The Effect of Mild Traumatic Brain Injury on Reaction Time, Dual Tasking Reaction Time and Heart Rate Variability in Driving Simulation

By

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Thesis

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This project is dedicated in memory of my Mother.

Abstract

The present study was performed to address some gaps in current literature related to dual tasking, reaction time, and heart rate variability (HRV) in concussed individuals during driving simulation, and to determine the extent to which reaction time, heart rate (HR), HRV, and dual tasking ability are impaired during driving scenarios of varying difficulty in concussed subjects when compared to a healthy control group. Testing was performed with a Systems Technology Incorporated Simulator Model 400 driving simulator. Ten healthy and ten concussed participants were exposed to multiple reaction time scenarios including pedestrian, vehicle, and cyclist incursions. Three dual task scenarios were also present during the simulation and were indicated by red triangles over either of the side view mirrors. Dual tasking ability was measured using STISIM dual task commands. Analysis of variance (ANOVA) was used to examine the interaction effect between group (concussed vs. non-concussed) and scenario on reaction time decline, dual task reaction time, HR, and fluctuation in HRV. No significant interaction effect between group and scenario was found for any of the four variables tested. There was a statistically significant difference in reaction time between groups $F(1, 18) = 2.072$, $p < .0001$, $\eta^2 = .600$ and a statistically significant difference in dual task reaction times between groups $F(1, 18) = 23.145$, $p < .0001$, $\eta^2 = .563$. No statistically significant differences were found for either HRV $F(2.956, 53.207) = 0.445$, $p = .719$, $\eta^2 = .140$ or HR $F(1, 18) = 0.367$, $p = 0.552$, $\eta^2 = .020$.

The findings suggest that there is a need for evaluation or screening before returning to driving after concussion. More research needs to be done to both determine deficits in driving performance following concussion, and for the development of a comprehensive screening and assessment tool for health care professionals to utilize when assessing concussed patients.

Table of Contents

LIST OF TABLES

Table

LIST OF FIGURES

Figure

Chapter 1: Literature Review

Concussions are the result of mild traumatic brain injuries (mTBIs) that result from a direct or indirect impact to the head (Scorza, Raleigh, & O'Connor, 2012). These are functional injuries that are caused predominantly by shear stress on the brain tissue due to rotational or angular forces (Scorza et al., 2012). These injuries can cause a myriad of symptoms that range from headaches and dizziness, to difficulty concentrating, impaired memory, and vestibular deficits (Brooks & Hunt, 2006). The effect of concussions on driving performance and dual tasking (the ability to perform two activities at the same time) during driving is a relatively new and unexplored field of study. Although studies performed by Preece, Geffen, and Horswill (2013) and Preece, Horswill, and Geffen (2010) examined reaction time and perceptive ability of concussed participants via questionnaires or video testing, few have been performed with the participant in a driving scenario. It is imperative that this gap is addressed so the effect of concussion on the ability to safely operate a vehicle is understood. The development of this type of assessment would provide the catalyst for future research aimed at developing strategies for concussion management on an individual basis to ensure the safety of the concussed person and others sharing the road with them. Furthermore, dual tasking studies performed on subjects following concussion (10 days to 1 year post-injury) are generally completed within gait and balance constructs by utilizing force plate analysis and Stroop Tests, and not on the ability to perform tasks secondary to driving, such as manipulating the radio/CD player or answering a cell phone. The available literature is also limited in assessing the effect of concussion on heart rate (HR) and heart rate variability (HRV) during dual tasking. Heart rate variability is the variability in cycle length between the peaks of the QRS complex (the three major graphical deflections shown on electrocardiogram readout), otherwise known as RR intervals (Malik et al., 1996).

Heart rate variability provides clinicians and researchers an avenue to observe the heart's ability to handle stressors and relaxations experienced by the body. These stressors and relaxations are controlled by the autonomic nervous system, with stressors (stress inducing factors) stimulating the sympathetic branch and relaxations (stress reducing factors) stimulating the parasympathetic branch of the autonomic nervous system (Akselrod et al., 1981). Heart rate variability can be can be assessed in the time domain (assessing sequence of RR intervals over time) or in the frequency domain (using samples to analyze with a Fourier transformation (Malik et al., 1996). This measure can be used to determine differences in stress response to cognitively demanding driving tasks between concussed and healthy drivers. This measure may indicate a pathway for further alterations in concussed drivers' reaction time and dual task ability during driving.

This study aims to determine the effects of concussion on reaction time, HR, HRV, and dual tasking reaction time during driving simulation. Furthermore, this study aims to provide a basis in the literature for future research to guide the development of a standardized return to driving guideline for concussed individuals. Justifying the need for further research regarding the effect of concussion on reaction time and HRV during dual tasking and how these effects relate to the safe operation of a motor vehicle would prove valuable to clinician and patient alike. A standardized methodology would benefit clinician's ability to monitor and assess when an individual should return to driving after suffering a concussion. Furthermore, these guidelines would increase the safety of concussed individuals and the general public by ensuring those who have experienced concussion do not return to driving when there are apparent deficits in his/her ability to operate a motor vehicle.

Concussion and the Neurometabolic Cascade

Five out of every 1,000 Canadians experience a mild traumatic brain injury each year, with as many as 30% of these injuries occurring due to motor vehicle accidents (BIAWW, 2012). In North America alone, there are as many as 750,000 concussions reported each year, and this number is on the rise. Due to the prevalence of mild traumatic brain injury (mTBI), it is important that we address the causes of concussion and its associated symptoms first. Although concussion can be caused by linear acceleration impacts, they are generally caused by sudden impacts to the head resulting in angular or rotational acceleration/deceleration to the brain (Marshall, 2012). Angular acceleration occurs when the head is impacted off its axis, causing it to rotate, leading to shear forces acting on the brain. The structures of the brain are forced into different directions at the same time. Sheer deformations of the brain caused by these rotational accelerations/decelerations are the predominant mechanism of injury in concussion (Adams, Graham, Murray, & Scott, 1982; Gennarelli et al., 1982; Unterharnscheidt & Higgins, 1969). Impacts that occur to other areas of the body with enough force to transfer the rotational or angular energy to the head may also result in concussion. This external trauma triggers a series of neurometabolic events that take place within the brain. Majerske et al. (2008) provide a brief overview of these neurometabolic events, starting with

> the release of excitatory neurotransmitters, which result in cellular membrane disruption and ionic imbalances. Increasing amounts of adenosine triphosphate (ATP) are required in an attempt to correct these ionic imbalances, and an increase in glucose metabolism is observed within the first 24 hours after concussion. This increased glucose metabolism, combined with an initial decrease in cerebral blood flow, results in a mismatch between the energy required and that available to brain structures (page 265).

The effects of the neurometabolic cascade on different ions, enzymes, and blood flow are outlined in Giza and Hovda's (2001) illustration represented in Figure 1.

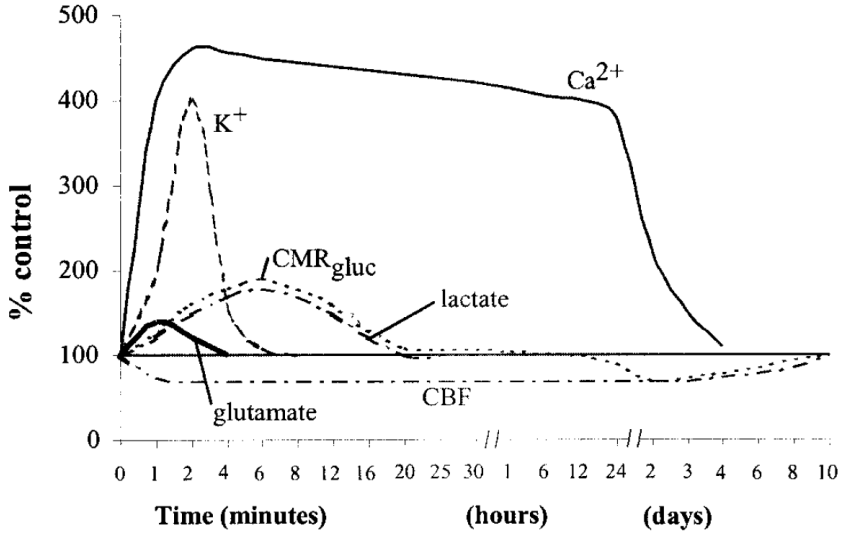

Figure 1. The physiologic effect of the neurometabolic cascade. This figure illustrates the effect of the neurometabolic cascade on neurotransmitter ions potassium (K^+) and calcium (Ca^{2+}), cerebral blood flow (CBF), and other enzymes (lactate, cerebral glucose, glutamate) in the brain. Copied from "Ionic and metabolic consequences of concussion," C. C. Giza and D. A. Hovda, 2001, *Journal of Athletic Training, 36*(3), p. 229.

Moments after a concussive impact occurs, the membranes of the neurons are disrupted, axons are stretched, and the voltage dependent potassium channels are opened, increasing the amount of extracellular potassium (Katayama, Becker, Tamura, & Hovda, 1991; Takahashi, Manaka, & Sano, 1981). This surplus of extracellular potassium leads to neuronal suppression, known as *spreading depression* (Kraig & Nicholson, 1978; Prince, Lux, & Neher, 1973; Somjen & Giacchino, 1985; van Harreveld, 1978). Spreading depression may contribute to amnesia, loss of consciousness, or other cognitive dysfunction seen after a concussive injury (Giza & Hovda, 2001). Following this, glycolysis (energy production via the breakdown of glucose) is increased due to the activation of energy-requiring membrane pumps (Bull & Cummins, 1973; Mayevsky

& Chance, 1974; Rosenthal, LaManna, Yamada, Younts, & Somjen, 1979). These pumps activate in an attempt to restore ionic balance that was disrupted by the impact. Increased glycolysis results in increased lactate production and impaired oxidative metabolism, leading to reduced ATP production (Biros & Dimlich, 1987; Meyer, Kondo, Nomura, Sakamoto, & Teraura, 1970; Nilsson & Nordström, 1977; Nilsson & Pontén, 1977; Yang, DeWitt, Becker, & Hayes, 1985). Neuronal dysfunction, as a result of the increased lactate production and decreased ATP production, leads to acidosis, membrane damage, cerebral edema (fluid retention), and altered blood brain barrier permeability (Gardiner, Smith, Kgström, Shohami, & Siesjö, 1982; Kalimo, Rehncrona, Söderfeldt, Olsson, & Siesjö, 1981; Siemkowicz & Hansen, 1978).

Cerebral blood flow is adversely affected by the concussive impact due to its direct relation to neuronal activity and glucose metabolism. As illustrated in Figure 1, cerebral blood flow can decrease to 50% of normal, potentially creating an energy crisis for the brain and leading to inadequate blood supply and ischemia (Yamakami & McIntosh, 1989; Yuan, Smith, Smith, & DeWitt, 1988). Within hours of concussion, calcium ions begin to accumulate in the brain and may persist for 48 to 96 hours (Cortez, McIntosh, & Noble, 1989; Fineman, Hovda, Smith, Yoshino, & Becker, 1993; McIntosh, 1993; Osteen, Moore, Prins, & Hovda, 2001). Excitatory amino acids are released as a result of the previous potassium efflux, activating N-methyl-D-aspartate channels (Katayama, Becker, Tamura, & Hovda, 1990). These channels provide an avenue for calcium ions to enter the cell. An excessive amount of intracellular calcium ions can be taken up by the mitochondria (the powerhouse of the cell), leading to impaired oxidative metabolism (the ability to create energy from carbohydrates using oxygen) and energy failure. As illustrated in Figure 1, the ionic calcium levels begin to drop by day 2 and

fully recover 10 days post-injury. This increase in intracellular calcium has the potential to trigger cell death through overactivation of phospholipases (enzymes that cleave phospholipids), calpains (proteins active in cell cycle progression), protein kinases (enzymes that modify proteins via the attachment of phosphate groups), nitric oxide synthase (enzyme catalyzing the production of nitric oxide), and endonucleases (enzymes responsible for cleaving phosphodiester bonds in polynucleotide chains; Farooqui & Horrocks, 1991; Iwasaki, Yamamoto, Iizuka, Yamamoto, & Konno, 1987; Kampfl et al., 1997, Roberts-Lewis & Siman, 1993; Siesjö, 1992; Verity, 1992). Changes to these processes can lead to free radical production, highly reactive atoms or groups of atoms that have unpaired valence electrons. These free radicals have the potential to damage bodily tissues and activate apoptotic genetic signals that program cell death (Morgan & Curran, 1986). After the initial increase in glycolysis, cerebral glucose use is decreased by one day post-injury, and remains low for 5 to 10 days in animal models. Positron emission tomography performed on humans show a decrease in cerebral glucose metabolism lasting from 2 to 4 weeks post-injury (Bergsneider et al., 2000).

Intracellular magnesium levels are decreased immediately after injury, and remain low for up to 96 hours (Vink & McIntosh, 1990; Vink, Faden, & McIntosh, 1988; Vink, McIntosh, Demediuk, & Faden, 1987; Vink, Mcintosh, Weiner, & Faden, 1987). Neuronal dysfunction is initiated through multiple mechanisms as a result of the decreased magnesium levels. Glycolytic and oxidative ATP synthesis is impaired, and the decreased magnesium levels affect cellular membrane potential and the initiation of protein synthesis. N-methyl-D-aspartate channels have the potential to be opened with low levels of magnesium, which as previously mentioned, will lead to a further influx of calcium ions into the cell (Giza & Hovda, 2001).

The mechanical stretching of axons leads to a myriad of complications including membrane disruption, and increased permeability of the axolemma (the cell membrane surrounding the axon) for up to 6 hours post-injury. The mechanical stretching also results in an influx of calcium ions, mitochondrial swelling, neurofilament compaction, and instability via phosphorylation, the addition of a phosphate group to a molecule (Mata, Staple, & Fink, 1986; Maxwell, McCreath, Graham, & Gennarelli, 1995; Nakamura et al., 1990; Nixon, 1993; Pettus, Christman, Giebel, & Povlishock, 1994). Increased levels of calcium ions lead to microtubule breakdown occurring 6 to 24 hours post-injury (Maxwell & Graham, 1997; Pettus & Povlishock, 1996). Abnormalities can also occur within the axonal cytoskeleton, which lead to the accumulation of organelles at damaged areas of the axon. This accumulation results in swelling of the axon to the point of axotomy (severance) or formation of axonal bulbs (Maxwell & Graham, 1997). These effects are observed as soon as 4 hours post-injury and can continue for weeks in humans (Blumbergs et al., 1994).

Finally, alterations in neurotransmitters are believed to result in long-term memory and cognitive deficits. These changes can arise from dysfunctional excitatory neurotransmission in the glutamatergic, adrenergic, and cholinergic systems (Feeney, Sutton, Boyeson, Hovda, & Dail, 1985; Giza, Maria, & Hovda, 2006; Gorman, Fu, Hovda, Murray, & Traystman, 1996). Long-term potentiation in the hippocampus may be impaired, which affects the ability of the hippocampus to continually strengthen synaptic connections between neurons. Alterations in choline acetyltransferase, the enzyme responsible for the synthesis of the neurotransmitter acetylcholine, may lead to the loss of forebrain cholinergic neurons, which require acetylcholine to function. These alterations can contribute to the development of learning and special memory deficits, as demonstrated in animal models (Hepler, Wenk, Olton, & Coyle, 1985; Miyamoto,

Kato, Narumi, & Nagaoka, 1987). Furthermore, inhibitory neurotransmissions, such as those responsible for inhibition of hippocampal dentate granule cells (which function in the formation of spatial memories) can be altered, predisposing the brain to the development of seizures (Lee, Smith, Hovda, & Becker, 1995). The alterations that occur at the cellular level following a concussive impact are illustrated in Figure 2.

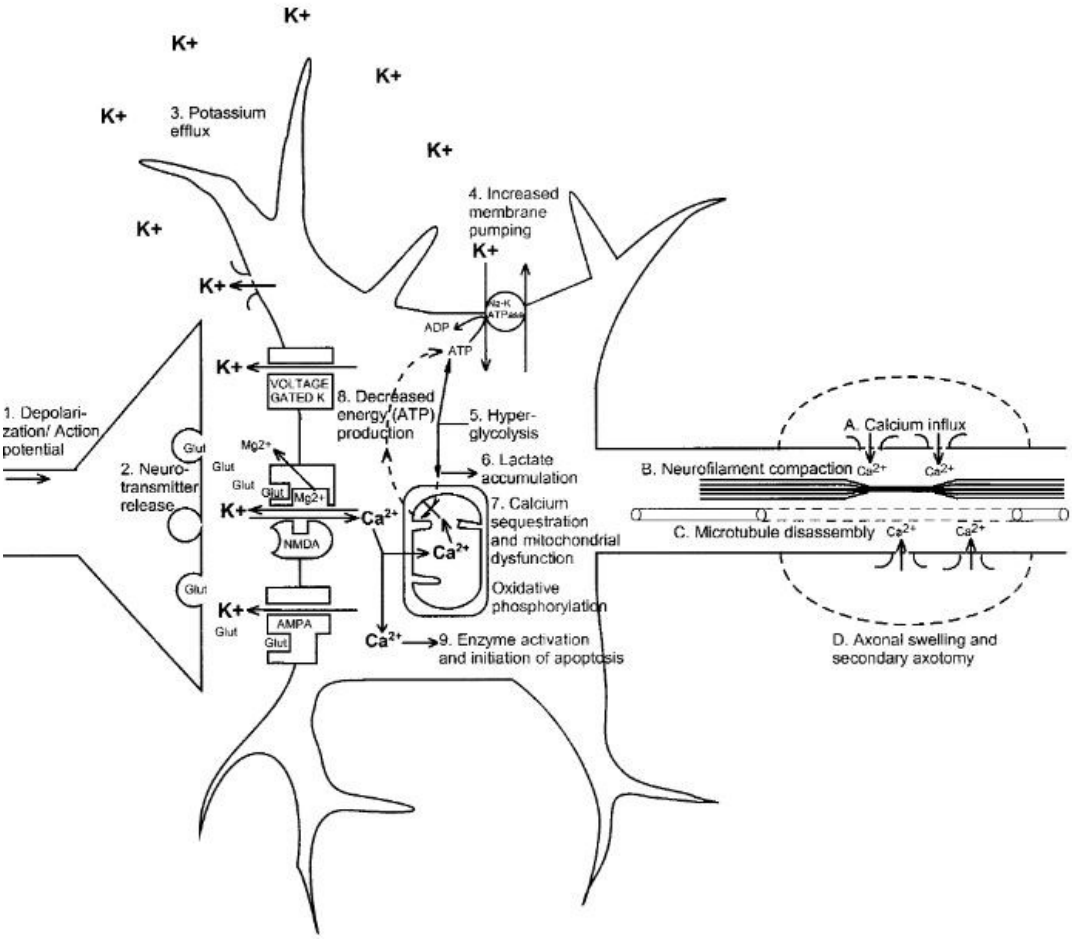

Figure 2. The order of ionic and cellular alteration during the neurometabolic cascade. This figure illustrates the different ionic and inter/intracellular changes that occur in the neuron following a concussive impact. Copied from "Ionic and metabolic consequences of concussion," C. C. Giza and D. A. Hovda, 2001, *Journal of Athletic Training, 36*(3), p. 231.

