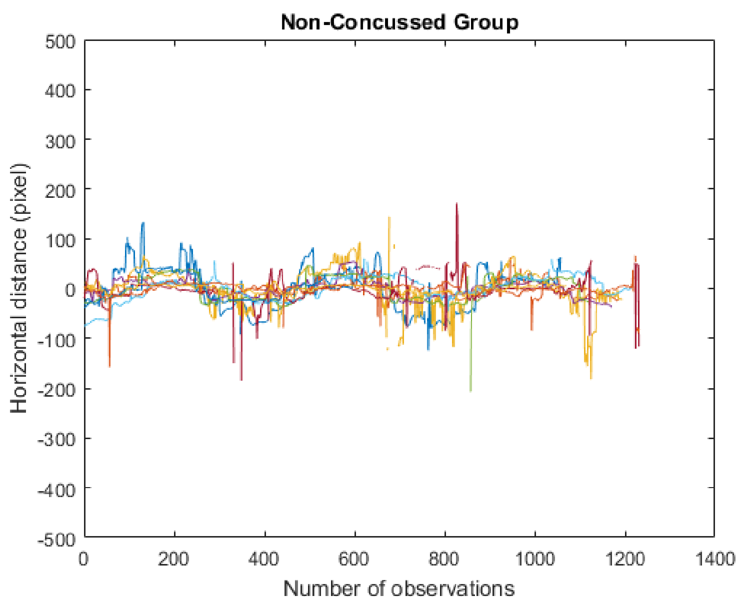

Figure 60- Horizontal fixation deviations for the non-concussed participants for the Vertical Smooth Pursuits

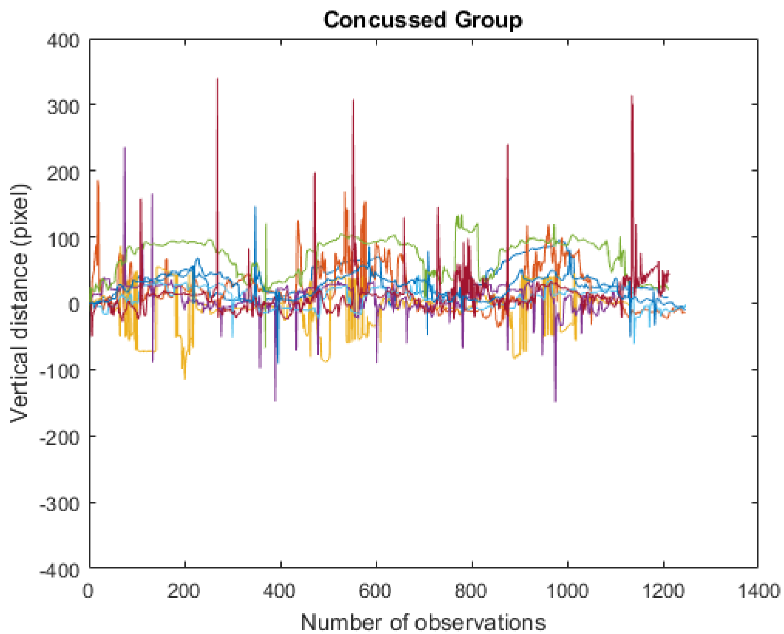

Figure 61- Horizontal fixation deviations for the concussed participants for the Vertical Smooth Pursuits

Figures 62 and 63 supports the test results. The different between the variances and numbers of fixation points of the participants' in each group is shown on heat maps and gaze plots.

Figure 62- Heat map of the concussed (left) and non-concussed (right) participants for the Vertical Smooth Pursuits

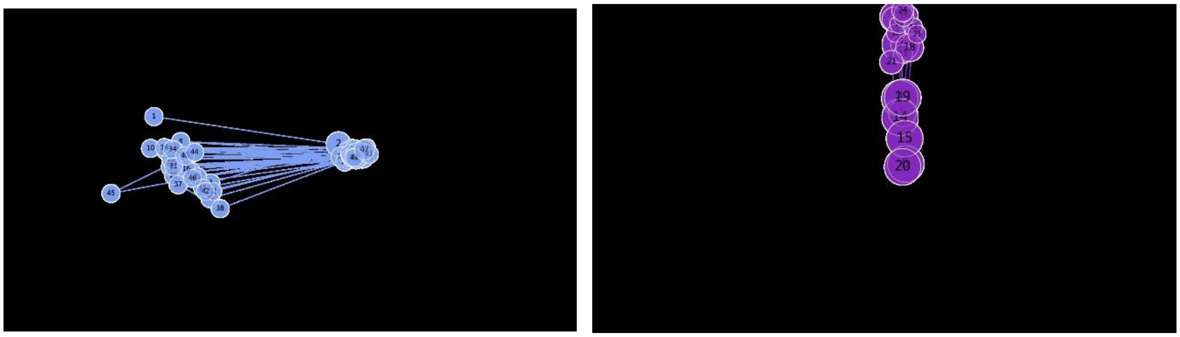

Figure 63- Gaze points of the concussed (left) and non-concussed (right) participants for the Vertical Smooth Pursuits

Figures 64 and 65 show histograms of the peaks in fixation points in concussed and non-concussed participants who are doing a vertical smooth pursuit test using Matlab.

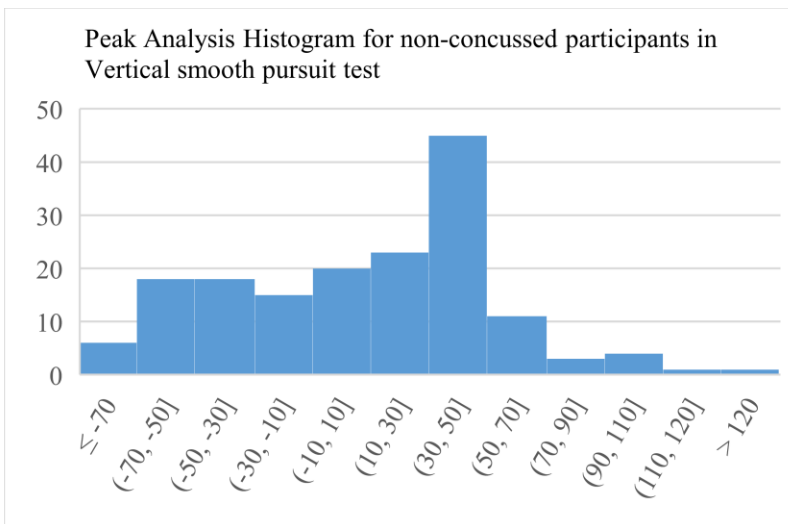

Figure 64- Peak Analysis Histogram for non-concussed participants in Vertical smooth pursuit test

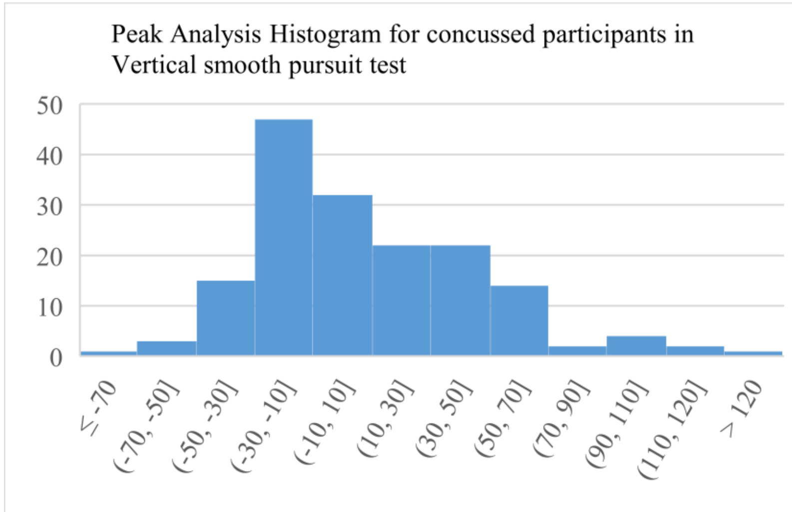

Figure 65- Peak Analysis Histogram for concussed participants in Vertical smooth pursuit test

CHAPTER 5

CONCLUSION

The non-concussed participants in the study were expected to show a statistically significant difference in comparison to the concussed participants. They were expected to show more stable patterns with lower standard deviations. They were also anticipated to show more deliberate and tactical gaze points and eye movement patterns.

In this study, an eye-tracker was utilized for assessment of concussion by means of cognitive tests. It is hoped that the testing methodologies developed will assist doctors and physical therapists who diagnose concussions. Existing methodologies for concussion diagnosis are very subjective and open to interpretation. This method provides a means to more objectively diagnose a concussion and track healing progress with follow-up testing. Application of this methodology and these techniques should assist doctors with objective diagnosis of concussion by using an eye-tracker and implementing cognitive tests such as a horizontal vestibular ocular test. In addition, they will be able to assess the extent of healing in concussed patients by using the follow-up testing techniques.

5.1 Driving simulator tests

The driving simulator test results showed a significant decline of the driving performance of the teen drivers after a concussion. Drivers with concussion symptoms tended to drive relatively faster and spend more time looking at their environment. They had more undeliberate eye movements. One of the reasons might be because concussions can affect the brain's ability to stay focused on a specific task.

Since driving is a complex task which needs a high level of attention, driving while attention and focusing skills are impaired is risky. So, looking at driving performance results such as speed maintenance disability, inattention, and distraction while driving can address the issues of impairment that a driver with a concussion might have.

The results showed that concussed patients drive relatively faster than non-concussed drivers do. One of the reasons might be due to the driver's difficulty understanding the risk of excessive speed. It suggests that a concussed driver might be unable to comprehend their relative driving speed, rather than purposefully intending to exceed a safe driving speed.

Based on the experiment results, the concussed group tended to show more distracted driving and to spend more time looking away from and fixating on objects off the road. While non-concussed participants were more likely to focus on the road, speedometer and mirrors, the concussed participants showed more random and distracted eye movements. More undeliberate eye movement is one of the symptoms of concussion. The concussed group were also less able to control the car and showed greater number of deviations from their straight lane. There may be two causes for this. First, due to the concussed drivers' cognitive limitations, they cannot focus on their driving tasks, so they demonstrated more undeliberate maneuvers. Second, they usually have physical limitations such as difficulty with balance and fine motor movement.

With regard to hazard anticipation skills, in general, the results demonstrate that when encountering a potential hazard, a healthy teen driver was more likely to be able to control the situation. They were more able to scan for the hazard showing greater numbers of fixations. They felt more confident during driving in comparison with the concussed patients. One of the primary goals of this study was to investigate the effect of a concussion on hazard anticipation skills of the teen drivers. The results showed a significant difference between the hazard anticipation ability of the concussed and the non-concussed participants. While the concussed participants showed difficulty recognizing, reacting and mitigating the hazards, the non-concussed teens were more likely to scan and focus at the hazardous area and react properly.

This was demonstrated by the eye tracking results, which showed a significant difference between the two groups. While the non-concussed participants were more able to identify, focus, and fixate on the hazardous area, the concussed participants showed significantly more frequent distracted eye glances, were less able to focus, and showed less deliberate eye movements. The results support existing research that shows that patients with concussion symptoms have great difficulty keeping their eyes focused on targets (Katrahmani & Romoser, 2018b, 2018a). One of the potential reasons might be the effects of concussion on the brain.

Analyzing participants' data from the eye-tracker, we can conclude that it is difficult to interpret if a concussed patient is fit-to-drive. For instance, the level of impairment in hazard anticipation skills is not very clear. It is because in the simulator scenarios, the hazards presented were not rated for severity of danger or risk. For instance, in the situation where a driver was able to identify a hazard, but unable to recognize the next hazard, and another driver behaved the opposite by not identifying the first, but correctly appreciating the second, both driver reactions were measured as one correct hazard anticipation and one missed hazard. However, the risk level and the consequences of each hazard has not been identified. In general, decision making regarding whether or not a person is fit-to-drive needs more research focusing on different aspects of driving skills.

In conclusion, further investigation on the effects of concussion on the driving behavior of teen drivers is critically important. This experiment has demonstrated that using the eye-tracking data is a useful way to find the residual damage of a concussion on our study participants. The results of this study suggest a need for further research on teen drivers who have suffered a concussion.

5.2 Non-simulator tests

5.2.1 Horizontal Saccades

The results showed that using an eye-tracker provided a helpful concussion assessment tool. Patients with concussion symptoms showed a higher level of saccadic impairments when compared to non-concussed people. Concussed participants were less able to control their eye movements and move their eyes back and forth between two targets. They were less able to fixate at the targets, and their fixation points were less accurate.

In addition, concussed participants showed more undeliberate eye movements. In a fixed time period, concussed participants showed more random and unnecessary fixations, mostly far from the target points. In the case of eye movements' speed, in comparison with non-concussed participants, concussed participants had difficulty moving their eyes rapidly while trying to fixate on targets. In comparison to non-concussed participants, they had slower eye movements and less accuracy with target fixations within a specific time period.

5.2.2 Horizontal vestibular ocular reflex (VOR).

The purpose of this test was to compare the VOR responses of the concussed group to those of the non-concussed group and establish whether this method would be a useful methodology for concussion diagnosis. The eye-tracking results showed that concussed patients had a higher frequency of undeliberate eye movements during a horizontal vestibular ocular reflex test. The concussed group had significant differences in their fixation points' distances, either longitudinal, latitudinal or total distances.

While the non-concussed patients were more successful in keeping their eyes focused at the target, the concussed group had more saccadic eye movements and a lesser ability to keep their focus on one point. The concussed group had more unintended fixation and gaze points while the non-concussed group had fewer fixation and gaze points, with greater accuracy on the target point.

5.2.3 Visual search and scanning ability

This test investigated the difference between the response times of patients with concussions symptoms and healthy participants. Statistical analysis showed a significant difference between the response times of concussed versus non-concussed participants, which suggested that concussion injury will affect cognitive motor speed. On average, concussed participants spent more time finding the target letters among scattered letters. The heat maps further confirmed that the concussed participants had more frequent undeliberate eye-movements and more random glances at letters. They often ignored the target letters and failed to perceive them even if they glanced at them. Comparison of gaze plots of concussed to non-concussed participants showed that concussed participants had more frequent fixations and spent more time on each fixation point.

5.2.4 Target acquisition

The results of the target acquisition test showed that although concussed and non-concussed participants spent almost the same amount of time dragging and dropping the balls to the basket, concussed patients had significantly less accuracy dropping balls into the basket. This suggested that concussed patients experienced lower levels of concentration and impaired cognitive or physical control abilities. In other word, a concussion may damage the part of the brain that controls eye focus and aim.

5.2.5 Horizontal Smooth Pursuits

In this test, the results showed a significant difference between the eye movement patterns of concussed and non-concussed participants. The participants' fixation points during the test were examined and the vertical distances from the horizontal mean line were investigated. The results show a significant difference between the vertical deviations of fixation points in concussed versus non-concussed group. The concussed patients were less able to follow the moving circle and showed more vertical deviations and unsteady eye movements. This suggested that concussion may impair the patient's ability to control eye movement and focus on a moving target.

5.2.6 *Vertical Smooth Pursuits*

In this test, the results showed a significant difference between the eye movement patterns of concussed and non-concussed participants. The participants' fixation points during the test were recorded and the horizontal distances from the vertical mean line were measured. The results showed that concussed patients generally showed greater standard deviation from the vertical mean than the non-concussed group. This finding, that the concussed group was less able to follow the moving circle with a lesser deviation and smoother eye movements, again suggested that a concussion injury may impair the patient's ability to control eye movement and focus on a moving target.

In conclusion, the visual cognitive tests results showed that concussions can affect the ability to focus on a moving object and keep the eyes concentrated on the objects. Concussions also cause patients to be less able to establish and maintain focus on fixation points and they demonstrate longer reaction times.

5.3 **Discussion**

This study showed significant differences between eye movement patterns of concussed and non-concussed teens. The results may be interpreted from two different aspects: the initial diagnosis and the fitness to drive assessment.