Although the neurometabolic cascade occurs via the same mechanism in anyone who experiences a concussion, the symptoms are subjective and vary greatly from person to person. A person who has been impacted with force significant enough to cause a concussion may experience short-term neurological impairments as outlined above. Additionally, they may experience acute clinical symptoms that indicate the impact has elicited functional disturbances, despite no suggestion of structural damage to the brain (Herring, Cantu, Guskiewicz, Putukian, & Kibler, 2011). Neurological imaging taken post-concussion typically displays normal results with no evidence of structural damage (Herring et al., 2011). Functional disturbances, as a result of a concussion, can manifest in many forms. Table 1 illustrates the most common signs and symptoms associated with a concussive impact.

Table 1

Signs and Symptoms of Concussion

Signs	Symptoms
• Headache	• Poor balance or coordination
• Dizziness	• Slow or slurred speech
• Feeling dazed, stunned	• Poor concentration
• Sensitivity to light	• Vacant stare
• Tiredness	• Confusion, disorientation
• Irritability	• Amnesia
• Seeing stars	• Loss of consciousness
• Sleepiness	• Personality change
• Nausea	• Inappropriate behaviour

Adapted from "Current concepts in concussion diagnosis and management in sports: A clinical review," by D. Brooks and B. M. Hunt, 2006, *British Columbia Medical Journal, 48*(9), 455.

These common signs and symptoms tend to resolve within 10 to 14 days of sport specific concussion, with age, sex, and history of previous concussive injury playing a role in the duration of the symptoms (Leddy, Sandhu, Sodhi, Baker, & Willer, 2012). Although 10 to 14

days is the time frame provided for resolution of concussion symptoms, it is approximate and not officially established nor agreed upon within the literature (Leddy et al., 2012). The approximate time for resolution of symptoms for individuals who suffer a concussion outside of a sport related activity is 3 months, with up to 33% of these individuals still experiencing symptoms after the initial 3-month post-injury period (Leddy et al., 2012). These side effects from concussion pose significant obstacles for an individual returning to his/her daily activities. Returning to work can prove difficult whether the type of employment is office oriented or requiring physical labour, as concentration and vestibular abilities are impaired (Leddy et al., 2012). Furthermore, the signs and symptoms listed in Table 1 can make it difficult for a concussed individual to not only attend work, but also to go out and perform everyday tasks such as shopping, interacting with other people, and understanding information being relayed to them (Leddy et al., 2012). In the driving context, impaired concentration and stimulus identification lead to longer reaction time and reduced ability to identify and safely process the multiple visual and auditory stimuli that are consistently present while operating a motor vehicle (Cantin, Lavalliere, Simoneau, & Teasdale, 2009; Johansson & Rumour, 1971; Makishita & Matsunaga, 2008). Now that an overview of the mechanics, physiology, and symptomology of concussions has been concluded, the discussion can focus on the specific skills of reaction time, dual tasking, and stimulus identification that may be affected by concussion; these are vital skills that must be considered when determining if a person can operate a vehicle in a safe manner.

Reaction Time

Reaction time is defined as the amount of time it takes for a person to respond to a stimulus from initial presentation to voluntary movement (Ghuntla, Gokhale, Mehta & Shah, 2014). Reaction time is dependent on the number of possible factors such as the difficulty of

signal discrimination, amount of mental processing involved, and association between possible choices to react to a specific stimulus (Triggs & Harris, 1982). Reaction time is considered an important component of safe vehicle operation. Simulator testing has shown faster reaction times in individuals with no history of accident involvement relative to drivers with collision history (Barrett, Kobayashi & Fox, 1968; Djuric & Filipovic, 2009). In the case of the study by Djuric & Filipovic (2009), all 30 participants were in an age range where age related decline of reaction time was minimal. Furthermore, simulator studies have shown that longer reaction times in sudden obstacle incursion or emergency situations can lead to collision (Barrett, Kobayashi & Fox, 1968; Pang, Yan, Ma & Zhao, 2013). The available literature specific to the effect of concussion on reaction time during driving is quite limited. A connection, however, between reaction time tests performed on post-concussive athletes and driving reaction time literature can be made to infer what kind of deficits would be seen in a driving environment. With respect to driving, understanding reaction time and average reaction times is required in order to determine if concussion has the potential to have a detrimental impact on performance. Green (2000) divides driving reaction time into three specific categories as shown in Table 2.

Table 2

Breakdown of Reaction Time During Driving

Category	Description
Mental processing time: *Subdivided into:* a) Sensation b) Perception c) Response selection and programming	Time required for driver to perceive external stimulus and make decision on how to respond. a) The time required to detect an object in path of vehicle. Auditory stimulus elicits faster reaction times than visual stimulus. b) The time required to evaluate and understand the stimulus. Perception time increases as the number of simultaneous stimuli increases. c) The time required to determine a response to the stimulus and mentally program a movement to carry out response. As the number of simultaneous stimuli increases, so does the time required to make a response selection.
Movement time	The time required to physically carry out the response programmed by the brain. As the complexity of the movement increases, so does the movement time. Practice can decrease movement time.
Device response time	The time required for the apparatus to perform task. This time is independent of the mental and physical reaction time of the individual. i.e., time required for a vehicle to come to a complete stop after the brakes have been activated.

Adapted from "How long does it take to stop? Methodological analysis of driver perception-brake times." By M. Green, 2000, *Transportation Human Factors*, *2*(3), 195-216.

With respect to measuring reaction time in driving environments, Makishita and Matsunaga (2008) found that 50 trials completed by 10 healthy subjects yielded a median

braking reaction time of 0.76 seconds, with scores ranging from 0.35 to 1.21 seconds. These values were consistent with previous values reported by Johansson and Rumour (1971) who measured brake reaction time in response to auditory stimuli in the form of a horn. Furthermore, the findings of Cantin, Lavalliere, Simoneau, and Teasdale's 2009 study on cognitive load and reaction time produced similar results. These studies provide an accurate estimation of the time required for a person to mentally navigate the steps outlined in Table 2. There is evidence with regards to concussion's negative impact on reaction time in settings unrelated to driving. Eckner, Kutcher, and Richardson (2011) tested nine collegiate athletes' pre- and post-concussion to evaluate reaction time by having the athletes perform a seated catching exercise (clinical reaction time) and a computer based reaction time test. Eckner et al. (2011) found that average reaction time in the clinical settings increased from a mean (SD) of 193 (21) to 219 (31) milliseconds, while the average reaction time in the computer test increased from 247 (75) milliseconds to 462 (120) milliseconds. As illustrated in Figure 3, Fazio, Lovell, Pardini, and Collins (2007) reported slower reaction times for both symptomatic and asymptomatic concussed athletes when compared to a control group. These 192 participants (78 symptomatic, 44 asymptomatic, and 70 non-concussed) were tested using the Immediate Post-Concussion Assessment and Cognitive Test, a computer based reaction time test (Fazio et al., 2007).

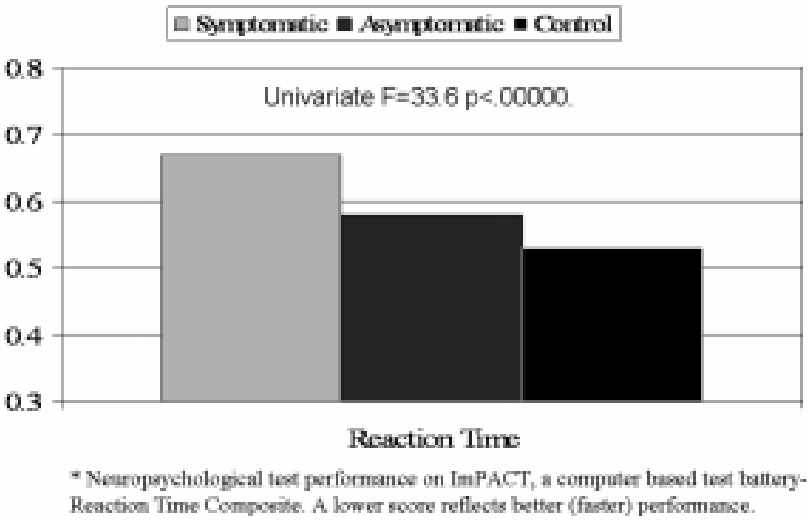

Figure 3. Computer based reaction time test. The differences in reaction time in seconds between symptomatic, asymptomatic, and non-concussed participants. Copied from "The relation between post-concussion symptoms and neurocognitive performance in concussed athletes." V. Fazio, M. Lovell, J. Pardini, and M. Collins, 2001. *NeuroRehabilitation*, *22*(7), 214.

In contrast to the studies reporting slower reaction time, DeHaan et al. (2007) reported faster saccadic and stop signal reaction times in participants who were tested within two days of suffering an mTBI when compared to a control group. The test required the participant to perform a saccade (fast movement of the eye) task, which was not to be performed if an auditory stop signal was played (DeHann et al., 2007). DeHann et al. (2007) demonstrated that participants with mTBI inaccurately stopped saccades in 15% of trials where no stop signal was present, suggesting that mTBI affected the person's ability to cancel planned actions. When comparing these results to driving reaction time and planning, it can be hypothesized that concussions may negatively impact driving performance. These adverse effects could potentially manifest in distraction or longer reaction times to external stimuli. The ability to inhibit or modify a planned mental action (such as those seen in Table 2) during a driving scenario may also be negatively affected. In order to understand differences in reaction times between healthy

and concussed participants, there is a need to address which areas of the brain and their associated processes are being utilized in response to external stimuli. Furthermore, there is a need to investigate which of these processes are being affected by concussive injuries. These areas of interest are addressed by the following section examining human attention network models.

Human Attention Networks Models

Human attention network models provide the basis for attention and the ability to dual task in driving. According to one well known model, the human attention model is divided into alerting, orienting, and executive control networks (Fan, 2001). The alerting network is responsible for maintaining alertness and arousal during continuous tasks (van Donkelaar et al., 2005). This network is controlled by the locus coruleus, right frontal cortex, and the parietal cortex (Fan, McCandliss, Fossella, Flombaum & Posner, 2005). The orienting network is responsible for dividing sensory resources into specific regions of space in order to detect objects quickly and accurately (van Donkelaar et al., 2005). This network is controlled by the superior parietal lobe, temporal-parietal junction, frontal eye fields, and the superior colliculus (Corbetta et al., 2000; Fan et al., 2005). Finally, the executive control network is responsible for an individual's ability to choose between different task demands, and the ability to resolve contextual conflicts efficiently (van Donkelaar et al., 2005). The executive control network is controlled by the anterior cingulate cortex, lateral ventral cortex, prefrontal cortex, and the basal ganglia (Corbetta et al., 2000; Fan et al., 2005).

Studies performed on concussed individuals reveal deficits in both the orienting and executive control networks. Orienting network deficits result in difficulty with locating cues within a known space before a target or symbol is shown (Felmingham, Baguley, & Green, 2004;

Ponsford & Kinsella, 1992; Spikman, Zomeren & Deelman, 1996; Stuss et al., 1989a; Stuss et al., 1989b). This directly ties into the ability to respond to dual task markers as presented in the driving simulator. If a concussed individual experiences difficulty orienting themselves to the attentional cues presented during simulation, he/she may be more likely to miss these tasks or respond to them too slowly. With respect to the executive control network, concussed individuals exhibit difficulty determining and acting on relevant stimuli among irrelevant stimuli (Ponsford & Kinsella, 1992; Stuss et al., 1989a; Stuss et al., 1989b). This may lead to concussed drivers being unable to successfully define and respond to relevant stimuli in their field of view that are required for safe vehicle operation. This impaired stimulus identification may negatively impact performance in the driving simulator by increasing reaction times, leading to the possibility of task failure or vehicle collision. Multiple studies have reported that concussed individuals experience deficits in the human attention network that not only impair reaction time, but also the ability to locate attentional cues in space and to differentiate between relevant and irrelevant stimuli (Ponsford & Kinsella, 1992; Stuss et al., 1989a; Stuss et al., 1989b). These characteristics exhibited by concussed individuals indicate that the ability to perform dual-tasking scenarios while operating a motor vehicle have the potential to be limited in both the time required to perform the dual task and their ability to properly locate and identify the stimulus required for successful completion of the task.

Dual Tasking

Driving is a dynamic activity that requires focus and attentiveness in order to be performed safely (Yale, Hansotia, Knapp, & Ehrfurth, 2003). Driving forces an individual to perceive, process, and react to multiple stimuli at any given moment. This large amount of stimulus requires dual tasking, the ability to identify and successfully process more than one

incoming stimulus at any given time (Yale et al., 2003). Dual tasking is directly related to the human attention network, and is made possible by multiple areas of the brain working synergistically to carry out successful stimulus reaction (Lin, Chen, Chiu, Lin, & Ko, 2011).

Modern drivers are faced with a significant number of distractions that negatively impact their ability to safely operate a vehicle. The Alberta Transportation Ministry states that 20% to 30% of all collisions involve driver distraction (Alberta Transport, 2011). As illustrated in Table 3, the Canadian Automobile Association provides some alarming statistics about the quantity and danger of driver distraction.

Table 3

Distraction Statistics and Likelihood of Collision or Near Collision from the Canadian Automobile Association

Distractions Identified by CAA	**Percentage of Reported Distractions**
Outside stimulus	29.9
Radio/CD adjustment	11.4
Vehicle occupants	10.9
Moving item in car	4.3
Using other device	2.9
Adjusting climate	2.8
Food/drink	1.7
Cellular phones	1.5
Distraction	**Likeliness of Collision or Near Collision**
Texting	23 times more likely
Talking on cell phone	4 to 5 times more likely
Reading	3 times more likely
Applying makeup	3 times more likely
Reaching for moving object	9 times more likely
Dialing on hand held device	3 times more likely
Talking or listening on hand held device	1.3 times more likely

Adapted from “Distracted driving.” Canadian Automobile Association, 2014.

Distraction during driving is virtually unavoidable and requires the driver to divert attention from the road resulting in compromised safety. One of the most common and widely used devices causing driver distraction is the cellular telephone (Lee, Champagne, & Francescutti, 2013). The use of these devices during driving is not limited to phone calls and verbal communication now that text messaging has become so prevalent. Surveys have shown that as many as 80% of young drivers admit to texting and driving (Lee et al., 2013). Since it is established that concussion and mTBIs can affect reaction time and movement planning, it is important to address how these injuries can influence a person's ability to dual task and how it relates to driving. Drews, Yazdani, Godfrey, Cooper, and Strayer (2009) performed a study on 40 participants regarding the effect of dual tasking and texting on driving performance during simulation. It was reported that texting increased response time to brake lights and created disparity in forward and lateral control of the vehicle. Similarly, these findings were reinforced by Park, Salsbury, Corbett, and Aiello (2013), who measured the effects of texting and driving on reaction time. They reported that mean reaction times slowed from 0.51 (0.41) seconds to 1.22 (0.36) seconds when texting was present. Strayer, Drews, and Johnston (2003) stated that conversing on a hands-free cell phone during driving impaired attention on the external environment and decreased recognition memory for objects and road signs in the simulation. These findings illustrated the dangers of dual tasking and increased cognitive load when operating a vehicle.

Research involving dual tasking and concussion are generally related to gait variability and center of mass displacement. Cossette, Oullet, and MyFayden (2014) tested a group of seven mTBI subjects and seven healthy controls to ascertain the locomotor-cognitive dysfunctions that were caused by dual-tasking. The study used several cognitive tests for the dual task measure

such as “Stroop (naming the ink colour of a word indicating an incongruent colour), verbal fluency (naming as many words beginning by a given letter), and [mental] arithmetic (counting backward by two from a given number)” (Cossette et al., 2014, page 1595). Locomotor abilities were assessed with walking, obstacle avoidance, and a step down test (Cossette et al., 2014). Cossette et al. (2014) found a significant difference in speed between healthy and mTBI groups when performing dual tasking during walking and obstacle avoidance. Howell, Osternig, and Chou (2014) tested balance control during dual tasking using a Stroop Test on a group of 19 healthy control subjects and 19 adolescents returning to his/her pre-concussion activity after a two month break. Howell et al. (2014) reported increased centre of mass displacement mediolaterally as well as increased peak velocity with dual task walking. These findings were not reproduced when the testing was performed as a single task measure (Howell et al., 2014). When reviewing these findings, it is reasonable to make the connection that the altered reaction time and physiological markers in concussed patients may be further exacerbated in dual task driving situations. Now that inferences have been made based on a variety of studies involving reaction time, concussion, and dual tasking, a review of the current literature specifically linking the effect of concussion on driving performance will be discussed.