From the aspect of diagnosis, the test results are consistent with the doctors' diagnoses. As detailed above, the proper interpretation of the eye tracking methodology, which recorded patients' eye movements and precisely documented the saccadic movements, in conjunction with appropriate cognitive testing, has the potential to support more objective diagnosis of concussion. These methodologies and techniques also have the potential to enable more accurate assessment of patients' healing progress by means of follow up testing.

From the aspect of assessment of fitness to drive following concussion injury, the results showed that teen drivers with a concussion are less able to control the car, typically showed higher incidence of distracted driving, and were less able to anticipate and react to the hazards. Since driving is a complex task which requires high levels of physical and cognitive ability, such as ability to physically control the car, to controlling speed, and to react to environmental hazards, it can be concluded that driving with a concussion is very risky and should be delayed until objective assessment indicates the driver's concussion symptoms are abated.

Figure 66 shows the heatmap which has been provided by combination of Horizontal smooth pursuit, vertical smooth pursuit and also Horizontal vestibular ocular reflex tests results, in which:

X*: Standard deviation of fixation points while mean is equal to zero in Horizontal smooth pursuit test.*

Y: *Standard deviation of fixation points while mean is equal to zero in Vertical smooth pursuit test.*

Z: *Standard deviation of fixation points in Horizontal vestibular ocular test.*

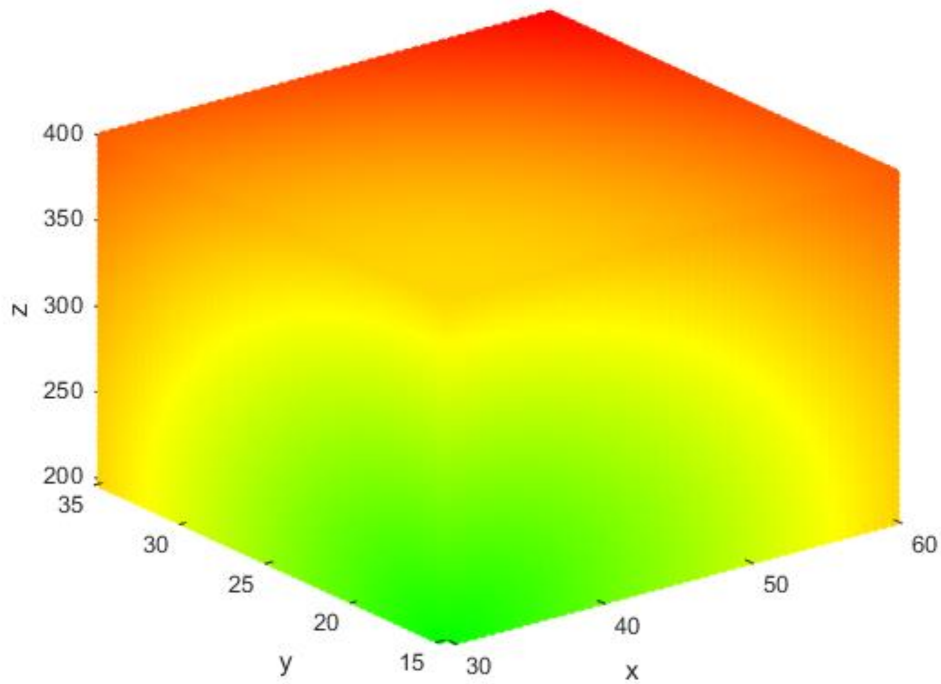

Figure 66- Heatmap defining threshold for diagnosing concussions

The Matlab code which was developed for finding a threshold between the concussed and non-concussed participants is as below (Figure 67):

```
clear
n=15;
m=1;
for i=1:n+1
    x=30+(i-1)*30/n;
    for j=1:n+1
        y=15+(j-1)*20/n;
        for k=1:n+1
            z=200+(k-1)*200/n;
            A(:,m)=[x;y;z];
            m=m+1;
        end
    end
end
D=sqrt(3);
plot3(A(1,1),A(2,1),A(3,1),'g.')
hold on
for i=2:m-1
    x=A(1,i);
    y=A(2,i);
    z=A(3,i);
    d=sqrt(((x-30)/30)^2+((y-15)/20)^2+((z-200)/200)^2);
    if d<=D/2
        c=[2*d/D 1 0];
    else
        c=[1 2-2*d/D 0];
    end
    plot3(x,y,z,'o','MarkerEdgeColor',c,'MarkerFaceColor',c)
end
% Coordinates of the point
x0=38;y0=20;z0=250;
plot3(x0,y0,z0,'k*','linewidth',2)
hold off
xlabel('x')
ylabel('y')
zlabel('z')
```

Figure 67- Matlab code to diagnose a concussion

The range of X, Y and Z have been determined by using the results of the analysis for each of the three tests mentioned above. The numbers are standard deviations. Based on the results of analysis from collected data, the ranges of X= [30:60], Y= [15:35], and Z= [200:400] extracted for each test, in which the lower boundaries mean the participant does not have visual symptoms (Green color), and the upper boundaries mean that the visual symptoms are severe (Red color). For instance, assuming a practitioner who asks a participant to do the horizontal smooth pursuit, vertical smooth pursuit and the horizontal vestibular ocular test. The practitioner should normalize the data and find the standard deviation of the fixation points. If they enter three extracted standard deviations (one for each test) and enter the points as x_0, y_0 and z_0, a black point will appear inside the cubic on the heatmap. The practitioner can find if the patient is concussed or not. If the black point appears in the green area, it means that the patient is not concussed. If it appears in the yellow area, the patient might be diagnosed a concussion and further tests should be implied. If the point appears in the red area, there is a high chance that the patient has a concussion.

For example, assuming a practitioner has four patients and enters four points of A= (35, 16, 230), B= (40, 18, 300), C= (50, 20, 350), and D= (58, 25, 390). The practitioner can use the Matlab code in Figure 67 to plot the points (Figure 68). The results would show that patient “A” is in the green area, meaning that patient “A” does not show severe concussion symptoms. Points “B” and “C” are in the yellow area, so patients “B” and “C” are in the risk of having a concussion and they need more investigations. However, point “D” is in the red area, which means that patient “D” shows severe concussion symptoms and should be diagnosed as a concussed patient.

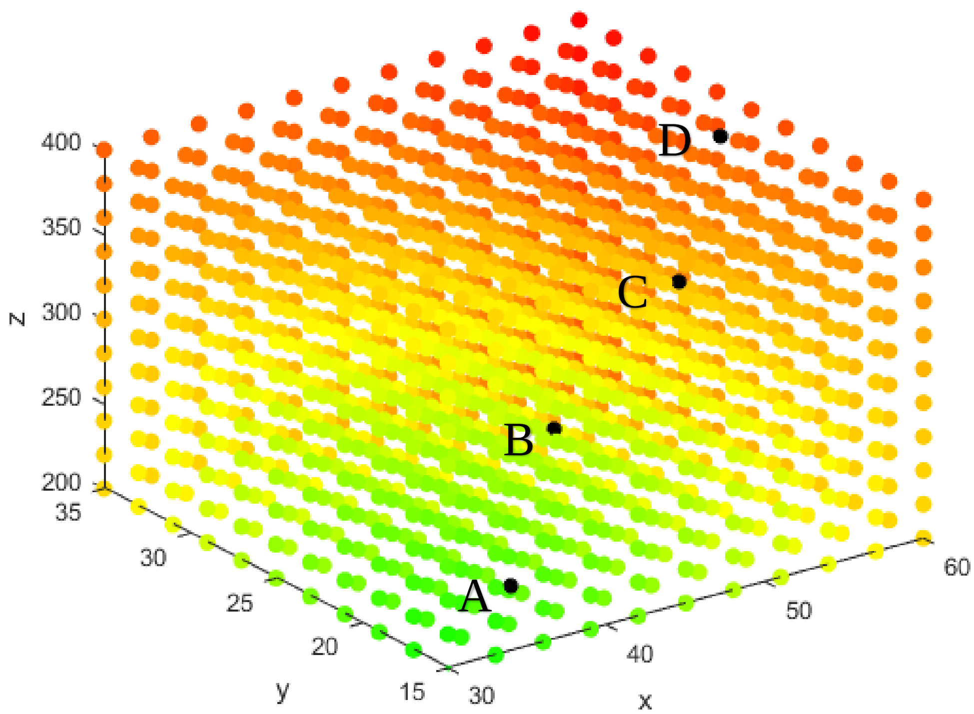

Figure 68- Examples of using diagnosis model

5.4 <u>Limitations</u>

There has been limited research about the assessment of eye movement impairments in concussed patients using eye-tracking devices. One of the difficulties in this experiment was establishing the eye-tracker calibration on concussed patients. Another concern was that concussed patients would develop simulator sickness which would necessitate ending the simulator-based experiments if such attrition was unacceptably high. The effects of other factors, like severity of concussion, location of the brain injury, and experience of the drivers, was handled as described in Table 24.

Table 24 -Research limitations and solutions

	Limitation	Description
1	Experience of the drivers	Counter-balancing of the ages and genders of the control group participants with the concussed group
2	Location of the brain injury	As concussion occurs without brain bleeding, and the brain hits the skull for less than a second, as long as the patient has a concussion symptom, location of the brain injury does not matter
3	Severity of the concussion	Concussed participants were selected from patients who still had concussion symptoms longer than two weeks. All of the research patients experienced the same severity of concussion symptoms.

5.5 Areas of Future Research

Based on the experiment results, possible future research should include:

- Implementation of this research protocol on more patients, with additional testing to provide a greater range of reliable and accurate diagnosis methods.
- Longitudinal follow up assessments immediately following concussion, including assessments at each follow up of changes in patients' eye movement behaviors, and in conjunction with targeted therapy.
- Development of more cognitive tests to diagnose which areas of the brain which are more typically involved in concussion, in a variety of test groups.
- Development of weighted hazard anticipation and situation awareness scenarios based on their risk level for a better judgment of the risk of driving after a concussion.

REFERENCES

Alexander, M. P. (1995). Mild traumatic brain injury: pathophysiology, natural history, and clinical management. *Neurology*. Retrieved from http://psycnet.apa.org/psycinfo/1996-92438-001

ANDREASSEN, J., BACH-NIELSEN, P., HECKSCHER, H., & LINDENEG, O. (1957). Reassurance and Short Period of Bed Rest in the Treatment of Concussion. *Acta Medica Scandinavica*, *158*(3–4), 239–248.

Arfanakis, K., Haughton, V. M., Carew, J. D., Rogers, B. P., Dempsey, R. J., & Meyerand, M. E. (2002). Diffusion tensor MR imaging in diffuse axonal injury. *American Journal of Neuroradiology*, *23*(5), 794–802.

Aubry, M., Cantu, R., Dvorak, J., Graf-Baumann, T., Johnston, K., Kelly, J., … Schamasch, P. (2002). Summary and agreement statement of the first International Conference on Concussion in Sport, Vienna 2001. *British Journal of Sports Medicine*, *36*(1), 6–7.

Babcock, L., Byczkowski, T., Wade, S. L., Ho, M., Mookerjee, S., & Bazarian, J. J. (2013). Predicting postconcussion syndrome after mild traumatic brain injury in children and adolescents who present to the emergency department. *JAMA Pediatrics*, *167*(2), 156–161.

Balasundaram, A. P., Sullivan, J. S., Schneiders, A. G., & Athens, J. (2013). Symptom response following acute bouts of exercise in concussed and non-concussed individuals–A systematic narrative review. *Physical Therapy in Sport*, *14*(4), 253–258.

Barnes, G. R. (2008a). Cognitive processes involved in smooth pursuit eye movements. *Brain and Cognition*, *68*(3), 309–326.

Basser, P. J., & Pierpaoli, C. (2011). Microstructural and physiological features of tissues elucidated by quantitative-diffusion-tensor MRI. *Journal of Magnetic Resonance, 213*(2), 560–570.

Bazarian, J. J., Veazie, P., Mookerjee, S., & Lerner, E. B. (2006a). Accuracy of mild traumatic brain injury case ascertainment using ICD-9 codes. *Academic Emergency Medicine*, *13*(1), 31–38.

Bazarian, J. J., Veazie, P., Mookerjee, S., & Lerner, E. B. (2006b). Accuracy of mild traumatic brain injury case ascertainment using ICD-9 codes. *Academic Emergency Medicine*, *13*(1), 31–38.

BAZARIAN, J. J., WONG, T., HARRIS, M., LEAHEY, N., MOOKERJEE, S., & DOMBOVY, M. (1999). Epidemiology and predictors of post-concussive syndrome after minor head injury in an emergency population. *Brain Injury*, *13*(3), 173–189.

https://doi.org/10.1080/026990599121692

Bigler, E. D. (2008). Neuropsychology and clinical neuroscience of persistent post-concussive syndrome. *Journal of the International Neuropsychological Society*, *14*(1), 1–22.

Bottari, C., Lamothe, M.-P., Gosselin, N., Gélinas, I., & Ptito, A. (2012). Driving difficulties and adaptive strategies: the perception of individuals having sustained a mild traumatic brain injury. *Rehabilitation Research and Practice*, *2012*. Retrieved from https://www.hindawi.com/journals/rerp/2012/837301/abs/

Brahm, K. D., Wilgenburg, H. M., Kirby, J., Ingalla, S., Chang, C.-Y., & Goodrich, G. L. (2009). Visual impairment and dysfunction in combat-injured servicemembers with traumatic brain injury. *Optometry & Vision Science*, *86*(7), 817–825.

Brewer, T. L., Metzger, B. L., & Therrien, B. (2002). Trajectories of cognitive recovery following a minor brain injury. *Research in Nursing & Health*, *25*(4), 269–281. https://doi.org/10.1002/nur.10045

Brouwer, W. H., Ponds, R. W., Van Wolffelaar, P. C., & Van Zomeren, A. H. (1989). Divided attention 5 to 10 years after severe closed head injury. *Cortex*, *25*(2), 219–230.

Brouwer, W. H., & Withaar, F. K. (1997). Fitness to drive after traumatic brain injury. *Neuropsychological Rehabilitation*, *7*(3), 177–193.

Brouwer, W. H., Withaar, F. K., Tant, M. L., & van Zomeren, A. H. (2002). Attention and Driving in Traumatic Brain Injury: A Question of Coping with Time-Pressure. *The Journal of Head Trauma Rehabilitation*, *17*(1), 1–15.

Brown, N. J., Mannix, R. C., O’Brien, M. J., Gostine, D., Collins, M. W., & Meehan, W. P. (2014). Effect of cognitive activity level on duration of post-concussion symptoms. *Pediatrics*, *133*(2), e299–e304.

Buckley, T. A., Munkasy, B. A., & Clouse, B. P. (2015). Acute cognitive and physical rest may not improve concussion recovery time. *J Head Trauma Rehabil*. Retrieved from http://pdfs.journals.lww.com/headtraumarehab/9000/00000/Acute_Cognitive_and_Physical_Rest_May_Not_Improve.99691.pdf

Caplan, B., Bogner, J., Brenner, L., Cifu, D. X., Wares, J. R., Hoke, K. W., … Carne, W. (2015a). Differential eye movements in mild traumatic brain injury versus normal controls. *Journal of Head Trauma Rehabilitation*, *30*(1), 21–28.

Caplan, B., Bogner, J., Brenner, L., Cifu, D. X., Wares, J. R., Hoke, K. W., … Carne, W. (2015b). Differential eye movements in mild traumatic brain injury versus normal controls. *Journal of Head Trauma Rehabilitation*, *30*(1), 21–28.

Capó-Aponte, J. E., Urosevich, T. G., Temme, L. A., Tarbett, A. K., & Sanghera, N. K. (2012). Visual dysfunctions and symptoms during the subacute stage of blast-induced mild traumatic brain injury. *Military Medicine*, *177*(7), 804–813.