Driving and Concussion

Several methods, including driving simulation, computer based testing, and questionnaires have been used to test the effect of brain injury on driving performance and perception. Lew et al. (2005) analyzed the driving performance of 11 subjects with traumatic brain injury (TBI) and 16 healthy controls using a simulated road test. The TBI subjects performed considerably worse than healthy subjects, specifically in the regulation of speed, steering, and ability to follow traffic rules, leading the TBI group to produce five times as many

traffic infractions/accidents (Lew et al., 2005). The poor driving performance observed in this simulation study could potentially be exacerbated by distractions and unpredictable hazards if the subject were operating an actual vehicle. Preece et al., (2010) completed a study in which 42 subjects with an mTBI and 43 subjects who sustained orthopedic injuries including strains, lacerations, or fractures to the extremities were asked to watch video footage of traffic scenarios from a first person perspective. The subjects were then required to click as quickly as possible on anything he/she deemed a traffic hazard in the video (Preece et al., 2010). Preece et al. (2010) found that mTBI subjects responded to traffic hazards significantly more slowly than the orthopedic injury group, prompting a recommendation that mTBI sufferers should refrain from driving for at least the first 24 hours post-accident due to impairment in hazard perception.

Research has also been done on post-mTBI driver perception in order to determine if the subjects were cognizant of his/her injury's detrimental effect on driving ability. Bottari, Lamothe, Gosselin, Gelinas, and Ptito (2012), interviewed 27 post-mTBI (mean of 15 months post-injury) subjects to assess perception of driving abilities, as well as the difficulties they faced and methods used to cope with those difficulties. Bottari et al. (2012) revealed that 93% of participants reported at least one difficulty perceived as having an impact "on everyday activities. Most frequently named problems affecting driving were fatigue and reduced concentration. In addition, 74% of participants had adapted their driving or developed strategies to compensate for driving difficulties" (p. 1). The findings of this study are especially significant when put into the context of those reported by Preece et al., in 2013, who administered an 11-item self-report questionnaire to 81 mTBI subjects about their hopes for recovery; five of the questionnaire items also discussed return to driving expectations. Of the 81 subjects, 48% planned on actively reducing his/her driving, while the participants who intended on moderating

his/her driving, only planned to do so for a mean period of 16.59 days (Preece et al., 2013). Preece et al. (2013) also noted that previous head injury and pain were associated with a subject's inclination to reduce his/her driving. These low numbers are alarming when considering the percentage of drivers that have experienced impairment of hazard perception and difficulty with driving. With regards to the general trend across driving and the concussion literature, D'apolito, Massonneau, Paillat, and Azouvi (2013) performed a review of 35 articles from the PubMed and Cochrane databases from 2000 to 2010 that addressed the topic of brain injury and its impact on driving ability. The review highlighted the issue that brain injury subjects were not only at a higher risk for accidents, but also that "no methodology is currently validated to assess impact of brain injury, especially cognitive sequelae, on driving capacity, given the low level of evidence of studies" (p. 63). Although the current literature is somewhat limited and lacking a standardized methodology for testing these scenarios, it is obvious that brain injuries have negative implications for the driver. These negative effects are not only experienced in the acute phase of the injury but, in extreme circumstances, can also permanently impair a person's capacity to perform tasks required for safe driving.

Having discussed the physiology of concussion, human attention models, reaction time, dual tasking, and concussion's effect on driving; we can now shift our focus to the effect of concussion on HRV. As individuals are exposed to reaction time and dual task scenarios (such as those present in a driving simulator), cognitive demand increases as the complexity of the task they are required to perform increases. Due to this increased cognitive demand, alterations occur in both HR and HRV in both healthy and concussed subjects (Gall, Parkhouse, & Goodman, 2004; Luque-Casado, Zabala, Morales, Mateo-March, & Sanabria, 2013; Park et al., 2013).

Heart Rate Variability

Dual tasking and cognitive load have a clear effect on reaction time in both healthy and concussed subjects, but they also affect HR and HRV (Luque-Casado et al., 2013). Heart rate is defined as the number of heart beats per minute (bpm), while HRV is defined as the time and variation between two heart beats as expressed in normal cardiac sinus rhythm (Reed, Robertson, & Addison, 2005). This variability is dictated by the balance between sympathetic and parasympathetic control of the sinoatrial rhythm (Freeman, Dewey, Hadley, Myers, & Froelicher, 2006). This balance is also indicative of an individual's response to external stressors and relaxors (Akselrod et al., 1981). Heart rate variability is strongly dependent on the average HR of an individual (depicted in Figure 3) and is also dependent on the individual's age. The most common measure of HRV is obtained by examining the change in the R-R intervals in the QRS complex as depicted in Figure 4.

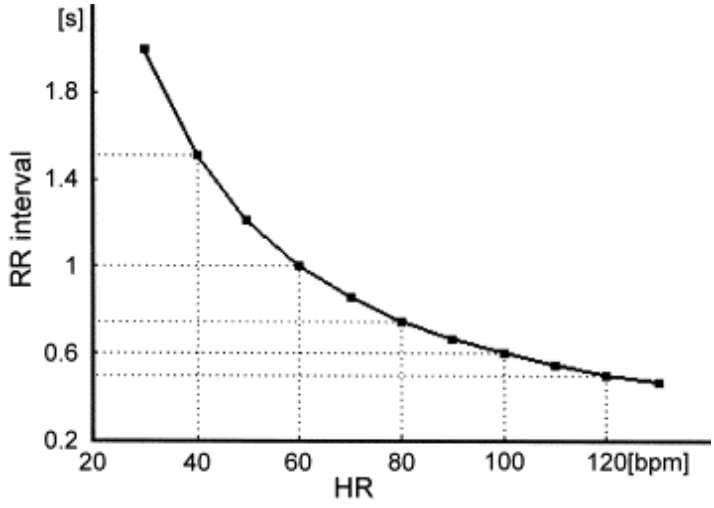

Figure 4. The relationship between HR and RR intervals depicts the inverse relationship between HR and RR intervals. As heart rate increases, RR intervals decrease. Copied from "Determinants of heart rate variability." H. Tsuji, F. Venditti, E. Manders, J. Evans, M. Larson, C. Feldman, and D. Levy, 1996. *Journal of the American College of Cardiology*, *28*(6), 1543.

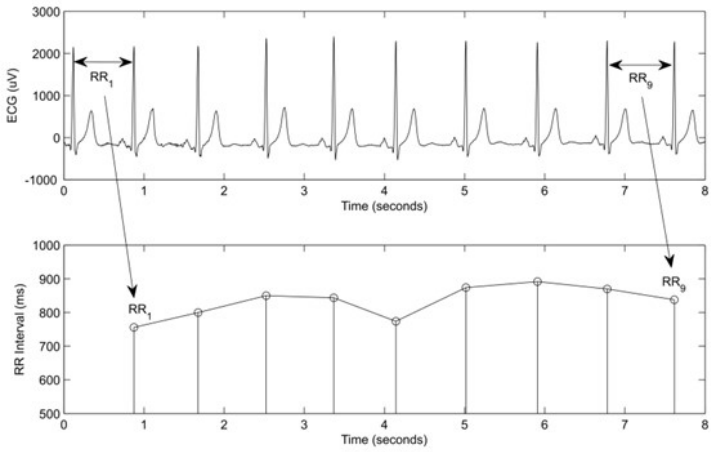

Figure 5. Measuring HRV. The distance between each R wave in the QRS complex provides the researcher with a simple measure of heart rate variability. Copied from "Determinants of heart rate variability." H. Tsuji, F. Venditti, E. Manders, J. Evans, M. Larson, C. Feldman, and D. Levy, 1996. *Journal of the American College of Cardiology*, *28*(6), 1543.

Analysis of HRV variability can be performed in the time domain (assessing amplitude sequence of the RR intervals over time) or in the frequency domain (assessing the magnitude sequence of the RR intervals using fast Fourier transformation techniques; Malik et al., 1996). Heart rate variability is comprised of two spectral components, low frequency (LF) and high frequency (HF) power densities (Aubert & Ramaekers, 1999; Electrophysiology, 1996). These components can be expressed in milliseconds squared, when obtained from sequences of R-R intervals, or in bpm squared, when calculated from a series of instantaneous heart rates.

Increasing cognitive load has been shown to have a significant effect on HR and HRV in both healthy and concussed subjects (Luque-Casado et al., 2013). As cognitive load increases, HR increases while HRV decreases in the time domain. Park et al. (2013) examined the effect of dual tasking in simulated driving using a time domain analysis. Their results demonstrated a mean heart rate increase of 4.30 ± 2.77 bpm to 8.85 ± 4.99 bpm, which can be attributed to greater cognitive workload and stress in the presence of a dual task scenario. Furthermore, it has

been shown that concussed subjects had a 33% lower RR interval value during exercise compared to the control group (Gall et al., 2004). Gall et al. (2004) also demonstrated that concussed subjects exhibited a significant rise in HR from resting to exercise. Exercise in this study is a form of cognitive load, which is in line with the findings of Park et al. (2013) and Luque-Casado et al. (2013). There is limited literature regarding HR and HRV in driving simulation, however. Since driving is a cognitively demanding activity incorporating dual tasking, we would expect to see a significant increase in HR and a decrease in HRV based on the results of studies performed outside of a driving environment.

Research Problem

The research problem regarding concussion and driving arises from the lack of literature examining dual tasking, reaction time, and HRV in concussed individuals during driving simulation. Some studies have examined reaction time and dual tasking in driving simulation using healthy participants, but not using concussed subjects (Drews et al., 2009, Johansson and Rumour, 1971; Strayer et al., 2003). A search of the PubMed, Lakehead University's SearchItAll, and ResearchGate databases using "driving", "concussion", "dual task", "reaction time", and "driving simulation" as keywords (both independently and in combination with one another) revealed limited literature linking concussion and driving. Furthermore, reaction time in relation to driving in concussed participants has been examined through personal perception questionnaires and computer based testing, but not in an ecologically valid driving environment (Preece et al., 2010). It has been established that concussion has a significant effect on reaction time, dual tasking ability, and cardiovascular output, but there is limited literature connecting these factors to a driving environment (Cossette et al., 2014; DeHann et al., 2007; Gall et al., 2004; Luque-Casado et al., 2013). Since alterations to HRV and deficits in reaction time during

dual tasking in concussed individuals has been illustrated in previous studies via gait, balance, exercise, and computer based testing, it is important to examine how these deficits affect their performance during driving simulation (Cossette et al., 2014; Eckner et al., 2011; Fazio et al., 2007; Gall et al., 2004; Howell et al., 2014; Luque-Casado et al., 2013). This connection is important as it provides an avenue for future research to better understand how concussions alter performance during vehicular operation. It will also aid in the development a standardized methodology for assessing a concussed driver, which is currently lacking.

Addressing these gaps in the literature will have implications for both clinicians and concussed individuals. Clinically, understanding the effect concussion has on safe driving ability is the first step in creating a standardized guideline for clinicians to refer to when assessing concussed patients to determine fitness to drive. The introduction of a standardized methodology that is valid and reliable would be beneficial to better monitor individuals who have suffered concussions and their returning to driving based on safe and reliable guidelines, rather than the individuals' perception of whether his/her injury warrants time away from driving. For example, the development of a protocol that incorporates a standardized method of evaluation such as the Sport Concussion Assessment Tool 3 (SCAT-3) with physiological measures such as HR, HRV, reaction time, and dual tasking ability in conjunction with driving simulation could be used to assess concussed patients and the degree to which his/her ability to operate a motor vehicle has been impaired. It is difficult, however, to establish a standard when dealing with the broad and complex neurological system and injury to this system such that occurs in concussion. For the individual, having these guidelines would help ensure both his/her own safety and that of others sharing the road with them. Future research linking concussion, dual tasking, and driving ability may be able to build on the limited body of literature to provide a framework upon which

researchers can attend to these issues. Therefore, the aim of this study is to provide a basis in the literature for future studies on this subject. Based on this rationale, the following purpose was formulated.

Purpose

The purpose of this study was to determine the extent to which reaction time is impaired during dual tasking activities of varying complexity in concussed subjects when compared to a healthy control group during driving simulation. This study also assessed the effect of increasing cognitive load on HR and HRV in both healthy and concussed subjects.

The following questions were used to guide the study:

1. Is there an interaction effect between group and scenario on reaction time in driving simulation?

2. Is there an interaction effect between group and scenario on dual task reaction times in driving simulation?

3. Is there an interaction effect between group and scenario on heart rate variability in driving simulation?

4. Is there an interaction effect between group and scenario on heart rate in driving simulation?

5. Is there a difference in the number of traffic infractions committed by each group?

Chapter 2: Methods

Participants

Ten healthy participants and ten concussed participants between the ages of 18 and 45 were recruited for the study.

Inclusion/Exclusion Criteria.

Healthy. Healthy participants needed to be between the ages of 18 and 45 years. This age range was chosen due to the relatively stable reaction time ranges as demonstrated by Makishita and Matsunaga (2008) and Cantin et al. in 2009. Participants who exceed this age range tend to exhibit significant age related reaction time increase with regards to driving (Cantin et al., 2009; Makishita & Matsunaga, 2008). Participants were required to possess a valid G-class driver's license or their province's license class equivalent if they were not from Ontario. Information was obtained from participants regarding neurological, psychiatric, motor, or substance abuse disorder/impairment on the medical demographic questionnaire that could have affected their driving ability. If they disclosed any disorder or impairment via the medical questionnaire, they were not included in the study. No participants noted any conditions that excluded them from participation in the study.

Concussed. Concussed participants were required to meet all the inclusion criteria of the healthy participants, but also had to be between two weeks and one year post-injury. This is the timeframe in which symptoms may still manifest after the acute stage of the injury has ended and the participant has returned to his/her daily activities, such as driving (Leddy et al., 2012). In order to participate in the study, medical clearance from the Lakehead University Concussion Clinic was required. If a patient from the concussion clinic did not meet the requirements to participate in the study he/she was not referred to the researchers.

Instrumentation

Screening Tools

Medical and demographic questionnaire. This questionnaire was used to obtain participant information about neurological, psychiatric, motor and substance abuse disorders that could have impaired his/her driving. This document gave participants the opportunity to state any underlying health conditions that could have potentially affected their reaction time, HR, or ability to successfully operate the driving simulator (Appendix A).

Sport concussion assessment tool 3 (SCAT-3). This is a standardized evaluation tool used for assessing concussed individuals or those who have experienced an mTBI. It was administered and filled out by Dr. Dave McKee, Sports Medicine Physician and Emergency Medicine Physician, at the Lakehead University Concussion Clinic before the participant was referred to the researcher (Appendix B).

Physical activity readiness questionnaire (PAR-Q). A standardized form given to participants to determine if they should check with their doctor before increasing their level of physical activity. If a participant answered yes to one or more questions, he/she were required to obtain clearance from a physician before proceeding (Appendix C).

Equipment and Software

STISIM drive® model 400. Reaction time and dual tasking ability was measured using the STISIM Drive® Model 400 (Appendix D), located in room BB-1024 of the Braun Building on the Lakehead University Campus. This simulator provided a 135° forward field of view and auditory feedback to the participant. The dash included a fully operational speedometer, tachometer, as well as a signal light switch, blind spot check buttons, and a functioning horn. The

simulator has been shown to provide valid and reproducible data that is indicative of actual driving performance (Bédard, Parkkari, Weaver, Riendeau, & Dahlquist, 2010).

Polar SP0810 heart-rate monitor. Heart rate and HRV data was collected using a Polar SP0810 heart-rate monitor (Appendix E). Intraclass correlation values of .85-.99 were achieved when compared to a CardioPerfect 12-lead Electrocardiogram (ECG; Nunan et al., 2009). This wireless device was interfaced to a PowerLab unit and the data was collected and computed via Lab Chart for the measures of HR and HRV. This device was used instead of an ECG as it is minimally invasive and was less distracting for participants during operation of the simulator.

PowerLab. The PowerLab unit is a data acquisition interface consisting of 16 input channels. This interface is capable of recording up to 400,000 samples per second and was used as an interface for the Polar SP0810 HR monitor to collect HRV data. PowerLab interface was connected to a computer via USB to transmit data into LabCharts7.

LabChart 7. This software package is designed to analyze a large variety of signal types including electromyography, cardiac output, and force production. Heart rate variability was assessed using the HRV Add-On package that allows for analysis of RR intervals. This add-on allowed for analysis in both real time and post data collection scenarios.

Procedures

Recruitment

Healthy participants were recruited using convenience sampling, a non-probability sampling technique where the sample is selected based on ease of access (Lund, 2015). This recruitment process was done by word of mouth and posters placed around the Lakehead University, Thunder Bay campus. The locations for the poster included the Agora, Chancellor Paterson Library, ATAC, Sanders Building, and the Hangar. Ten concussed participants were

recruited via convenience sampling from the Lakehead University Concussion Clinic at the discretion of Dr. Dave McKee. The clinic notified suitable participants of the study and let the researchers know when subjects were interested in being part of the study via email. Once the researchers were notified by email, the SCAT-3 forms and participant contact information was collected so he/she could be contacted to arrange testing times.