Carroll, L., Cassidy, J. D., Peloso, P., Borg, J., Von Holst, H., Holm, L., … Pépin, M. (2004). Prognosis for mild traumatic brain injury: results of the WHO Collaborating Centre Task Force on Mild Traumatic Brain Injury. *Journal of Rehabilitation Medicine*, *36*(0), 84–105.

Carroll, L. J., Cassidy, J. D., Cancelliere, C., Côté, P., Hincapié, C. A., Kristman, V. L., … Hartvigsen, J. (2014). Systematic review of the prognosis after mild traumatic brain injury in adults: cognitive, psychiatric, and mortality outcomes: results of the International Collaboration on Mild Traumatic Brain Injury Prognosis. *Archives of Physical Medicine and Rehabilitation*, *95*(3), S152–S173.

Cartensen, L. L. (2007). Growing old or living long: A new perspective on the aging brain. *Public Policy & Aging Report*, *17*(1), 13–17.

Chrisman, S. P., Quitiquit, C., & Rivara, F. P. (2013). Qualitative study of barriers to concussive symptom reporting in high school athletics. *Journal of Adolescent Health*, *52*(3), 330–335.

Chrisman, S. P., Rivara, F. P., Schiff, M. A., Zhou, C., & Comstock, R. D. (2013). Risk factors for concussive symptoms 1 week or longer in high school athletes. *Brain Injury*, *27*(1), 1–9.

Cifu, D. X., & Gitchel, G. (2014). Effects of hyperbaric oxygen on eye-tracking abnormalities in males after mild traumatic brain injury. *Journal of Rehabilitation Research and Development*, *51*(7), 1047.

Ciuffreda, K. J., Kapoor, N., Rutner, D., Suchoff, I. B., Han, M. E., & Craig, S. (2007). Occurrence of oculomotor dysfunctions in acquired brain injury: a retrospective analysis. *Optometry-Journal of the American Optometric Association*, *78*(4), 155–161.

Comerford, V. E., Geffen, G. M., May, C., Medland, S. E., & Geffen, L. B. (2002). A rapid screen of the severity of mild traumatic brain injury. *Journal of Clinical and Experimental Neuropsychology*, *24*(4), 409–419.

Cook, A. W., Hunt, W. E., McLaurin, R. L., Mosberg, W. H., Ogle, W. S., Walker, A. E., … Voris, H. C. (1996). Report of the Ad Hoc Committee to study head injury nomenclature: proceedings of the Congress of Neurological Surgeons in 1964. *Clin Neurosurg*, *12*, 386–394.

Covassin, T., Crutcher, B., & Wallace, J. (2013). Does a 20 minute cognitive task increase concussion symptoms in concussed athletes? *Brain Injury*, *27*(13–14), 1589–1594.

Craton, N., & Leslie, O. (2014). Is rest the best intervention for concussion? Lessons learned from the whiplash model. *Current Sports Medicine Reports*, *13*(4), 201–204.

De Kruijk, J. R., Leffers, P., Meerhoff, S., Rutten, J., & Twijnstra, A. (2002). Effectiveness of bed rest after mild traumatic brain injury: a randomised trial of no versus six days of bed rest. *Journal of Neurology, Neurosurgery & Psychiatry*, *73*(2), 167–172.

DeMatteo, C., Stazyk, K., Singh, S. K., Giglia, L., Hollenberg, R., Malcolmson, C. H., … others. (2015). Development of a conservative protocol to return children and youth to activity following concussive injury. *Clinical Pediatrics*, *54*(2), 152–163.

DeMatteo, C., Volterman, K. A., Breithaupt, P. G., Claridge, E. A., Adamich, J., & Timmons, B. W. (2015). Exertion Testing in Youth with Mild Traumatic Brain Injury/Concussion. *Medicine and Science in Sports and Exercise*, *47*(11), 2283–2290.

Dick, R. W. (2009). Is there a gender difference in concussion incidence and outcomes? *British Journal of Sports Medicine*, *43*(Suppl 1), i46–i50.

DiFazio, M., Silverberg, N. D., Kirkwood, M. W., Bernier, R., & Iverson, G. L. (2016). Prolonged activity restriction after concussion are we worsening outcomes? *Clinical Pediatrics*, *55*(5), 443–451.

Dora Szymanowicz OD, M. S., Preethi Thiagarajan BS Optom, M. S., Ludlam, D. P., Green, W., Neera Kapoor OD, M. S., & others. (2012). Vergence in mild traumatic brain injury: a pilot study. *Journal of Rehabilitation Research and Development*, *49*(7), 1083.

Drew, A. S., Langan, J., Halterman, C., Osternig, L. R., Chou, L.-S., & van Donkelaar, P. (2007). Attentional disengagement dysfunction following mTBI assessed with the gap saccade task. *Neuroscience Letters*, *417*(1), 61–65.

Drickamer, M. A., & Marottoli, R. A. (1993). Physician responsibility in driver assessment. *The American Journal of the Medical Sciences*, *306*(5), 277–281.

Dziemianowicz, M. S., Kirschen, M. P., Pukenas, B. A., Laudano, E., Balcer, L. J., & Galetta, S. L. (2012). Sports-related concussion testing. *Current Neurology and Neuroscience Reports*, *12*(5), 547–559.

Echemendia, R. J., Bruce, J. M., Bailey, C. M., Sanders, J. F., Arnett, P., & Vargas, G. (2012). The utility of post-concussion neuropsychological data in identifying cognitive change following sports-related MTBI in the absence of baseline data. *The Clinical Neuropsychologist*, *26*(7), 1077–1091.

Felleman, D. J., & Van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. *Cerebral Cortex*, *1*(1), 1–47.

Furman, G. R., Lin, C.-C., Bellanca, J. L., Marchetti, G. F., Collins, M. W., & Whitney, S. L. (2013). Comparison of the balance accelerometer measure and balance error scoring system in adolescent concussions in sports. *The American Journal of Sports Medicine*, 0363546513484446.

Galetta, K. M., Morganroth, J., Moehringer, N., Mueller, B., Hasanaj, L., Webb, N., … Balcer, L. J. (2015). Adding Vision to Concussion Testing: A Prospective Study of Sideline Testing in Youth and Collegiate Athletes. *Journal of Neuro-Ophthalmology*, *35*(3), 235–241. https://doi.org/10.1097/WNO.0000000000000226

Galski, T., Bruno, R. L., & Ehle, H. T. (1992). Driving after cerebral damage: A model with implications for evaluation. *American Journal of Occupational Therapy*, *46*(4), 324–332.

Gardner, A., Shores, E. A., Batchelor, J., & Honan, C. A. (2012). Diagnostic efficiency of ImPACT and CogSport in concussed rugby union players who have not undergone baseline neurocognitive testing. *Applied Neuropsychology: Adult*, *19*(2), 90–97.

Gibson, S., Nigrovic, L. E., O'Brien, M., & Meehan III, W. P. (2013). The effect of recommending cognitive rest on recovery from sport-related concussion. *Brain Injury*, *27*(7–8), 839–842.

Giza, C. C., & Hovda, D. A. (2001). The neurometabolic cascade of concussion. *Journal of Athletic Training*, *36*(3), 228.

Gordon, K. E., Dooley, J. M., & Wood, E. P. (2006). Is migraine a risk factor for the development of concussion? *British Journal of Sports Medicine*, *40*(2), 184–185.

Graydon, F. X., Young, R., Benton, M. D., Genik, R. J., Posse, S., Hsieh, L., & Green, C. (2004). Visual event detection during simulated driving: Identifying the neural correlates with functional neuroimaging. *Transportation Research Part F: Traffic Psychology and Behaviour*, *7*(4), 271–286.

Gregory, D. R. (1981). The physician's role in highway safety–reporting requirements. *American Association for Automotive Medicine Quarterly Jurnal*, *3*(4), 29–33.

Guskiewicz, K. M., McCrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003). Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *Jama*, *290*(19), 2549–2555.

Guskiewicz, K. M., Register-Mihalik, J., McCrory, P., McCrea, M., Johnston, K., Makdissi, M., … Meeuwisse, W. (2013). Evidence-based approach to revising the SCAT2: introducing the SCAT3. *British Journal of Sports Medicine*, *47*(5), 289–293.

h Daneshvar, D., Picano, J. D., David, O., & c McKee, A. (2014). Self-reported concussion history: impact of providing a definition of concussion. *Ann c McKee1*, *2*, 6–8.

Halstead, M. E., Walter, K. D., & others. (2010). Sport-related concussion in children and adolescents. *Pediatrics*, *126*(3), 597–615.

Hartvigsen, J., Boyle, E., Cassidy, J. D., & Carroll, L. J. (2014). Mild traumatic brain injury after motor vehicle collisions: what are the symptoms and who treats them? A population-based 1-year inception cohort study. *Archives of Physical Medicine and Rehabilitation*, *95*(3), S286–S294.

Hawley, C. A. (2001). Return to driving after head injury. *Journal of Neurology, Neurosurgery & Psychiatry*, *70*(6), 761–766.

Heitger, M. H., Anderson, T. J., & Jones, R. D. (2002). Saccade sequences as markers for cerebral dysfunction following mild closed head injury. *Progress in Brain Research*, *140*, 433–448.

Heitger, M. H., Anderson, T. J., Jones, R. D., Dalrymple-Alford, J. C., Frampton, C. M., & Ardagh, M. W. (2004). Eye movement and visuomotor arm movement deficits following mild closed head injury. *Brain*, *127*(3), 575–590.

Heitger, M. H., Jones, R. D., Macleod, A. D., Snell, D. L., Frampton, C. M., & Anderson, T. J. (2009). Impaired eye movements in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability. *Brain*, awp181.

Hirth, V. A., Davis, B., Fridriksson, J., Rorden, C., & Bonilha, L. (2007). Cognitive performance and neural correlates of detecting driving hazards in healthy older adults. *Dementia and Geriatric Cognitive Disorders*, *24*(5), 335–342.

Huisman, T. A., Schwamm, L. H., Schaefer, P. W., Koroshetz, W. J., Shetty-Alva, N., Ozsunar, Y., … Sorensen, A. G. (2004). Diffusion tensor imaging as potential biomarker of white matter injury in diffuse axonal injury. *American Journal of Neuroradiology*, *25*(3), 370–376.

Iverson, G. L., Gaetz, M., Lovell, M. R., & Collins, M. W. (2004). Relation between subjective fogginess and neuropsychological testing following concussion. *Journal of the International Neuropsychological Society*, *10*(06), 904–906.

Ivins, B. J., Kane, R., & Schwab, K. A. (2009). Performance on the Automated Neuropsychological Assessment Metrics in a nonclinical sample of soldiers screened for mild TBI after returning from Iraq and Afghanistan: a descriptive analysis. *The Journal of Head Trauma Rehabilitation*, *24*(1), 24–31.

Kapoor, N., & Ciuffreda, K. J. (2002). Vision disturbances following traumatic brain injury. *Current Treatment Options in Neurology*, *4*(4), 271–280.

Kelly, J. P., Nichols, J. S., Filley, C. M., Lillehei, K. O., Rubinstein, D., & Kleinschmidt-DeMasters, B. K. (1991). Concussion in sports: guidelines for the prevention of catastrophic outcome. *Jama*, *266*(20), 2867–2869.

Kerr, Z. Y., Marshall, S. W., & Guskiewicz, K. M. (2012). Reliability of concussion history in former professional football players. *Medicine and Science in Sports and Exercise*, *44*(3), 377–382.

Kerr, Z. Y., Zuckerman, S. L., Wasserman, E. B., Covassin, T., Djoko, A., & Dompier, T. P. (2016). Concussion symptoms and return to play time in youth, high school, and college American football athletes. *JAMA Pediatrics*, *170*(7), 647–653.

Kostyun, R. O., & Hafeez, I. (2015). Protracted Recovery From a Concussion A Focus on Gender and Treatment Interventions in an Adolescent Population. *Sports Health: A Multidisciplinary Approach*, *7*(1), 52–57.

Kraus, M. F., Little, D. M., Donnell, A. J., Reilly, J. L., Simonian, N., & Sweeney, J. A. (2007). Oculomotor function in chronic traumatic brain injury. *Cognitive and Behavioral Neurology*, *20*(3), 170–178.

Kraus, M. F., Susmaras, T., Caughlin, B. P., Walker, C. J., Sweeney, J. A., & Little, D. M. (2007). White matter integrity and cognition in chronic traumatic brain injury: a diffusion tensor imaging study. *Brain*, *130*(10), 2508–2519.

Kushner, D. (1998). Mild traumatic brain injury: toward understanding manifestations and treatment. *Archives of Internal Medicine*, *158*(15), 1617–1624.

Langlois, J. A., Rutland-Brown, W., & Thomas, K. E. (2004). *Traumatic brain injury in the United States: emergency department visits, hospitalizations, and deaths*. Department of Health and Human Services, Centers for Disease Control and Prevention, Division of Acute Care, Rehabilitation Research and Disability Prevention, National Center for Injury Prevention and Control.

Langlois, J. A., Rutland-Brown, W., & Wald, M. M. (2006). The epidemiology and impact of traumatic brain injury: a brief overview. *The Journal of Head Trauma Rehabilitation*, *21*(5), 375–378.

Lau, B. C., Collins, M. W., & Lovell, M. R. (2011). Sensitivity and specificity of subacute computerized neurocognitive testing and symptom evaluation in predicting outcomes after sports-related concussion. *The American Journal of Sports Medicine*, *39*(6), 1209–1216.

Lau, B. C., Collins, M. W., & Lovell, M. R. (2012). Cutoff scores in neurocognitive testing and symptom clusters that predict protracted recovery from concussions in high school athletes. *Neurosurgery*, *70*(2), 371–379.

Leddy, J. J., Baker, J. G., Kozlowski, K., Bisson, L., & Willer, B. (2011). Reliability of a graded exercise test for assessing recovery from concussion. *Clinical Journal of Sport Medicine*, *21*(2), 89–94.

Levin, H. S., & Diaz-Arrastia, R. R. (2015). Diagnosis, prognosis, and clinical management of mild traumatic brain injury. *The Lancet Neurology*, *14*(5), 506–517.

Lings, S., & Jensen, P. B. (1991). Driving after stroke: a controlled laboratory investigation. *International Disability Studies*, *13*(3), 74–82.

Lovell, M. R., Collins, M. W., Podell, K., Powell, J., Maroon, J., & others. (2000). ImPACT: Immediate post-concussion assessment and cognitive testing. *Pittsburgh, PA: NeuroHealth Systems, LLC*.

Luoto, T. M., Silverberg, N. D., Kataja, A., Brander, A., Tenovuo, O., Öhman, J., & Iverson, G. L. (2014). Sport concussion assessment tool 2 in a civilian trauma sample with mild traumatic brain injury. *Journal of Neurotrauma*, *31*(8), 728–738.

Maerlender, A., Flashman, L., Kessler, A., Kumbhani, S., Greenwald, R., Tosteson, T., & McAllister, T. (2010). Examination of the construct validity of ImPACT™ computerized test, traditional, and experimental neuropsychological measures. *The Clinical Neuropsychologist*, *24*(8), 1309–1325.

Majerske, C. W., Mihalik, J. P., Ren, D., Collins, M. W., Reddy, C. C., Lovell, M. R., & Wagner, A. K. (2008). Concussion in sports: postconcussive activity levels, symptoms, and neurocognitive performance. *Journal of Athletic Training*, *43*(3), 265–274.

Marar, M., McIlvain, N. M., Fields, S. K., & Comstock, R. D. (2012). Epidemiology of concussions among United States high school athletes in 20 sports. *The American Journal of Sports Medicine*, *40*(4), 747–755.

Marinides, Z., Galetta, K. M., Andrews, C. N., Wilson, J. A., Herman, D. C., Robinson, C. D., … others. (2015). Vision testing is additive to the sideline assessment of sports-related concussion. *Neurology: Clinical Practice*, *5*(1), 25–34.