Both concussed and healthy participants were required to read a letter of information (Appendix F) before reading and signing a letter of informed consent (Appendix G). All participants were required to fill out a medical and demographic questionnaire to screen them for neurological, psychiatric, motor and substance abuse disorder that could have interfered with his/her driving (Appendix A). This questionnaire covered any underlying health conditions that could have potentially affected his/her reaction time, heart rate, or ability to successfully operate the driving simulator. If any underlying conditions exist, the participant was excluded from the study. Concussed participants who were eligible for the study were assessed with the SCAT-3 at the Lakehead University Concussion Clinic before being contacted by the researcher. (Appendix B).

Data Collection

Upon arrival to the driving simulator, the participants were required to read the letter of information and fill out the informed consent, medical and demographic questionnaire, and PAR-Q forms. Once the forms were complete, the participant was asked if he/she had any questions or required any clarification before beginning the orientation drive. When the participants were ready to proceed, they were seated in the STISIM Drive® Model 400 driving simulator a distance approximately 70% of his/her arm's length from the steering wheel with a backrest inclination of 10° (Majid et al., 2013; Yoo, An, Lee, & Choi, 2013). This position minimized fatigue and

maximized the transfer of torque from the participant to the steering wheel. The participant was then fitted with the Polar SP0810 HR monitor to record HR and HRV. Heart rate and HRV data was recorded into LabChart 7.

Participants performed a 10 minute orientation drive to let them become familiarized with the control and feel of the driving simulator before the data collection trials took place. During the orientation drive, he/she was exposed to examples of the dual tasking activities so he/she knew how to successfully respond to the prompts. Once a participant felt comfortable with the simulator, the 20-minute simulation and data collection began. The simulation was based on the Thunder Bay road system with traffic and pedestrians present. Weather was clear and visibility was not reduced. Reaction times were measured during predetermined scenarios and were recorded from the moment stimulus occurs to the moment the brake was depressed or evasive maneuver was performed. Heart rate and HRV were recorded throughout the duration of the simulation and were marked at the beginning and end of each dual task scenario and reaction time activity. This approach allowed the researcher to compare the data and determine if the dual tasking scenario had a significant effect on the HR and/or HRV of the participant. Participants were exposed to several reaction time scenarios. These scenarios included Vehicle incursion at intersection, pedestrian incursion from side of the road, sudden braking by a vehicle in front of participant, pedestrian incursion in school zone, braking by a vehicle in front of participant, and animal incursion. These scenarios are depicted in Figure 6.

Figure 6. Reaction time scenarios in driving simulation. From top left to bottom right: Vehicle incursion at intersection, pedestrian incursion from side of the road, sudden braking by a vehicle in front of participant, pedestrian incursion in school zone, braking by a vehicle in front of participant, and animal incursion.

During dual task events, red triangles were displayed over either of the side mirrors. These triangles were deactivated by the press of a button on either side of the steering column, accounting for the dual tasking component of the reaction time scenarios. These scenarios had a 3 second threshold for time to react before the scenario was considered failed (National Safety Council, 2012; Triggs & Harris, 1982). These scenarios are shown in Figure 7.

Figure 7. Dual task reaction time scenarios in driving simulation. From left to right: Cyclist incursion, motorcycle incursion, and animal incursion.

During each scenario, the participant was required to ensure continued safe operation of the vehicle and respond to changes in the environment (i.e., traffic coming to a halt, pedestrians crossing the road, vehicles backing out of driveways) accordingly. Once these changes in the environment occurred, reaction time data was collected to determine the deficit in response time based on the scenario being displayed.

In the event a participant was unsuccessful during a dual tasking scenario and collided with on screen stimuli, he/she continued with the simulation with no second chance at completing that specific activity. This technique was implemented to minimize any learning effect of the pre-programmed scenarios. If a participant began to experience symptoms of simulator sickness, the scenario was paused to allow him or her to take a break from the screen and/or have something to drink or eat. The researchers had water on hand, if required by the participant. When he/she felt ready to proceed, the simulation was resumed from the point of the original pause. If a participant felt he/she was unable to continue, the simulation was stopped and data collection was terminated.

Additional Information. The STISIM Drive Model 400 collected information regarding traffic infractions and driving performance throughout the simulation. This data was automatically collected by the software and was evaluated for any findings of interest. These

infractions included traffic light infractions, road edge excursions, centerline crossings, and collisions.

Data Analysis

Heart rate variability was analyzed for fluctuations in RR intervals. High frequencies (HF) and low frequencies (LF) of the HRV spectrum were assessed with power analysis in LabCharts to compute power densities based on interpolation of RR intervals using fast Fourier transformation with Hanning windowing (Press, 1992). Fast Fourier transform is a mathematical technique used to transform a function of time into a function of frequency, allowing for the analysis of power density, frequencies, or harmonics of a signal (Brigham, 1974). Analysis of LF HRV occurs at 0.04–0.15 Hz while the power density analysis of HF HRV occurs at 0.15–0.40 Hz (Milicevic, 2005). The power density measures of the spectrum for the LF and HF were used to compute a ratio by dividing the LF power density measures over the HF power density measures obtained from the power spectrum. A high LF power density combined with a low HF power density yields higher HRV values.

To answer the research questions, 2 (group) x (6 scenarios) Mixed Factorial ANCOVAs were performed on reaction time, HRV, and HR in the time domain to determine if there was a significant effect on the results when controlling for the covariate “age”. A 2 (group) x (3 scenarios) Mixed Factorial ANCOVA was also conducted on dual task reaction time to examine the effect of age. If the inclusion of age as a covariate did not affect the significance in any of the ANCOVA tests, then three 2 (group) x (6 scenario) Mixed Factorial ANOVAs were performed to determine if significant interactions existed between groups (healthy and concussed subjects) and scenarios (vehicle incursion, cyclist incursion, sudden braking by vehicle in front of participant, pedestrian incursion, and pedestrian incursion in a school zone) for reaction time,

HRV, and HR in time domain. Similarly, a 2 (group) x (3 scenarios) Mixed Factorial ANOVA was performed for dual task reaction time to examine any interaction effects.

If a significant interaction was found between groups and scenarios for a given dependent variable, the interaction was explained by examining simple main effects of the groups for each scenario. If significant differences were found for the scenario factor, a Bonferroni post-hoc analysis was performed to determine where the significant difference occurred between scenarios for each group. The significance level for all tests was $\alpha \leq .05$. IBM SPSS 20 statistical analysis software was used to conduct these analyses. Traffic infraction information was also analyzed descriptively by counting the number of infractions for each group (healthy or concussed).

Chapter 3: Results

The results of this study use descriptive and inferential statistics analysis techniques to help explain interaction and main effects of group membership and driving scenario encountered on measures of reaction time, dual task reaction time, HRV, and HR. Two-way factorial analysis of covariance (ANCOVA) were performed to determine if the covariant age had an effect on any of the dependent variables. After adjustment for age, there was not a statistically significant effect on interaction or main effects for reaction time, dual task reaction time, HRV, or %MaxHR.

Question 1

A two-way mixed factorial ANOVA was performed to determine if there was a significant interaction between group (healthy or concussed) and scenario (sudden braking by vehicle in front of participant vehicle, pedestrian incursion in a school zone, and vehicle, cyclist, and pedestrian incursions) on reaction time during driving simulation.

Descriptive statistics. Descriptive statistics, shown in Table 4, indicate lower mean reaction times for healthy participants in scenario 1 0.808 (0.23) seconds when compared to concussed participants 1.234 (0.229) seconds. This trend was observed across all 6 driving scenarios.

Table 4

*Descriptive statistics for group type * scenario on reaction time (seconds)*

	Group	Mean	Std. Deviation	N
Scenario 1	Healthy	.808	.227	10
	Concussed	1.234	.229	10
	Total	1.021	.312	20
Scenario 2	Healthy	.975	.167	10
	Concussed	1.233	.204	10
	Total	1.104	.224	20
Scenario 3	Healthy	.750	.358	10
	Concussed	.875	.320	10
	Total	.812	.336	20
Scenario 4	Healthy	.732	.194	10
	Concussed	1.078	.280	10
	Total	.905	.294	20
Scenario 5	Healthy	.813	.179	10
	Concussed	.979	.239	10
	Total	.896	.222	20
Scenario 6	Healthy	1.000	.326	10
	Concussed	1.256	.468	10
	Total	1.128	.414	20

Inferential statistics. As illustrated in Table 5, there was no statistically significant interaction between group (healthy or concussed) and driving scenario on reaction time, $F(3.043, 54.775) = 0.794$, $p = .504$, partial $\eta^2 = .035$. The Greenhouse-Geisser correction was used for repeated measures to adjust the degrees of freedom used in calculating the *p*-value and to minimize the possibilities of committing a type I error due to the violation of the sphericity assumption.

Table 5

*Interaction effect for group type * scenario on reaction time*

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Scenario	Sphericity Assumed	1.593	5	.319	4.082	.002	.178
	Greenhouse-Geisser	1.593	3.043	.524	4.082	.011	.178
	Huynh-Feldt	1.593	3.935	.405	4.082	.005	.178
	Lower-bound	1.593	1.000	1.593	4.082	.058	.178
Scenario	Sphericity Assumed	.310	5	.062	.794	.557	.035
*** Group**	Greenhouse-Geisser	.310	3.043	.102	.794	.504	.035
	Huynh-Feldt	.310	3.935	.079	.794	.531	.035
	Lower-bound	.310	1.000	.310	.794	.385	.035
Error	Sphericity Assumed	7.025	90	.078			
(Scenario)	Greenhouse-Geisser	7.025	54.775	.128			
	Huynh-Feldt	7.025	70.836	.099			
	Lower-bound	7.025	18.000	.390			

Table 6

Main effect of group type on reaction time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Group	2.072	1	2.072	26.469	$p < .001$	.600
Error	1.409	18	.078			

There was, however, a significant main effect of group type. As illustrated in Table 6, a statistically significant difference in reaction times was found between concussed and healthy participants, $F(1, 18) = 2.072$, $p < .001$, $\eta^2 = .600$. There was also a main effect of scenario. As illustrated in Table 5, statistically significant differences in reaction time were found between scenarios $F(3.043, 54.775) = 4.082$, $p = .011$, $\eta^2 = .178$. Greenhouse-Geisser correction was used again to minimize the possibilities of committing a type I error due to violation of sphericity assumption. Bonferonni pairwise comparisons indicate differences in reaction time between scenarios 2 (pedestrian incursion) and 3 (sudden braking by vehicle in lane). Scenario 2 elicited

significantly longer reaction times compared to scenario 3. All other scenario combinations had no significant differences in reaction time. These results are illustrated in Figure 8.

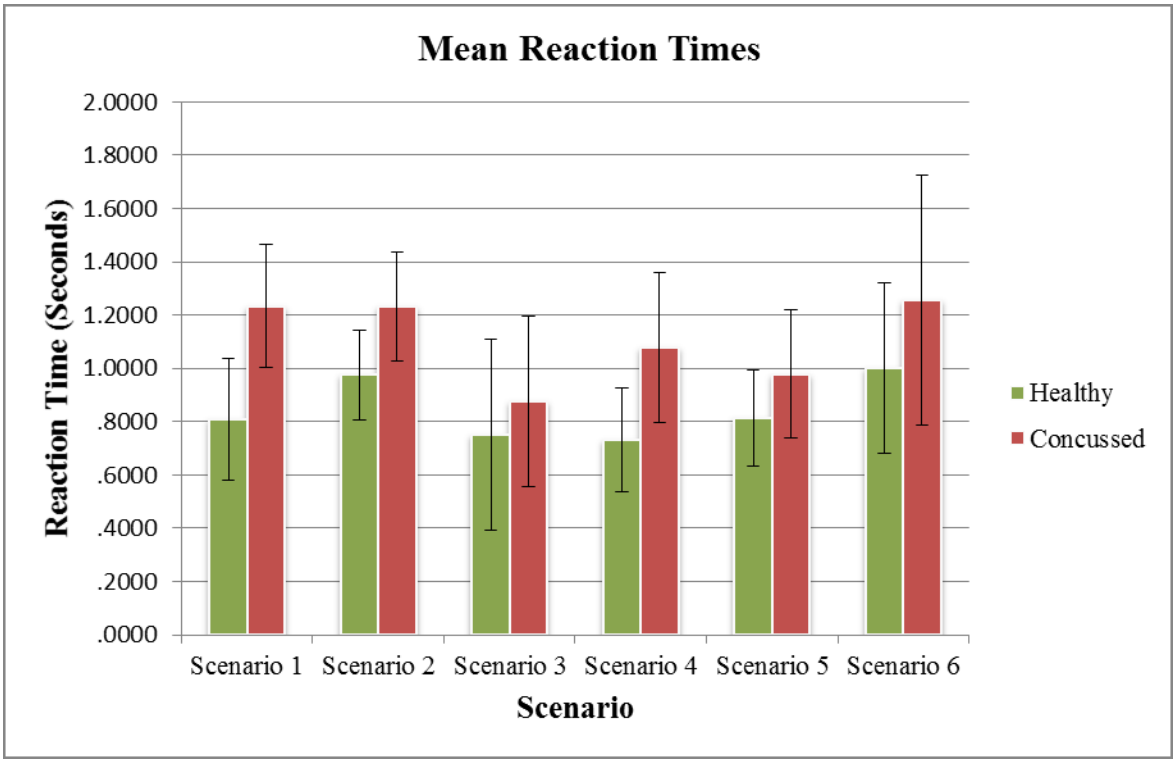

Figure 8. Mean reaction times and their standard deviation. This graph illustrates the differences in reaction time between healthy and concussed groups across 6 driving scenarios. From scenario one to six: Vehicle incursion into lane, pedestrian incursion into lane, sudden braking by vehicle in lane, pedestrian incursion in school zone, vehicle incursion into lane, and pedestrian incursion into lane.

Question 2

A two-way mixed factorial ANOVA was performed to determine if there was a significant interaction between group (healthy or concussed) and dual task scenario on dual task reaction time during driving simulation.

Descriptive statistics. Descriptive statistics, shown in Table 7, indicate lower mean reaction times for healthy participants when compared to concussed participants during scenario

one at 1.148 (0.335) seconds to 2.309 (0.662) seconds. This trend was observed across all 3 dual task scenarios.

Table 7

*Descriptive statistics for group type * scenario on dual task reaction time (seconds)*

	Group	Mean	Std. Deviation	N
Scenario 1	Healthy	1.148	.334	10
	Concussed	2.309	.662	10
	Total	1.728	.784	20
Scenario 2	Healthy	2.156	.831	10
	Concussed	3.000	.000	10
	Total	2.578	.717	20
Scenario 3	Healthy	1.712	.783	10
	Concussed	2.395	.872	10
	Total	2.053	.879	20

Inferential statistics. As illustrated in Table 8, there was no statistically significant interaction between group (healthy or concussed) and dual task scenario on dual task reaction time $F(2, 36) = 0.750$, $p = .479$, $\eta^2 = .027$.

Table 8

*Interaction effect for group type * scenario on dual task reaction time*

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Scenario	Sphericity Assumed	7.349	2	3.675	9.321	.001	.332
	Greenhouse-Geisser	7.349	1.875	3.921	9.321	.001	.332
	Huynh-Feldt	7.349	2.000	3.675	9.321	.001	.332
	Lower-bound	7.349	1.000	7.349	9.321	.007	.332
Scenario * Group	Sphericity Assumed	.591	2	.296	.750	.479	.027
	Greenhouse-Geisser	.591	1.875	.316	.750	.472	.027
	Huynh-Feldt	.591	2.000	.296	.750	.479	.027
	Lower-bound	.591	1.000	.591	.750	.398	.027
Error(Scenario)	Sphericity Assumed	14.191	36	.394			
	Greenhouse-Geisser	14.191	33.741	.421			
	Huynh-Feldt	14.191	36.000	.394			
	Lower-bound	14.191	18.000	.788			

Table 9

Main effect of group type on dual task reaction time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Group	12.042	1	12.042	23.145	$p < .001$	.563
Error	9.365	18	.520			

There was a significant main effect of group type. As illustrated in Table 9, a statistically significant difference in dual task reaction time was found between healthy and concussed participants, $F(1, 18) = 23.145$, $p < .001$, $\eta^2 = .563$. There was also a significant main effect of dual task scenario. As illustrated in Table 8, statistically significant differences in dual task reaction time were found between scenarios, $F(2, 36) = 9.321$, $p = .001$, $\eta^2 = .332$. Bonferroni pairwise comparisons indicate significant differences in reaction time between dual task scenarios 1 (cyclist incursion into lane) and 2 (participant incursion into lane), with scenario 2

eliciting longer dual task reaction times compared to scenario 1. All other scenario combinations had no significant differences in dual task reaction time. These results are illustrated in Figure 9.

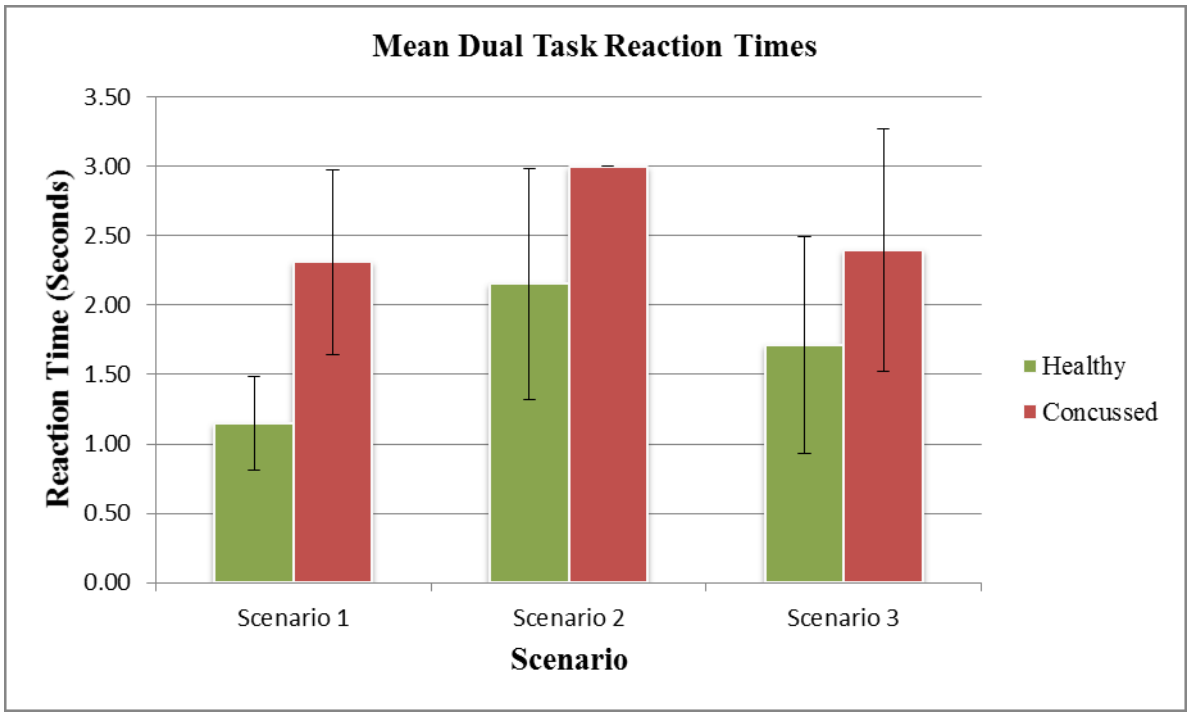

Figure 9. Mean reaction times with standard deviation. This graph illustrates the differences in dual task reaction time between healthy and concussed groups across 3 scenarios. Scenario 2 has no standard deviation reported for the concussed participants due as participants failed to meet the 3-second threshold to respond to the stimulus. From scenario one to three: Cyclist incursion into lane, participant incursion into lane, sudden braking by vehicle in lane.

An a posteriori n-1 Chi Square test was performed to determine if any significant differences occurred between groups in failing tests, this is highlighted in Table 16.

Table 16

N-1 Chi Square Tests on Failed Dual Task Scenarios

Scenario 1	**Pass**	**Fail**	**Total**
Healthy	10	0	10
Concussed	8	2	10
Total	18	2	20
'N-1' Chi squared = 2.11, $p = 0.15$			
Scenario 2	**Pass**	**Fail**	**Total**
Healthy	7	3	10
Concussed	0	10	10
Total	7	13	20
'N-1' Chi squared = 10.23, $p = 0.0001$			
Scenario 3	**Pass**	**Fail**	**Total**
Healthy	9	1	10
Concussed	5	5	10
Total	14	6	20
'N-1' Chi squared = 3.62, $p = 0.06$			

Question 3

A two-way mixed factorial ANOVA was performed to determine if there was a significant interaction between group (healthy or concussed) and scenario (sudden braking by vehicle in front of participant vehicle, pedestrian incursion in a school zone, and vehicle, cyclist, and pedestrian incursions) on HRV during the driving simulation.

Descriptive Statistics. Descriptive statistics, shown in Table 10, indicate lower mean HRV for healthy participants in scenario 1, 1.905 (1.388), when compared to concussed participants, 4.815 (4.891). This trend was observed across all driving scenarios with the exception of scenario 5. Healthy participants experienced higher HRV in scenario 5, 4.123 (2.093) when compared to concussed participants, 3.567 (4.686).

Table 10

*Descriptive statistics for group type * scenario on HRV*

	Group	Mean	Std. Deviation	N
	Healthy	1.905	1.388	10
Scenario 1	Concussed	4.815	4.891	10
	Total	3.360	3.804	20
	Healthy	3.222	3.004	10
Scenario 2	Concussed	4.387	8.727	10
	Total	3.804	6.380	20
	Healthy	2.274	1.400	10
Scenario 3	Concussed	3.986	4.944	10
	Total	3.130	3.644	20
	Healthy	4.517	5.215	10
Scenario 4	Concussed	5.349	4.422	10
	Total	4.933	4.725	20
	Healthy	4.123	2.093	10
Scenario 5	Concussed	3.567	4.686	10
	Total	3.845	3.544	20
	Healthy	3.410	2.512	10
Scenario 6	Concussed	6.598	7.522	10
	Total	5.004	5.698	20

Inferential statistics. As illustrated in Table 10, there was no statistically significant interaction between group (healthy or concussed) and driving scenario on HRV, $F(2.956, 53.207) = 0.445$, $p = .719$, $\eta^2 = .023$. The Greenhouse-Geisser correction was used for repeated measures to adjust the degrees of freedom used in calculating the *p*-value and to minimize the possibilities of committing a type I error due to the violation of the sphericity assumption.

Table 11

*Interaction effect for group type * scenario on HRV*

		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Scenario	Sphericity Assumed	62.125	5	12.425	.573	.721	.030
	Greenhouse-Geisser	62.125	2.956	21.017	.573	.633	.030
	Huynh-Feldt	62.125	3.797	16.363	.573	.675	.030
	Lower-bound	62.125	1.000	62.125	.573	.459	.030
Scenario * Group	Sphericity Assumed	48.275	5	9.655	.445	.816	.023
	Greenhouse-Geisser	48.275	2.956	16.331	.445	.719	.023
	Huynh-Feldt	48.275	3.797	12.715	.445	.766	.023
	Lower-bound	48.275	1.000	48.275	.445	.513	.023
Error (Scenario)	Sphericity Assumed	1952.916	90	21.699			
	Greenhouse-Geisser	1952.916	53.207	36.704			
	Huynh-Feldt	1952.916	68.342	28.576			
	Lower-bound	1952.916	18.000	108.495			

Table 12

Main effect of group type on HRV

	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Group	71.316	1	71.316	2.526	.129	.140
Error	508.193	18	28.233			

There was a main effect of group type as illustrated in Table 12. No statistically significant difference in HRV was found between concussed and healthy participants, $F(1, 18) = 2.526$, $p = 1.29$, $\eta^2 = .140$. There was no significant main effect of scenario. As illustrated in Table 11, no statistically significant difference in HRV were found between scenarios, $F(2.956, 53.207) = 0.573$, $p = .633$, $\eta^2 = .030$. The Greenhouse-Geisser correction was used again to minimize the possibilities of committing a type I error due to violation of sphericity assumption. These results are illustrated in Figure 11.

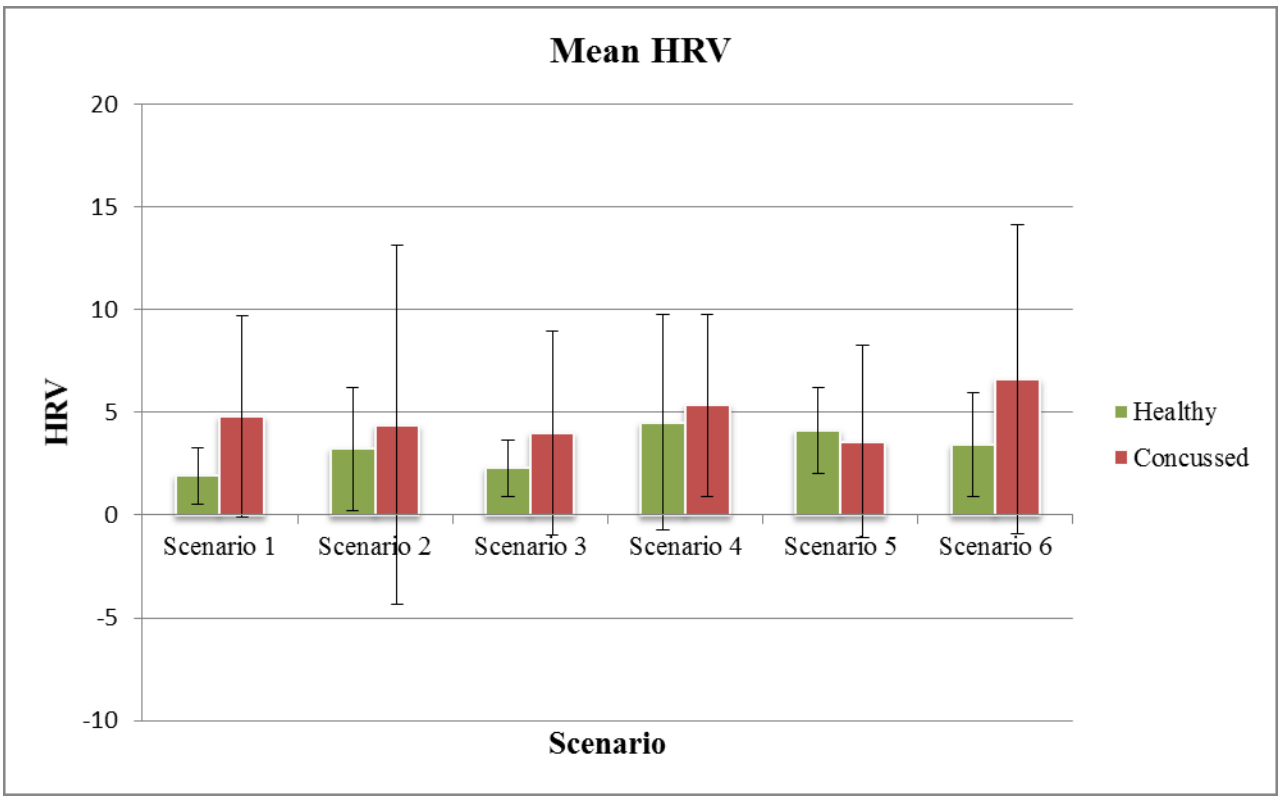

Figure 11. Mean HRV with standard deviation. This graph illustrates the differences in HRV between healthy and concussed groups across 6 driving scenarios. From scenario one to six: Vehicle incursion into lane, pedestrian incursion into lane, sudden braking by vehicle in lane, pedestrian incursion in school zone, vehicle incursion into lane, and pedestrian incursion into lane.

Question 4

A two-way mixed factorial ANOVA was performed to determine if there was a significant interaction between group (healthy or concussed) and driving scenario on the percent of maximum heart rate (%MaxHR) during driving simulation. %MaxHR was calculated based on the age of each participant and used to normalize heart rate data.

Descriptive Statistics. Descriptive statistics, shown in Table 13, indicate lower %MaxHR for healthy participants across all 6 driving scenarios when compared to concussed participants.

Table 13

*Descriptive statistics for group type * scenario on* %MaxHR

	Group	Mean	Std. Deviation	N
	Healthy	42.415	4.533	10
Scenario 1	Concussed	45.365	6.693	10
	Total	43.890	5.766	20
	Healthy	45.204	6.668	10
Scenario 2	Concussed	45.825	6.027	10
	Total	45.514	6.195	20
	Healthy	44.947	6.437	10
Scenario 3	Concussed	46.551	7.478	10
	Total	45.749	6.841	20
	Healthy	42.406	6.942	10
Scenario 4	Concussed	45.061	5.656	10
	Total	43.733	6.311	20
	Healthy	42.725	7.335	10
Scenario 5	Concussed	43.595	7.788	10
	Total	43.160	7.377	20
	Healthy	42.528	6.725	10
Scenario 6	Concussed	44.058	8.248	10
	Total	43.293	7.366	20

Inferential statistics. As illustrated in Table 14, there was no statistically significant interaction between group (healthy or concussed) and driving scenario on %MaxHR, $F(5, 90)= 0.574$, $p = .720$, $\eta^2 = .026$.

Table 14

*Interaction effect for group type * scenario on %MaxHR*

		Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Scenario	Sphericity Assumed	126.840	5	25.368	3.335	.008	.152
	Greenhouse-Geisser	126.840	3.856	32.896	3.335	.016	.152
	Huynh-Feldt	126.840	5.000	25.368	3.335	.008	.152
	Lower-bound	126.840	1.000	126.840	3.335	.084	.152
Scenario * Group	Sphericity Assumed	21.828	5	4.366	.574	.720	.026
	Greenhouse-Geisser	21.828	3.856	5.661	.574	.676	.026
	Huynh-Feldt	21.828	5.000	4.366	.574	.720	.026
	Lower-bound	21.828	1.000	21.828	.574	.459	.026
Error (Scenario)	Sphericity Assumed	684.621	90	7.607			
	Greenhouse-Geisser	684.621	69.405	9.864			
	Huynh-Feldt	684.621	90.000	7.607			
	Lower-bound	684.621	18.000	38.035			

Table 15

Main effect of group type on %MaxHR

	Type III Sum of Squares	df	Mean Square	F	Sig.	Eta Squared
Group	87.211	1	87.211	.367	.552	.020
Error	4278.487	18	237.694			

There was no significant main effect of group type. As illustrated in Table 15, no statistically significant difference in %MaxHR was found between healthy and concussed participants, $F(1, 18) = 0.367$, $p = 0.552$, $\eta^2 = .020$. There was a significant main effect of scenario. As illustrated in Table 14, statistically significant differences in %MaxHR were found between scenarios, $F(5, 90) = 3.335$, $p = 0.008$, $\eta^2 = .152$. Bonferroni pairwise comparisons indicated a significant difference in %MaxHR between driving scenarios 2 and 5, with scenario 2 eliciting a higher mean %MaxHR when compared to scenario 5. These results are illustrated in

Figure 14 and 15. Furthermore, the average HR throughout the duration of each scenario are illustrated in Figure 12.

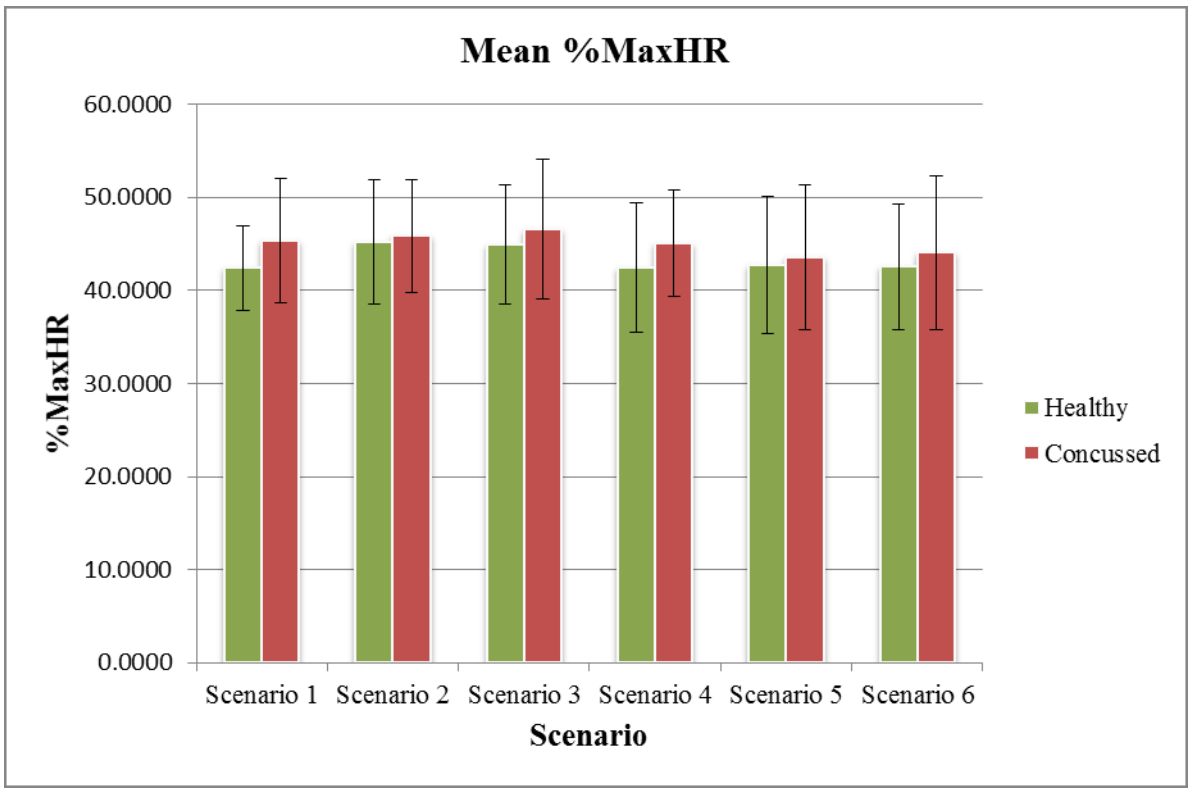

Figure 12. Mean %MaxHR. This graph illustrates the differences in %MaxHR between healthy and concussed groups across 6 driving scenarios. From scenario one to six: Vehicle incursion into lane, pedestrian incursion into lane, sudden braking by vehicle in lane, pedestrian incursion in school zone, vehicle incursion into lane, and pedestrian incursion into lane.