Maroon, J. C., Lovell, M. R., Norwig, J., Podell, K., Powell, J. W., & Hartl, R. (2000). Cerebral concussion in athletes: evaluation and neuropsychological testing. *Neurosurgery*, *47*(3), 659–672.

Marshall, S., Bayley, M., McCullagh, S., Velikonja, D., & Berrigan, L. (2012). Clinical practice guidelines for mild traumatic brain injury and persistent symptoms. *Canadian Family Physician*, *58*(3), 257–267.

Maruta, J., Lee, S. W., Jacobs, E. F., & Ghajar, J. (2010a). A unified science of concussion. *Annals of the New York Academy of Sciences*, *1208*(1), 58–66.

Maruta, J., Lee, S. W., Jacobs, E. F., & Ghajar, J. (2010b). A unified science of concussion. *Annals of the New York Academy of Sciences*, *1208*(1), 58–66.

Maruta, J., Spielman, L. A., Yarusi, B. B., Wang, Y., Silver, J. M., & Ghajar, J. (2016). Chronic post-concussion neurocognitive deficits. II. Relationship with persistent symptoms. *Frontiers in Human Neuroscience*, *10*. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4753289/

Maruta, J., Suh, M., Niogi, S. N., Mukherjee, P., & Ghajar, J. (2010). Visual tracking synchronization as a metric for concussion screening. *The Journal of Head Trauma Rehabilitation*, *25*(4), 293–305.

McAllister, T. W., Saykin, A. J., Flashman, L. A., Sparling, M. B., Johnson, S. C., Guerin, S. J., … Yanofsky, N. (1999). Brain activation during working memory 1 month after mild traumatic brain injury A functional MRI study. *Neurology*, *53*(6), 1300–1300.

McAllister, T. W., Sparling, M. B., Flashman, L. A., Guerin, S. J., Mamourian, A. C., & Saykin, A. J. (2001). Differential working memory load effects after mild traumatic brain injury. *Neuroimage*, *14*(5), 1004–1012.

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., … Kelly, J. P. (2003). Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *Jama*, *290*(19), 2556–2563.

McCrea, M., Guskiewicz, K., Randolph, C., Barr, W. B., Hammeke, T. A., Marshall, S. W., … Kelly, J. P. (2013). Incidence, clinical course, and predictors of prolonged recovery time following sport-related concussion in high school and college athletes. *Journal of the International Neuropsychological Society*, *19*(01), 22–33.

McCrea, M., Iverson, G. L., McAllister, T. W., Hammeke, T. A., Powell, M. R., Barr, W. B., & Kelly, J. P. (2009). An integrated review of recovery after mild traumatic brain injury (MTBI): implications for clinical management. *The Clinical Neuropsychologist*, *23*(8), 1368–1390.

McCrea, M., Kelly, J. P., Kluge, J., Ackley, B., & Randolph, C. (1997). Standardized assessment of concussion in football players. *Neurology*, *48*(3), 586–588.

McCrory, P., Meeuwisse, W., Aubry, M., Cantu, B., Dvorak, J., Echemendia, R., … others. (2013). Consensus statement on concussion in sport—the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Journal of Science and Medicine in Sport*, *16*(3), 178–189.

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, B., Dvořák, J., Echemendia, R. J., … others. (2013). Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *British Journal of Sports Medicine*, *47*(5), 250–258.

McCrory, P., Meeuwisse, W., Johnston, K., Dvorak, J., Aubry, M., Molloy, M., & Cantu, R. (2009). Consensus statement on Concussion in Sport–the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. *South African Journal of Sports Medicine*, *21*(2). Retrieved from http://www.ajol.info/index.php/sasma/article/download/44484/27996

McDonald, T., Burghart, M. A., & Nazir, N. (2016). Underreporting of concussions and concussion-like symptoms in female high school athletes. *Journal of Trauma Nursing*, *23*(5), 241–246.

Meehan, W. P., d'Hemecourt, P., Collins, C. L., & Comstock, R. D. (2011). Assessment and management of sport-related concussions in United States high schools. *The American Journal of Sports Medicine*, *39*(11), 2304–2310.

Meehan, W. P., d'Hemecourt, P., & Comstock, R. D. (2010). High school concussions in the 2008-2009 academic year mechanism, symptoms, and management. *The American Journal of Sports Medicine*, *38*(12), 2405–2409.

Meehan, W. P., O'Brien, M. J., Geminiani, E., & Mannix, R. (2015). Initial symptom burden predicts duration of symptoms after concussion. *Journal of Science and Medicine in Sport*. Retrieved from http://www.sciencedirect.com/science/article/pii/S1440244015002352

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*(1), 167–202.

Monte, V. E. D., & Geffen, G. M. (2005). Effects of mild traumatic brain injury: Comparison of direct and indirect injury groups. *Brain Impairment*, *6*(02), 109–116.

Moor, H. M., Eisenhauer, R. C., Killian, K. D., Proudfoot, N., Henriques, A. A., Congeni, J. A., & Reneker, J. C. (2015). The relationship between adherence behaviors and recovery time in adolescents after a sports-related concussion: an observational study. *International Journal of Sports Physical Therapy*, *10*(2), 225–233.

Mucha, A., Collins, M. W., Elbin, R. J., Furman, J. M., Troutman-Enseki, C., DeWolf, R. M., … Kontos, A. P. (2014). A Brief Vestibular/Ocular Motor Screening (VOMS) Assessment to Evaluate Concussions Preliminary Findings. *The American Journal of Sports Medicine*, 0363546514543775.

Novack, T. A., Baños, J. H., Alderson, A. L., Schneider, J. J., Weed, W., Blankenship, J., & Salisbury, D. (2006). UFOV performance and driving ability following traumatic brain injury. *Brain Injury*, *20*(5), 455–461.

Pierrot-Deseilligny, C., Müri, R. M., Ploner, C. J., Gaymard, B., Demeret, S., & Rivaud-Pechoux, S. (2003). Decisional role of the dorsolateral prefrontal cortex in ocular motor behaviour. *Brain*, *126*(6), 1460–1473.

Preece, M. H., Geffen, G. M., & Horswill, M. S. (2013). Return-to-driving expectations following mild traumatic brain injury. *Brain Injury*, *27*(1), 83–91.

Preece, M. H., Horswill, M. S., & Geffen, G. M. (2011). Assessment of drivers' ability to anticipate traffic hazards after traumatic brain injury. *Journal of Neurology, Neurosurgery & Psychiatry*, *82*(4), 447–451.

Ptak, T., Sheridan, R. L., Rhea, J. T., Gervasini, A. A., Yun, J. H., Curran, M. A., … Novelline, R. A. (2003). Cerebral fractional anisotropy score in trauma patients: a new indicator of white matter injury after trauma. *American Journal of Roentgenology*, *181*(5), 1401–1407.

Ptito, A., Chen, J.-K., & Johnston, K. M. (2007). Contributions of functional magnetic resonance imaging (fMRI) to sport concussion evaluation. *NeuroRehabilitation*, *22*(3), 217–227.

Register-Mihalik, J. K., Guskiewicz, K. M., McLeod, T. C. V., Linnan, L. A., Mueller, F. O., & Marshall, S. W. (2013). Knowledge, attitude, and concussion-reporting behaviors among high school athletes: a preliminary study. *Journal of Athletic Training*, *48*(5), 645–653.

Riemann, B. L., & Guskiewicz, K. M. (2000). Effects of mild head injury on postural stability as measured through clinical balance testing. *Journal of Athletic Training*, *35*(1), 19.

Rose, S. C., Weber, K. D., Collen, J. B., & Heyer, G. L. (2015). The diagnosis and management of concussion in children and adolescents. *Pediatric Neurology*, *53*(2), 108–118.

Samadani, U. (2015). A new tool for monitoring brain function: eye-tracking goes beyond assessing attention to measuring central nervous system physiology. *Neural Regeneration Research*, *10*(8), 1231.