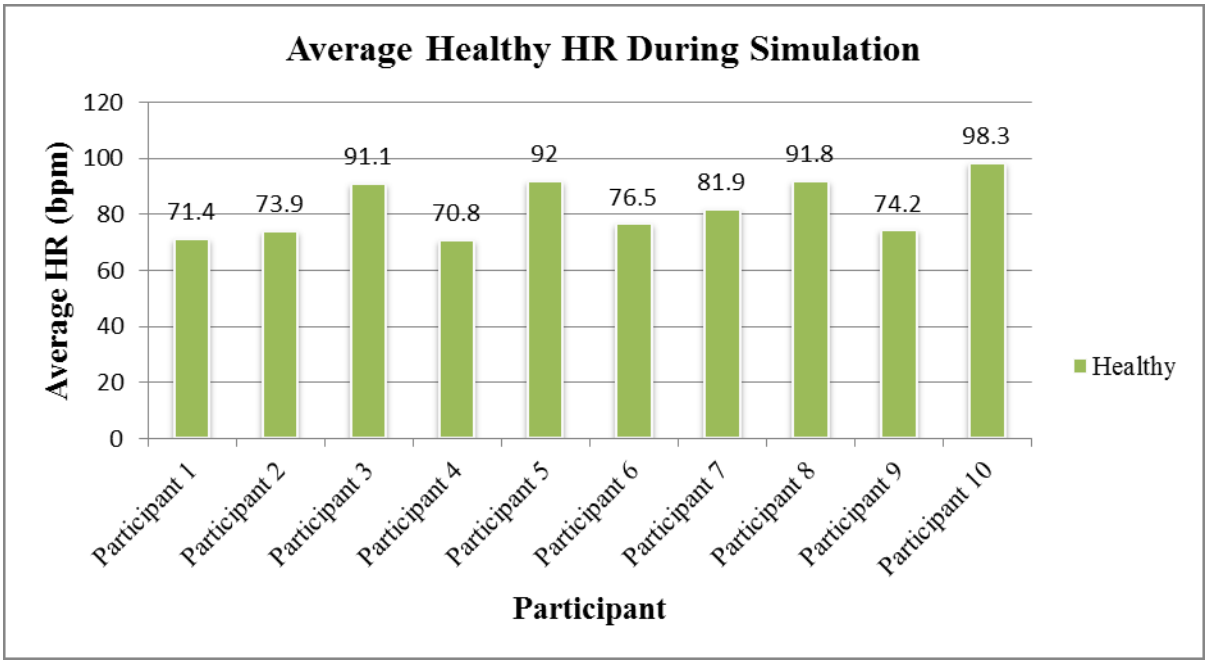

Figure 13. Average HR During Simulation. This graph illustrates the average HR of each healthy participant for the duration of the driving simulation.

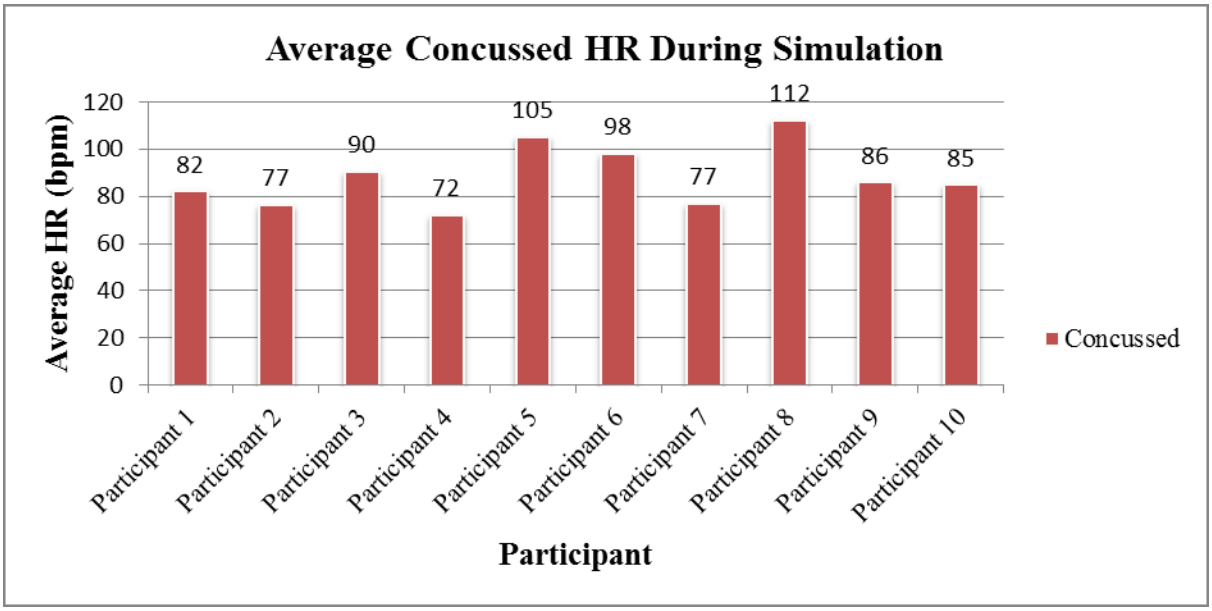

Figure 14. Average HR During Simulation. This graph illustrates the average HR of each concussed participant for the duration of the driving simulation.

Additional Findings

In addition to answering the research questions that guided this study, supplementary data were collected with the simulator to compare the number of different traffic violations that occurred between each group. Formal analysis on this data was not performed as it was examined post-data analysis. The most common infractions seen during the simulation were recorded and broken down into four categories shown in Figure 16.

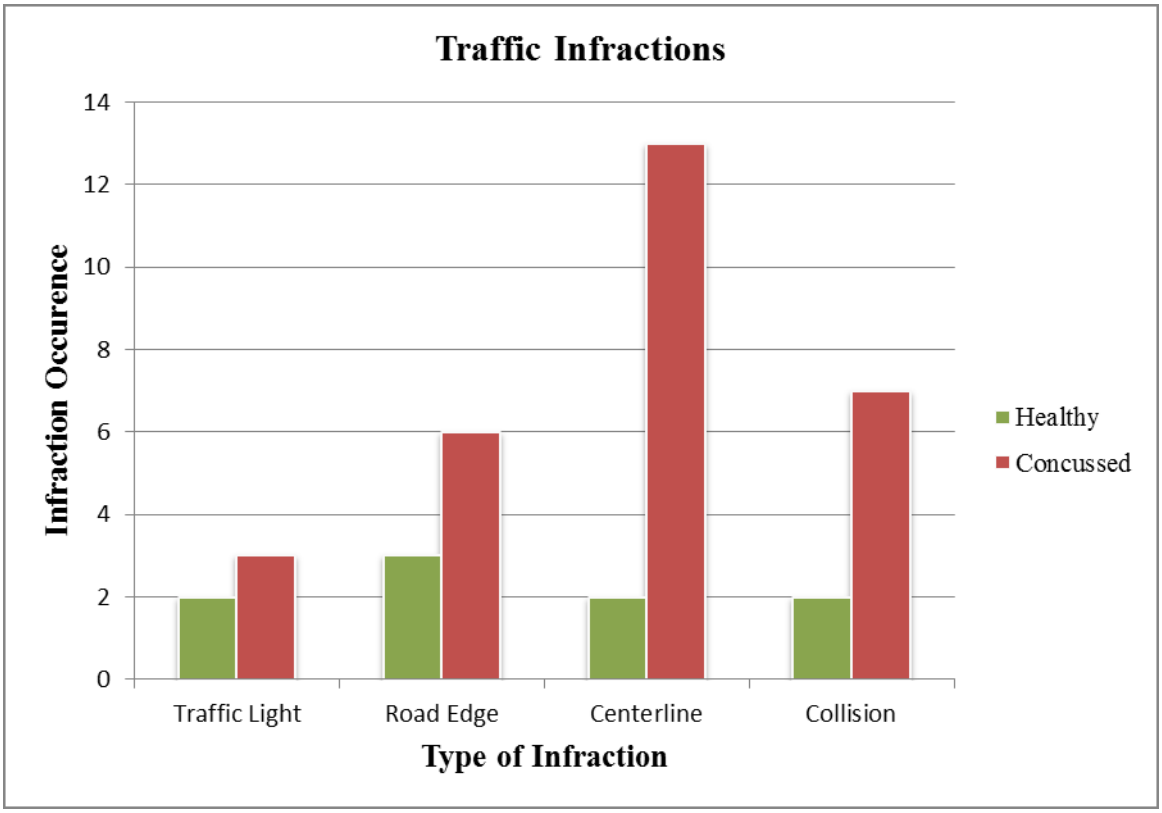

Figure 15. Traffic Infractions. This graph illustrates the traffic violations committed by each group of participants throughout the duration of the driving scenario. These infractions are broken down into traffic light violations, road edge excursions, centerline crossings, and collisions with vehicles and/or pedestrians.

During the course of data collection, no participants in either group experienced any symptoms of simulator sickness or required to take a break from the screen. This matches the

findings of the directed study listed in Appendix G, suggesting that the protocol is well tolerated by both healthy and concussed subjects.

Chapter 4: Discussion

Reaction Time

Analysis of reaction time during each of the six driving scenarios revealed mean reaction times that fell within the normal range previously established by Makishita and Matsunaga (2008) and Johansson and Rumour (1971). These reaction times are illustrated in Figure 8 in the results section. Although it is established that age can have an effect on reaction time (Cantin et al., 2009; Makishita & Matsunaga, 2008), an ANCOVA revealed no statistically significant age related reaction time decline.

Group differences in reaction time were statistically significant, suggesting that on average, concussed individuals experience slower reaction times routinely when compared to a healthy control group. These findings agree with previous research performed on ImPACT by Fazio et al. (2007), suggesting that even asymptomatic concussed individuals experience deficits in reaction time. It is important to note that ImPACT is a neurocognitive test with a reaction time component, and does not directly correlate with driving performance. Scenario differences were also statistically significant for both groups, suggesting that the type and difficulty of each scenario plays a role in the response of the participant. The scenarios involving sudden braking or incursion by a vehicle yielded the fastest reaction times by both groups, while pedestrian incursions or events occurring at intersections yielded the slowest reaction times. For the concussed participants, this may indicate an impaired ability in identifying potential hazards that are not presented directly in front of them in their lane during driving. This possibility would agree with previous literature citing difficulty differentiating between relevant and irrelevant stimuli, such as vehicles making a lane incursion versus those driving with traffic. (Ponsford & Kinsella, 1992; Stuss et al., 1989a; Stuss et al., 1989b). The negatively affected ability to cancel planned actions as a result of concussion may also be attributed to delays in braking in order to

respond to onscreen stimulus (DeHann et al., 2007). Furthermore, this may indicate executive control network deficits in the concussed participant group. These deficits may lead to discrepancy in reaction times during the various traffic scenarios and vehicle/pedestrian incursions when compared to the normal healthy control group (Ponsford & Kinsella, 1992; Stuss et al., 1989).

There were no significant interactions found between group designations and driving scenario on measures of reaction time, demonstrating that differences in reaction time between groups were not dependent on the type of driving scenario encountered. Finally, it is important to note that while the reaction times for the concussed participants were statistically significantly slower, they still fell within the high end of the normal range of driving reaction time for healthy adults as demonstrated by Makishita and Matsunaga (2008) and Johansson and Rumour (1971). Despite the fact that the concussed participants fell within the high end of the normal range of driving reaction times, there is a clear discrepancy between groups that suggests concussed individuals may experience issues when operating a motor vehicle. Situations such as those requiring a sudden stop in traffic, or those in which the driver must react to obstacles entering the roadway from the shoulder of the road (i.e., deer crossing the road, cyclist, or pedestrian walking out into the roadway) seem to be difficult for a concussed individual to navigate successfully based on the results of this study.

Dual Task Reaction Time

Dual task reaction time analysis between the two groups revealed slower mean dual task reaction times in the concussed group across 3 dual task scenarios. It has been shown that the addition of a dual task in a driving environment increased mean reaction times and vehicle control in healthy subjects, although no literature placed concussed subjects in these

environments (Drews et al., 2009; Park et al., 2013). However, Cossette et al., (2014) demonstrated that in concussed subjects dual tasking during gait activities revealed significant issues in obstacle avoidance and balance in concussed subjects when compared to healthy subjects. Despite the lack of literature examining dual tasking in concussed subjects during driving, the present study illustrated a significantly slower mean dual task reaction time when compared to healthy subjects.

Group differences in dual task reaction times were statistically significant. This concurs with previous findings reporting slower reaction times during computer based testing such as the ImPACT and driver hazard perception testing in concussed individuals when compared to healthy controls (Fazio et al. 2007; Preece et al., 2010). Scenario differences also resulted in significant differences, with scenario 2 illustrating the slowest reaction times out of all the scenarios for both groups. This particular scenario displayed the dual task marker over the right side view mirror, which lead to difficulty recognizing it when the subject's attention was on the driving event in front of them (sudden braking by vehicle in the lane). None of the concussed subjects had reaction times fast enough to meet the cut-off threshold for this scenario, while only three of the healthy subjects failed this scenario. With respect to the orienting network of the human attention network, this may be the result of difficulty locating and acting upon cues within a known space (Felmingham et al., 2004; Ponsford & Kinsella, 1992; Spikman et al., 1996). In the present study, the cue would be the red triangle displayed above either side view mirror. Strayer, Drews, and Johnston's 2003 study on dual tasking during driving may also provide insight to the higher number of failed scenarios in the concussed group. It was reported that attention and road sign recognition was impaired, making it possible that this same phenomena occurred with respect to the dual task indicators in the simulation.

There were no significant interactions found between group and driving scenario on dual task reaction times, demonstrating that differences in dual task reaction time between groups were not dependent on the type of driving scenario encountered. This suggests that the orienting network deficits resulted in difficulty locating cues within a known space regardless of the driving scenario encountered while reacting to the dual task markers (Ponsford & Kinsella, 1992; Stuss et al., 1989; Spikman et al., 1996). The significant findings of reaction time and dual task reaction time deficits are important as they replicate the results of a previous pilot study, shown in Appendix H. These findings suggest that the differences in dual task reaction times in concussed subjects should be of concern to a clinician before clearing the subject for a return to driving. These differences occurred regardless of the type of scenario encountered, suggesting that the orienting network deficits may have affected the fundamental skills of driving, such as blind spot and mirror checking, regulation of speed and control of the vehicle within the driver's respective lane. Furthermore, the potential difficulties with attention and road sign identification could prove unsafe, especially when encountering stop signs or signs indicating the start of school or construction zones. If a clinician is able to assess these deficits with a standardized protocol, they can ensure that their client's are returning to the road only when it is safe for them to do so.

Heart Rate Variability

Analysis of HRV during each of the six driving scenarios revealed lower mean HRV for healthy subjects when compared to concussed subjects. While it is well established that age can have a considerable effect on HRV, an ANCOVA revealed no statistically significant differences in HRV when controlling for age differences (Akselrod et al., 1981). If the study included

participants near the maximum inclusive age (45), it is expected that there would be some significant changes in HRV as a result of age discrepancy between participants.

Group differences in mean HRV were not statistically significant. It is important to note the sizeable standard deviation for both healthy (3.242 ± 2.603 ms^2) and concussed (4.815 ± 5.865 ms^2) participants. Previous research has shown that both physical and cognitive activity elicited significant changes in HRV between healthy and concussed subjects, with concussed subjects having lower HRV than healthy subjects when under physical or mental stress (Gall et al., 2004; Luque-Casado et al., 2013). Although the effect of driving on HRV in concussed subjects is not documented, the scenarios used in the present study may not have provided sufficient stress to produce the changes in HRV that we would expect to see between the two groups based on the previous research. Furthermore, there was no significant main effect of scenario on HRV, suggesting that scenarios that revealed the largest discrepancies in reaction time had no appreciable effect on the HRV of either group.

There were no significant interactions found between group and driving scenario, demonstrating that differences in HRV between groups were not dependent on the type of driving scenario encountered. Further research needs to be performed to determine the type and intensity of driving scenario required to bring about the significant changes in HRV seen in other studies involving cognitive load and physical activity. This can be implemented by programming a course with varying weather conditions, road types and conditions, and more aggressive scenarios. Additionally, further research needs to incorporate a larger sample size to ensure normal distribution.

Heart Rate

Analysis of HR during each of the six driving scenarios revealed lower mean %MaxHR for healthy subjects when compared to concussed subjects. An ANCOVA revealed no statistically significant differences in %MaxHR when controlling for age. In order to normalize the HR data between subjects, the percentage of maximum HR was determined by using the formula "220-Age". This was used to determine the participant's maximum HR, by which the HR gathered at each scenario were divided.

Group differences in %MaxHR were not statistically significant. Much like the previous discussion in the HRV section, we would expect to see a significant increase in HR in the concussed subjects when compared to healthy subjects during times of cognitive load (Luque-Casado et al., 2013, Park et al., 2013). This outcome again suggested that the cognitive load provided by the driving scenarios was insufficient to evoke a strong cardiovascular response in the concussed subjects. Although the %MaxHR is higher across all concussed participants, the concussed participants also had higher average HR for the duration of the driving simulation, regardless of their encounters with the measured scenarios.

The main effect of scenario revealed a statistically significant difference between scenarios 2 and 5 on %MaxHR, with both groups experiencing higher values during scenario 2 and lower values during scenario 5. This outcome can be attributed to the presentation of each scenario. Scenario 2 is comprised of the sudden incursion of a pedestrian from the shoulder of the road, while scenario 5 is a braking motorcycle in front of the participant in their lane. The braking vehicle is a much more common event to occur during driving, which is why it may not have been so surprising to the participants. The jump in HR during scenario 2 and 3 was observed in real time by the researcher on LabChart7 during data collection.

There was no statistically significant interaction effect between groups and driving scenario on %MaxHR, demonstrating that differences %MaxHR between groups were not dependent on the type of driving scenario encountered. Much like HRV, more research should be performed to determine the type of events that a concussed individual could encounter during driving that would have a significant effect on HR.

Additional Findings

The supplementary data illustrated in Figure 16 suggests more infractions across all 4 categories by the concussed subjects relative to the healthy control group. The largest discrepancy occurred in the centerline crossing category, which saw the concussed group accumulating 13 infractions to the healthy group's 2. This result is similar to the findings of Drews et al. (2009), where dual-tasking measures implemented in driving simulation lead to decreased lateral control of the vehicle. However, these infractions occurred throughout the duration of the simulation, not just at dual tasking events. Furthermore, the frequency count suggested that there was a higher number of collisions in the concussed group, with 7 collisions to the healthy group's 2. These collisions all occurred during reaction time scenarios and can be attributed to the slower reaction time demonstrated in the results section. An impaired ability to locate and act upon relevant stimuli in the driving environment may also contribute to these collisions, which in turn would increase the time required to formulate a response to the scenarios (Ponsford & Kinsella, 1992; Stuss et al., 1989a; Stuss et al., 1989b).

Limitations

Although reaction time and dual task reaction time produced significant results, it is important to address the limitations of the study. There are multiple factors that may affect the reaction time and driving performance of participants in the simulator. Levels of stress, mood,

attentiveness, and interest in the driving task can alter whether or not a person responds to driving scenarios to his/her fullest potential. If a participant does not take the test seriously, it may result in more traffic infractions than if he/she performed the test as if he/she were in a real car. These factors can affect both healthy and concussed participants of the study. Also, subjective symptoms reported by the concussed participants varied. These varied symptoms, combined with the time frame since the initial injury (approximately 3-4 months in the present study) may have influenced the range of scores for both reaction time and dual task reaction times as more participants were tested.

For several variables, there was not a normal distribution and the presence of outliers. The mixed factorial ANOVA test is robust to the violation of the assumption of normality, although the sample size in this study was relatively small. Despite this, these outliers were considered genuinely unusual variables, and were analyzed to ensure they did not affect the results of the statistical tests.

Acquiring an adequate number of concussed participants that were eligible for the study proved difficult. To remedy this, future studies performed with this population should recruit from both the Lakehead Concussion Clinic as well as through clinics and other health care providers in the community.

Conclusion

The present study was performed to address the lack of literature examining dual tasking and reaction time in concussed individuals during driving simulation, and to determine the extent that reaction time and dual tasking is impaired during driving scenarios of varying difficulty in concussed subjects when compared to a healthy control group. Additionally the effect of these driving scenarios on HR and HRV was also assessed. A comprehensive search of the literature

revealed studies that had examined reaction time, dual tasking, and HRV in concussed participants within gait, balance, and computer based testing scenarios, but never in a driving environment. It is important to address this gap in the literature due to the lack of standardized testing methodology and absence of guidelines for an individual returning to driving after concussion.

The present study revealed statistically significant differences in both mean reaction time and mean dual task reaction times between the healthy and concussed groups. These outcomes suggest an impaired ability to identify and react to potential hazards and differentiate between relevant and irrelevant stimuli in their field of view. These outcomes may also indicate deficits in both the orienting and executive control networks. These findings align with previous studies and should be considered by the clinician when clearing a patient to return to driving. In terms of research, more concussed participants should be evaluated in a variety of driving scenarios to see if these deficits carry over across multiple types of simulator settings. No statistically significant differences were found in terms of HRV or %MaxHR during selected driving scenarios between the two groups. This result suggests that further research should explore alternate driving scenarios to determine if a significant response can be triggered in the concussed subjects, as seen in previous literature regarding exercise and cognitive load. Additional findings suggest a larger number of traffic infractions and collisions for the concussed group when compared to the healthy group. The reaction time and dual task reaction time findings agree with the deficits expected based on previous literature regarding the orienting and executive control networks.

In summary, this study aimed to provide a basis for the assessment of concussed subjects in a driving environment to determine what detrimental effects their injuries have had on their ability to operate a motor vehicle. The findings suggest that there is a need for evaluation or

screening before returning to driving, and that more research needs to be done to both determine all of the deficits in driving performance following concussion, and for the development of a comprehensive screening and assessment tool for health care professionals to utilize when assessing concussed patients.

Future Research

The present study hopes to serve as a foundation in the literature for the assessment of concussed individuals returning to driving. More research will need to be performed to assess acute versus post-concussed individuals from different age ranges, times from injury, and driving experience in order to gain a better understanding of the deficits incurred by concussive injury on driving performance. Furthermore, future research can place individuals in a variety of driving situations not covered in this study, such as inclement weather, freeways, closed course obstacle tests, and scenarios involving reversing and parking. Future research can also incorporate existing tests such as the Attention Network Test (ANT) and the SCAT-3 to validate and compare programmed driving simulations to better understand the effect of concussion on the attention network. By doing this, researchers could compare the type of driving scenarios that have the greatest effect on the attention networks to the deficits seen in concussed participants who performed the ANT. Garnering a broader understanding of concussions effect on safe driving ability is the first step to creating a standardized guideline for clinicians and health care practitioners to use when assessing concussed patients and determining if they are fit to drive.

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Appendix A

Drivers Health Questionnaire

These questions have been designed to give a clear picture of your present health status and to identify any potential health problems for the future. All your answers are confidential and will only be seen by the health assessor and researchers. However, should a significant health problem be detected requiring medical investigation, you will be given a letter to take to your family doctor.

Name:

Date of Birth:

Occupation:

Email:

Approximate monthly kilometers:

Hours driven per week:

Class of license:

Years since license issue:

What type of vehicle do you drive?

If you are a post-concussed individual:

Do you feel safe driving since experiencing a concussion? If no, why not?

Have you stopped driving since your injury? If so, how long has it been?

Personal Medical History

Please put ✔for YES and **X** for NO. Leave blank if unsure. If you answer YES, please give brief details in Supplementary information.

1) Do you or have you ever suffered from any of the following diseases or disorders of the brain?

Stroke **[ ]**

Headaches **[ ]**

Migraines **[ ]**

Dizziness/Balance Problems **[ ]**

Chronic Fatigue Syndrome **[ ]**

Attention Deficit Hyperactivity Disorder **[ ]**

Learning Disorder **[ ]**

Sleep Disorder **[ ]**

Epilepsy/Seizures **[ ]** Visual Disorder **[ ]**

2) Do you or have you ever suffered from any of the following mental health conditions?

Anxiety **[ ]** Autism Spectrum Disorder **[ ]**

Bipolar **[ ]** Stress **[ ]**

Schizophrenia **[ ]** Post-Traumatic Stress Disorder **[ ]**

Depression **[ ]** Other Mental Illness **[ ]**

3) Have you ever undergone a surgical operation? If yes, give details below

4) Have you ever suffered from any serious injury requiring hospital treatment? If yes, give details below

5) Have you ever been treated for an injury to your neck? If yes, give details below

6) Do you experience any pain or difficulty rotating your head left or right?

Supplementary Information ***Please insert question number and relevant details in the space provided***	
Question Number	**Brief Details i.e. condition, dates, investigations, duration of treatment etc**

Concussion History

If you have suffered from multiple concussions in the past, please provide information about them in the following table.

Date	Mechanism of Injury	Loss of Consciousness	Amnesia	Age	Time to Recovery

Medications

Please put ✔for YES and **X** for NO. Leave blank if unsure.

1) Are you taking any of the following medications?

Anticoagulants **[ ]**

Analgesics (pain medication) **[ ]**

Anti-psychotics **[ ]**

Anti-depressants **[ ]**

Sleeping medications **[ ]**

Anxiety medications **[ ]**

Seizure medications **[ ]**

Other **[ ]**

Name of Medicine	Dosage	Times taken per day
.....	.....	.....
.....	.....	.....
.....	.....	.....
.....	.....	.....
.....	.....	.....

2) Nutritional or Herbal Supplements: Please state any you are currently taking

Name of Supplement	Dosage	Times taken per day
.....	.....	.....
.....	.....	.....
.....	.....	.....
.....	.....	.....
.....	.....	.....

Smoking Status

Do you smoke?

If yes please state: Cigarettes **[ ]** Cigars **[ ]** Pipe **[ ]** Other **[ ]**

How many a day?

If you do not smoke now, have you ever smoked?

If yes please state: Cigarettes **[ ]** Cigars **[ ]** Pipe **[ ]** Other **[ ]**

Alcohol Status

One unit = ½ pint of Beer/Cider, a small glass of wine, or a pub measure of spirits

1) What is your average weekly consumption of alcohol in units?

2) Did you regularly drink more in the past?

Never: Once per week or more:

Occasionally: Every day:

3) How many days per month do you consume alcohol?

4) On the days you consumed alcohol, how many drinks were consumed on average?

5) How many times per month do you have 5 or more drinks at one time?

Exercise Status

Please put ✔for YES and **X** for NO. Leave blank if unsure.

1) Do you have a regular exercise routine? [ ]

2) Do you do at least ½ hour of brisk exercise five times a week? [ ]

3) If not, how much exercise do you do in a week?

4) What type(s) of exercise/activity do you do? Please list below

5) Do you have a sedentary job? [ ]

6) Do you often drive short distances rather than walk? [ ]

7) Do you normally take the lift or escalator rather than the stairs? [ ]

8) Do you have a disability that prevents you from exercising? [ ]

9) Do you find time to relax each day? [ ]

Vision History

When did you last visit an optician?

Do you wear corrective lenses? If yes, what is your visual impairment?

Short-Sight [ ] Long-Sight [ ] Other [ ]

If Other, please give details .....

.....

Are you required to wear glasses for driving? [ ]

Do you wear contact lenses? If yes, what is your visual impairment?

Short-Sight [ ] Long-Sight [ ] Other [ ]

If Other, please give details .....

.....

Family History

Please put ✔for YES and **X** for NO. Leave blank if unsure

Do you have a family history of any of the following conditions?

Migraines **[ ]**

Seizure **[ ]**

Attention Deficit Hyperactivity Disorder **[ ]**

Alcohol/Substance Abuse **[ ]**

Dementia/Memory Deficits **[ ]**

Bleeding Disorder **[ ]**

Learning Disorders **[ ]**

Mental Illness **[ ]**

Appendix B

Sport Concussion Assessment Tool 3 (SCAT3)

*See attached PDF

SCAT3™

Sport Concussion Assessment Tool – 3rd Edition

For use by medical professionals only

Name | Date/Time of Injury: Date of Assessment: | Examiner:

What is the SCAT3?[1]

The SCAT3 is a standardized tool for evaluating injured athletes for concussion and can be used in athletes aged from 13 years and older. It supersedes the original SCAT and the SCAT2 published in 2005 and 2009, respectively[2]. For younger persons, ages 12 and under, please use the Child SCAT3. The SCAT3 is designed for use by medical professionals. If you are not qualified, please use the Sport Concussion Recognition Tool[1]. Preseason baseline testing with the SCAT3 can be helpful for interpreting post-injury test scores.

Specific instructions for use of the SCAT3 are provided on page 3. If you are not familiar with the SCAT3, please read through these instructions carefully. This tool may be freely copied in its current form for distribution to individuals, teams, groups and organizations. Any revision or any reproduction in a digital form requires approval by the Concussion in Sport Group.

NOTE: The diagnosis of a concussion is a clinical judgment, ideally made by a medical professional. The SCAT3 should not be used solely to make, or exclude, the diagnosis of concussion in the absence of clinical judgement. An athlete may have a concussion even if their SCAT3 is "normal".

What is a concussion?

A concussion is a disturbance in brain function caused by a direct or indirect force to the head. It results in a variety of non-specific signs and/or symptoms (some examples listed below) and most often does not involve loss of consciousness. Concussion should be suspected in the presence of **any one or more** of the following:

- Symptoms (e.g., headache), or
- Physical signs (e.g., unsteadiness), or
- Impaired brain function (e.g. confusion) or
- Abnormal behaviour (e.g., change in personality).

SIDELINE ASSESSMENT

Indications for Emergency Management

NOTE: A hit to the head can sometimes be associated with a more serious brain injury. Any of the following warrants consideration of activating emergency procedures and urgent transportation to the nearest hospital:

- Glasgow Coma score less than 15
- Deteriorating mental status
- Potential spinal injury
- Progressive, worsening symptoms or new neurologic signs

Potential signs of concussion?

If any of the following signs are observed after a direct or indirect blow to the head, the athlete should stop participation, be evaluated by a medical professional and **should not be permitted to return to sport the same day** if a concussion is suspected.

Any loss of consciousness?	☐ Y ☐ N
"If so, how long?"	
Balance or motor incoordination (stumbles, slow/laboured movements, etc.)?	☐ Y ☐ N
Disorientation or confusion (inability to respond appropriately to questions)?	☐ Y ☐ N
Loss of memory:	☐ Y ☐ N
"If so, how long?"	
"Before or after the injury?"	
Blank or vacant look:	☐ Y ☐ N
Visible facial injury in combination with any of the above:	☐ Y ☐ N

1 Glasgow coma scale (GCS)

Best eye response (E)	
No eye opening	1
Eye opening in response to pain	2
Eye opening to speech	3
Eyes opening spontaneously	4
Best verbal response (V)	
No verbal response	1
Incomprehensible sounds	2
Inappropriate words	3
Confused	4
Oriented	5
Best motor response (M)	
No motor response	1
Extension to pain	2
Abnormal flexion to pain	3
Flexion/Withdrawal to pain	4
Localizes to pain	5
Obeys commands	6
Glasgow Coma score (E + V + M)	of 15

GCS should be recorded for all athletes in case of subsequent deterioration.

2 Maddocks Score[3]

"I am going to ask you a few questions, please listen carefully and give your best effort."

Modified Maddocks questions (1 point for each correct answer)

What venue are we at today?	0	1
Which half is it now?	0	1
Who scored last in this match?	0	1
What team did you play last week/game?	0	1
Did your team win the last game?	0	1
Maddocks score		of 5

Maddocks score is validated for sideline diagnosis of concussion only and is not used for serial testing.

Notes: Mechanism of Injury ("tell me what happened"?):

Any athlete with a suspected concussion should be REMOVED FROM PLAY, medically assessed, monitored for deterioration (i.e., should not be left alone) and should not drive a motor vehicle until cleared to do so by a medical professional. No athlete diagnosed with concussion should be returned to sports participation on the day of injury.

BACKGROUND

Name: _____ Date: _____

Examiner: _____

Sport/team/school: _____ Date/time of injury: _____

Age: _____ Gender: ☐ M ☐ F

Years of education completed: _____

Dominant hand: ☐ right ☐ left ☐ neither

How many concussions do you think you have had in the past? _____

When was the most recent concussion? _____

How long was your recovery from the most recent concussion? _____

Have you ever been hospitalized or had medical imaging done for a head injury? ☐ Y ☐ N

Have you ever been diagnosed with headaches or migraines? ☐ Y ☐ N

Do you have a learning disability, dyslexia, ADD/ADHD? ☐ Y ☐ N

Have you ever been diagnosed with depression, anxiety or other psychiatric disorder? ☐ Y ☐ N

Has anyone in your family ever been diagnosed with any of these problems? ☐ Y ☐ N

Are you on any medications? If yes, please list: ☐ Y ☐ N

_____

SCAT3 to be done in resting state. Best done 10 or more minutes post excercise.

SYMPTOM EVALUATION

3 How do you feel?

"You should score yourself on the following symptoms, based on how you feel now".

	none	mild			moderate		severe
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6

Total number of symptoms (Maximum possible 22) _____

Symptom severity score (Maximum possible 132) _____

Do the symptoms get worse with physical activity? ☐ Y ☐ N

Do the symptoms get worse with mental activity? ☐ Y ☐ N

☐ self rated ☐ self rated and clinician monitored

☐ clinician interview ☐ self rated with parent input

Overall rating: If you know the athlete well prior to the injury, how different is the athlete acting compared to his/her usual self?

Please circle one response:

no different | very different | unsure | N/A

Scoring on the SCAT3 should not be used as a stand-alone method to diagnose concussion, measure recovery or make decisions about an athlete's readiness to return to competition after concussion. Since signs and symptoms may evolve over time, it is important to consider repeat evaluation in the acute assessment of concussion.

COGNITIVE & PHYSICAL EVALUATION

4 Cognitive assessment

Standardized Assessment of Concussion (SAC)[4]

Orientation (1 point for each correct answer)

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1
Orientation score		of 5

Immediate memory

List	Trial 1		Trial 2		Trial 3		Alternative word list		
elbow	0	1	0	1	0	1	candle	baby	finger
apple	0	1	0	1	0	1	paper	monkey	penny
carpet	0	1	0	1	0	1	sugar	perfume	blanket
saddle	0	1	0	1	0	1	sandwich	sunset	lemon
bubble	0	1	0	1	0	1	wagon	iron	insect
Total									

Immediate memory score total of 15

Concentration: Digits Backward

List	Trial 1		Alternative digit list		
4-9-3	0	1	6-2-9	5-2-6	4-1-5
3-8-1-4	0	1	3-2-7-9	1-7-9-5	4-9-6-8
6-2-9-7-1	0	1	1-5-2-8-6	3-8-5-2-7	6-1-8-4-3
7-1-8-4-6-2	0	1	5-3-9-1-4-8	8-3-1-9-6-4	7-2-4-8-5-6
Total of 4					

Concentration: Month in Reverse Order (1 pt. for entire sequence correct)

Dec-Nov-Oct-Sept-Aug-Jul-Jun-May-Apr-Mar-Feb-Jan	0	1
Concentration score		of 5

5 Neck Examination:

Range of motion Tenderness Upper and lower limb sensation & strength

Findings: _____

6 Balance examination

Do one or both of the following tests.