Samadani, U., Ritlop, R., Reyes, M., Nehrbass, E., Li, M., Lamm, E., … Huang, P. (2015). Eye-tracking Detects Disconjugate Eye Movements Associated with Structural Traumatic Brain Injury and Concussion. *Journal of Neurotrauma*, *32*(8), 548–556. https://doi.org/10.1089/neu.2014.3687

Schneider, J. J., & Gouvier, W. D. (2005a). Utility of the UFOV test with mild traumatic brain injury. *Applied Neuropsychology*, *12*(3), 138–142.

Schneider, J. J., & Gouvier, W. D. (2005b). Utility of the UFOV Test With Mild Traumatic Brain Injury. *Applied Neuropsychology*, *12*(3), 138–142. https://doi.org/10.1207/S15324826AN1203_3

Shenouda, C., Hendrickson, P., Davenport, K., Barber, J., & Bell, K. R. (2012). The effect s of concussion legislation one year later—what have we learned: a descriptive pilot survey of youth soccer player associates. *PM&R*, *4*(6), 427–435.

Shore, D., Gurgold, G., & Robbins, S. (1980). HANDICAPPED DRIVING-AN OVERVIEW OF ASSESSMENT AND TRAINING. In *Archives of Physical Medicine and Rehabilitation* (Vol. 61, pp. 481–481). WB SAUNDERS CO INDEPENDENCE SQUARE WEST CURTIS CENTER, STE 300, PHILADELPHIA, PA 19106-3399.

Silverberg, N. D., & Iverson, G. L. (2013). Is rest after concussion "the best medicine?": recommendations for activity resumption following concussion in athletes, civilians, and military service members. *The Journal of Head Trauma Rehabilitation*, *28*(4), 250–259.

Silverberg, N. D., Iverson, G. L., McCrea, M., Apps, J. N., Hammeke, T. A., & Thomas, D. G. (2016). Activity-related symptom exacerbations after pediatric concussion. *JAMA Pediatrics*, *170*(10), 946–953.

Singman, E. L. (2013). Automating the assessment of visual dysfunction after traumatic brain injury. *Medical Instrumentation*, *1*(1), 3.

Sivak, M., Olson, P. L., Kewman, D. G., Won, H., & Henson, D. L. (1981). Driving and perceptual/cognitive skills: behavioral consequences of brain damage. *Archives of Physical Medicine and Rehabilitation*, *62*(10), 476–483.

Slobounov, S. M., Gay, M., Zhang, K., Johnson, B., Pennell, D., Sebastianelli, W., … Hallett, M. (2011). Alteration of brain functional network at rest and in response to YMCA physical stress test in concussed athletes: RsFMRI study. *Neuroimage*, *55*(4), 1716–1727.

Stokx, L. C., & Gaillard, A. W. K. (1986). Task and driving performance of patients with a severe concussion of the brain. *Journal of Clinical and Experimental Neuropsychology*, *8*(4), 421–436. https://doi.org/10.1080/01688638608401332

Suh, M., Basu, S., Kolster, R., Sarkar, R., McCandliss, B., Ghajar, J., … others. (2006). Increased oculomotor deficits during target blanking as an indicator of mild traumatic brain injury. *Neuroscience Letters*, *410*(3), 203–207.

Symonds, C. P. (1928). Observations on the differential diagnosis and treatment of cerebral states consequent upon head injuries. *British Medical Journal*, *2*(3540), 829.

Thiagarajan, P., Ciuffreda, K. J., & Ludlam, D. P. (2011). Vergence dysfunction in mild traumatic brain injury (mTBI): a review. *Ophthalmic and Physiological Optics*, *31*(5), 456–468.

Thomas, D. G., Apps, J. N., Hoffmann, R. G., McCrea, M., & Hammeke, T. (2015). Benefits of strict rest after acute concussion: a randomized controlled trial. *Pediatrics*, *135*(2), 213–223.

Torres, D. M., Galetta, K. M., Phillips, H. W., Dziemianowicz, E. M. S., Wilson, J. A., Dorman, E. S., … Balcer, L. J. (2013a). Sports-related concussion anonymous survey of a collegiate cohort. *Neurology: Clinical Practice*, *3*(4), 279–287.

Torres, D. M., Galetta, K. M., Phillips, H. W., Dziemianowicz, E. M. S., Wilson, J. A., Dorman, E. S., … Balcer, L. J. (2013b). Sports-related concussion Anonymous survey of a collegiate cohort. *Neurology: Clinical Practice*, *3*(4), 279–287.

Van Kampen, D. A., Lovell, M. R., Pardini, J. E., Collins, M. W., & Fu, F. H. (2006). The "value added" of neurocognitive testing after sports-related concussion. *The American Journal of Sports Medicine*, *34*(10), 1630–1635.

Van Zomeren, A. H., Brouwer, W. H., & Minderhoud, J. M. (1987). Acquired brain damage and driving: a review. *Archives of Physical Medicine and Rehabilitation*, *68*(10), 697–705.

Van Zomeren, A. H., Brouwer, W. H., Rothengatter, J. A., & Snoek, J. W. (1988). Fitness to drive a car after recovery from severe head injury. *Archives of Physical Medicine and Rehabilitation*, *69*(2), 90–96.

Ventura, R. E., Jancuska, J. M., Balcer, L. J., & Galetta, S. L. (2015). Diagnostic Tests for Concussion: Is Vision Part of the Puzzle? *Journal of Neuro-Ophthalmology*, *35*(1), 73–81. https://doi.org/10.1097/WNO.0000000000000223

Voller, B., Benke, T., Benedetto, K., Schnider, P., Auff, E., & Aichner, F. (1999). Neuropsychological, MRI and EEG findings after very mild traumatic brain injury. *Brain Injury*, *13*(10), 821–827.

W, H., Horswill, M. S., & Geffen, G. M. (2010). Driving after concussion: The acute effect of mild traumatic brain injury on drivers' hazard perception. *Neuropsychology*, *24*(4), 493–503. https://doi.org/10.1037/a0018903.

Webster, J. S., Rapport, L. J., Godlewski, M. C., & Abadee, P. S. (1994). Effect of attentional bias to right space on wheelchair mobility. *Journal of Clinical and Experimental Neuropsychology*, *16*(1), 129–137.

Weiss, H. D., Stern, B. J., & Goldberg, J. (1991). Post-traumatic migraine: chronic migraine precipitated by minor head or neck trauma. *Headache: The Journal of Head and Face Pain*, *31*(7), 451–456.

White, O. B., & Fielding, J. (2012). Cognition and eye movements: assessment of cerebral dysfunction. *Journal of Neuro-Ophthalmology*, *32*(3), 266–273.

Wrightson, P., & Gronwall, D. (1981). Time off work and symptoms after minor head injury. *Injury*, *12*(6), 445–454.

Yuh, E. L., Cooper, S. R., Mukherjee, P., Yue, J. K., Lingsma, H. F., Gordon, W. A., … others. (2014). Diffusion tensor imaging for outcome prediction in mild traumatic brain injury: a TRACK-TBI study. *Journal of Neurotrauma*, *31*(17), 1457–1477.

APPENDIX A

Pre-study questionnaire

Section 1: Demographics

Gender: ☐ Male ☐ Female

Date of Birth: (Month / Year): _______ / _______ Age: ___________

Section 2: Driving History

Are you a licensed driver in the U.S.? ☐ Yes ☐ No

Do you have any other restrictions on your driver's license? ☐ Yes ☐ No

If yes, please describe: ____

Within the last three years, have you had any moving violations? ☐ Yes ☐ No

If so, what type and how many? ☐ Speeding How many times? _____

☐ Running red light How many times? _____

☐ Running stop sign How many times? _____

☐ Failure to yield How many times? _____

☐ Other _____________ How many times? _____

Within the last three years, have you been involved

in any automobile accidents? ☐ Yes ☐ No

If so, what type of accident(s)?

(Please check all that apply)

☐ Head-on collision (front of car to front of car contact)

☐ Rear-end collision (front of car to rear of car contact)

☐ Side impact or angled collision (front of car to side of car contact)

☐ Sideswipe (door to door contact)

☐ Single car accident (struck tree, sign, pedestrian)

☐ Multiple car accident (more than two cars involved)

☐ Other