Footwear (shoes, barefoot, braces, tape, etc.) _____

Modified Balance Error Scoring System (BESS) testing[4]

Which foot was tested (i.e. which is the **non-dominant** foot) ☐ Left ☐ Right

Testing surface (hard floor, field, etc.) _____

Condition	
Double leg stance:	Errors
Single leg stance (non-dominant foot):	Errors
Tandem stance (non-dominant foot at back):	Errors

And/Or

Tandem gait[4,7]

Time (best of 4 trials): _____ seconds

7 Coordination examination

Upper limb coordination

Which arm was tested: ☐ Left ☐ Right

Coordination score of 1

8 SAC Delayed Recall[4]

Delayed recall score of 5

INSTRUCTIONS

Words in *Italics* throughout the SCAT3 are the instructions given to the athlete by the tester.

Symptom Scale

"You should score yourself on the following symptoms, based on how you feel now".

To be completed by the athlete. In situations where the symptom scale is being completed after exercise, it should still be done in a resting state, at least 10 minutes post exercise.

For total number of symptoms, maximum possible is 22.
For Symptom severity score, add all scores in table, maximum possible is 22 x 6 = 132.

SAC[4]

Immediate Memory

"I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order."

Trials 2 & 3:

"I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before."

Complete all 3 trials regardless of score on trial 1 &2. Read the words at a rate of one per second. **Score 1 pt. for each correct response.** Total score equals sum across all 3 trials. Do not inform the athlete that delayed recall will be tested.

Concentration

Digits backward

"I am going to read you a string of numbers and when I am done, you repeat them back to me backwards, in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7."

If correct, go to next string length. If incorrect, read trial 2. **One point possible for each string length.** Stop after incorrect on both trials. The digits should be read at the rate of one per second.

Months in reverse order

"Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November .... Go ahead"

1 pt. for entire sequence correct

Delayed Recall

The delayed recall should be performed after completion of the Balance and Coordination Examination.

"Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order."

Score 1 pt. for each correct response

Balance Examination

Modified Balance Error Scoring System (BESS) testing[5]

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)[5]. A stopwatch or watch with a second hand is required for this testing.

"I am now going to test your balance. Please take your shoes off, roll up your pant legs above ankle (if applicable), and remove any ankle taping (if applicable). This test will consist of three twenty second tests with different stances."

(a) Double leg stance:

"The first stance is standing with your feet together with your hands on your hips and with your eyes closed. You should try to maintain stability in that position for 20 seconds. I will be counting the number of times you move out of this position. I will start timing when you are set and have closed your eyes."

(b) Single leg stance:

"If you were to kick a ball, which foot would you use? [This will be the dominant foot] Now stand on your non-dominant foot. The dominant leg should be held in approximately 30 degrees of hip flexion and 45 degrees of knee flexion. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

(c) Tandem stance:

"Now stand heel-to-toe with your non-dominant foot in back. Your weight should be evenly distributed across both feet. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."

Balance testing – types of errors

1. Hands lifted off iliac crest
2. Opening eyes
3. Step, stumble, or fall
4. Moving hip into > 30 degrees abduction
5. Lifting forefoot or heel
6. Remaining out of test position > 5 sec

Each of the 20-second trials is scored by counting the errors, or deviations from the proper stance, accumulated by the athlete. The examiner will begin counting errors only after the individual has assumed the proper start position. **The modified BESS is calculated by adding one error point for each error during the three 20-second tests. The maximum total number of errors for any single condition is 10.** If a athlete commits multiple errors simultaneously, only one error is recorded but the athlete should quickly return to the testing position, and counting should resume once subject is set. Subjects that are unable to maintain the testing procedure for a minimum of **five seconds** at the start are assigned the highest possible score, ten, for that testing condition.

OPTION: For further assessment, the same 3 stances can be performed on a surface of medium density foam (e.g., approximately 50 cm x 40 cm x 6 cm).

Tandem Gait[4,7]

Participants are instructed to stand with their feet together behind a starting line (the test is best done with footwear removed). Then, they walk in a forward direction as quickly and as accurately as possible along a 38mm wide (sports tape), 3 meter line with an alternate foot heel-to-toe gait ensuring that they approximate their heel and toe on each step. Once they cross the end of the 3m line, they turn 180 degrees and return to the starting point using the same gait. A total of 4 trials are done and the best time is retained. Athletes should complete the test in 14 seconds. Athletes fail the test if they step off the line, have a separation between their heel and toe, or if they touch or grab the examiner or an object. In this case, the time is not recorded and the trial repeated, if appropriate.

Coordination Examination

Upper limb coordination

Finger-to-nose (FTN) task:

"I am going to test your coordination now. Please sit comfortably on the chair with your eyes open and your arm (either right or left) outstretched (shoulder flexed to 90 degrees and elbow and fingers extended), pointing in front of you. When I give a start signal, I would like you to perform five successive finger to nose repetitions using your index finger to touch the tip of the nose, and then return to the starting position, as quickly and as accurately as possible."

Scoring: 5 correct repetitions in < 4 seconds = 1
Note for testers: Athletes fail the test if they do not touch their nose, do not fully extend their elbow or do not perform five repetitions. **Failure should be scored as 0.**

References & Footnotes

1. This tool has been developed by a group of international experts at the 4th International Consensus meeting on Concussion in Sport held in Zurich, Switzerland in November 2012. The full details of the conference outcomes and the authors of the tool are published in The BJSM Injury Prevention and Health Protection, 2013, Volume 47, Issue 5. The outcome paper will also be simultaneously co-published in other leading biomedical journals with the copyright held by the Concussion in Sport Group, to allow unrestricted distribution, providing no alterations are made.

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ATHLETE INFORMATION

Any athlete suspected of having a concussion should be removed from play, and then seek medical evaluation.

Signs to watch for

Problems could arise over the first 24–48 hours. The athlete should not be left alone and must go to a hospital at once if they:

- Have a headache that gets worse
- Are very drowsy or can't be awakened
- Can't recognize people or places
- Have repeated vomiting
- Behave unusually or seem confused; are very irritable
- Have seizures (arms and legs jerk uncontrollably)
- Have weak or numb arms or legs
- Are unsteady on their feet; have slurred speech

Remember, it is better to be safe.
Consult your doctor after a suspected concussion.

Return to play

Athletes should not be returned to play the same day of injury.
When returning athletes to play, they should be **medically cleared and then follow a stepwise supervised program,** with stages of progression.

For example:

Rehabilitation stage	Functional exercise at each stage of rehabilitation	Objective of each stage
No activity	Physical and cognitive rest	Recovery
Light aerobic exercise	Walking, swimming or stationary cycling keeping intensity, 70% maximum predicted heart rate. No resistance training	Increase heart rate
Sport-specific exercise	Skating drills in ice hockey, running drills in soccer. No head impact activities	Add movement
Non-contact training drills	Progression to more complex training drills, eg passing drills in football and ice hockey. May start progressive resistance training	Exercise, coordination, and cognitive load
Full contact practice	Following medical clearance participate in normal training activities	Restore confidence and assess functional skills by coaching staff
Return to play	Normal game play	

There should be at least 24 hours (or longer) for each stage and if symptoms recur the athlete should rest until they resolve once again and then resume the program at the previous asymptomatic stage. Resistance training should only be added in the later stages.

If the athlete is symptomatic for more than 10 days, then consultation by a medical practitioner who is expert in the management of concussion, is recommended.

Medical clearance should be given before return to play.

Scoring Summary:

Test Domain	Score		
	Date:	Date:	Date:
Number of Symptoms of 22			
Symptom Severity Score of 132			
Orientation of 5			
Immediate Memory of 15			
Concentration of 5			
Delayed Recall of 5			
SAC Total			
BESS (total errors)			
Tandem Gait (seconds)			
Coordination of 1			

Notes:

CONCUSSION INJURY ADVICE

(To be given to the **person monitoring** the concussed athlete)

This patient has received an injury to the head. A careful medical examination has been carried out and no sign of any serious complications has been found. Recovery time is variable across individuals and the patient will need monitoring for a further period by a responsible adult. Your treating physician will provide guidance as to this timeframe.

If you notice any change in behaviour, vomiting, dizziness, worsening headache, double vision or excessive drowsiness, please contact your doctor or the nearest hospital emergency department immediately.

Other important points:

- Rest (physically and mentally), including training or playing sports until symptoms resolve and you are medically cleared
- No alcohol
- No prescription or non-prescription drugs without medical supervision. Specifically:
  - No sleeping tablets
  - Do not use aspirin, anti-inflammatory medication or sedating pain killers
- Do not drive until medically cleared
- Do not train or play sport until medically cleared

Clinic phone number

Patient's name _____

Date/time of injury _____

Date/time of medical review _____

Treating physician _____

Contact details or stamp

Appendix C

Physical Activity Readiness Questionnaire

Physical Activity Readiness Questionnaire - PAR-Q (revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	1.	**Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	2.	**Do you feel pain in your chest when you do physical activity?**
☐	☐	3.	**In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	4.	**Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	5.	**Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	6.	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	7.	**Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

→ **DELAY BECOMING MUCH MORE ACTIVE:**

- If you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- If you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____ DATE _____

SIGNATURE OF PARENT or GUARDIAN (for participants under the age of majority) _____ WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

1:12

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continued on other side...

Appendix D

STISIM Drive® Model 400

Appendix E

Polar SP0810 Heart-Rate Monitor

Appendix F

Letter of Information
[ON LAKEHEAD LETTERHEAD]

Study Title: The Effect of Concussion on Reaction Time and Heart Rate Variability During Dual-tasking in Driving Simulation

Researchers: Dennis Dumphy

Before agreeing to participate in this research, we strongly encourage you to read the following explanation of this study. This statement describes the purpose and procedures of the study. This study has been approved by the Research Ethics Board of Lakehead University.

Explanation of Procedures

This study is designed to examine the ways in which dual tasking scenarios affect reaction time and heart rate variability in health and concussed individuals. We are conducting this study to learn more about this question since it has not been studied much in the past. Participation in the study requires completion of the following forms: Informed Consent, Medical Health Questionnaire, and if you've experienced previous concussion, the SCAT3. You will then be seated in the driving simulator and hooked up to a heart rate monitor. You will be given a 5 minute test run to familiarize yourself with the controls of the driving simulator. The simulation will last approximately 20 minutes and require you to safely navigate the vehicle on the road with other cars and pedestrians present. You will be required to perform several different dual tasking scenarios while driving and will be instructed by the researcher as to when these will be performed.

Risks and Discomforts

There are no risks or discomforts that are anticipated from your participation in the study. Potential risks or discomforts include possible dizziness or motion sickness while operating the driving simulator. If you are a subject in the study who has previously experiences a concussion, there is a small chance that the simulation could trigger or worsen symptoms of the injury.

Benefits

Benefits of participation in this study include knowledge of your reaction time in a driving environment, your ability to respond to multiple stimuli and how these stimuli affect your heart rate and heart rate variability.

Confidentiality

Everything from the forms to the physical evaluations will all take place at Lakehead University. Upon the completion of this research study only the researcher Dennis Dumphy and his supervisor Dr. Carlos Zerpa will have access to the records. The records will be kept in a locked cabinet in Dr. Zerpa's office during and after completion of the study, and electronic files will be stored on a password protected computer. These records will be kept for a minimum period of five years. The researcher intends to use the data that is collected in conference poster presentations and in their thesis defense presentation.

Appendix G

Informed Consent
[ON LAKEHEAD LETTERHEAD]

By signing this form, I agree that I have read and understood the letter of information for "The Effect of Concussion on Reaction Time and Heart Rate Variability During Dual-tasking in Driving Simulation." I also agree to participate in this research study with the understanding of the following conditions:

1. My participation in this research study is voluntary and I may withdraw at any time. I may also choose not to answer any questions presented to you throughout the study.
2. I understand that this study will require approximately 60 minutes of my time.
3. I understand the potential risks and/or benefits of the study and what they are.
4. The information I provide will be securely stored with the adviser for a minimum of five years at Lakehead University. If the advisor should leave Lakehead University, the information will continue to be stored with the school.
5. I will receive copies of any publications in which the research is discussed if I so wish.
6. I will remain anonymous in any publication of the research findings. Exceptions may be made when the identity of the participant is essential to the goal/purpose of the project.

If you wish to receive a copy of your personal results or information about the results of the study as a whole, please provide your contact information below:

____ I would like to receive a copy of my personal results
____ I would like to receive information regarding the study as a whole

Mailing address:
Email Address:

All questions have been answered to my satisfaction. I understand and agree to the above statements.

_____
Name of Subject (please print)

_____ _____
Signature of Subject Date

_____
Name of Researcher (please print)

_____ _____
Signature of Researcher Date

Appendix H

Pilot Study

THE EFFECT OF CONCUSSION ON REACTION TIME AND DUAL TASKING ABILITY IN A SIMULATED DRIVING ENVIRONMENT: SOME PRELIMINARY RESULTS

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The purpose of this study was to determine the effect of concussion on drivers' reaction time and dual tasking ability in a simulated driving environment. Testing was performed with a STISIM Model 400 driving simulator. Participants (27 healthy and 7 two weeks to six months post-concussion) were exposed to multiple reaction time scenarios including pedestrian, vehicle, and cyclist incursions. Dual tasking ability was measured using STISIM dual task scenarios. There were longer reaction times in concussed participants ($t(7.578)=2.342$, $p=.049$) and a lower number of mean dual task passes in concussed participants ($t(8.914)=2.558$, $p=.031$), both of which were statistically significant. Understanding the effect concussion has on driving ability is the first step to creating a guideline for clinicians to refer to when assessing concussed patients and determining if they are fit to drive.

KEY WORDS: concussion, reaction time, dual tasking, driving

INTRODUCTION: Concussions are mild traumatic brain injuries (mTBIs) that result from a direct or indirect impact to the head (Scorza, Raleigh, & O'Connor, 2012). These functional injuries are caused predominantly by shear stress on the brain tissue due to rotational or angular forces resulting in myriad symptoms that range from headaches and dizziness to difficulty concentrating, impaired memory, and vestibular deficits (Scorza et al., 2012). Concussed individuals may also have deficits in both the orienting and executive control components of the human attention network model, leading to difficulty locating, identifying, and reacting to stimuli (Ponsford & Kinsella, 1992; Stuss et al., 1989). The effect of concussions on driving performance and the ability to perform two activities at the same time (dual tasking) during driving is a relatively new and unexplored field of study. Studies have been performed examining reaction time and dual tasking in driving simulation in healthy participants, but none have been performed using concussed subjects (Drews et al., 2009, Johansson & Rumar, 1971). Furthermore, reaction time in relation to driving after concussion has been examined through personal perception questionnaires and computer based testing, but not in an ecologically valid driving environment (Preece et al., 2010; Preece et al., 2013). It has been established that concussion has a significant effect on reaction time and dual tasking ability, but there is limited literature connecting these factors to a driving environment (Cossette, Ouellete, & McFadyen 2014; DeHann et al., 2007). Therefore, the purpose of this study was to compare driver reaction time and dual tasking ability in concussed and normal healthy populations in a simulated driving environment. This approach is important as it provides an avenue for future research to better understand how concussion alters performance during vehicular operation. It may also aid in the development of a standardized methodology for assessing a concussed driver.

METHODS: Healthy participants (n = 27) were recruited via convenience sampling and concussed participants (n = 7) were recruited by referral from a medical physician through the Lakehead University Concussion Clinic. Participants were excluded from the study if they had psychiatric, motor, or substance abuse disorders that could potentially affect their reaction time,

or ability to successfully operate the driving simulator. This information was obtained via a screening questionnaire completed by all participants. Concussed participants, ranging from two weeks to six months post concussive injury, were also assessed at the Lakehead University Concussion Clinic and medically cleared for participation with the use of the Sport Concussion Assessment Tool 3 (SCAT-3). Ethical approval was obtained from Lakehead University's Research Ethics Board. After obtaining informed consent from the participant, a 10 minute orientation drive was completed allowing the individual to familiarize themselves with the control and feel of the driving simulator. During this time, participants were exposed to examples of the dual tasking activities to understand how to successfully respond to the prompts. Once the participant was comfortable with the operation of the simulator, the 20 minute simulation and data collection began. The simulation was based on the City of Thunder Bay road system with traffic and pedestrians present. Weather conditions were clear and visibility was not reduced during the driving simulation. Reaction times were measured during pre-determined scenarios and recorded from the moment the stimulus occurred, to the moment the brake was depressed, or an evasive maneuver was performed. Participants were exposed to several reaction time scenarios. These scenarios included vehicle incursion, cyclist incursion, sudden braking by a vehicle in front of the participant, pedestrian incursion, and pedestrian incursion in a school zone. During these events, red triangles were displayed over either of the side view mirrors. These triangles were deactivated by the press of a button on either side of the steering column, accounting for the dual tasking component of the reaction time scenarios. During each scenario, the participant was required to safely operate the vehicle and respond appropriately to changes in the environment (e.g., traffic coming to a halt, pedestrians crossing the road, vehicles backing out of driveways). Reaction time data was *collected* based on the scenario displayed. If the participant was unsuccessful during a dual tasking scenario and came into contact with an on screen stimulus, he/she continued with the simulation but did not have a second chance at completing that specific activity. This technique was implemented to minimize any learning effect of the pre-programmed scenarios. If a participant experienced symptoms of simulator sickness, the scenario was paused to allow him/her to take a break from the screen and have something to drink or eat. When the participant felt ready to proceed, the simulation was resumed from the point of the original pause. If the participant was unable to continue, the simulation was stopped, data collection terminated, and the data was not included in the analysis. Due to the discrepancy in sample sizes between the healthy and concussed groups, two independent samples Welch-Satterthwaite *t*-tests were performed with an alpha level set at .05 to determine mean differences in reaction time and dual task pass rates between the healthy and concussed groups using SPSS for Windows.

RESULTS: As illustrated in Figure 1, the mean reaction times in concussed participants measured in milliseconds (M=1074, SD=202) were higher than the mean reaction times in healthy controls (M=1230, SD=165).

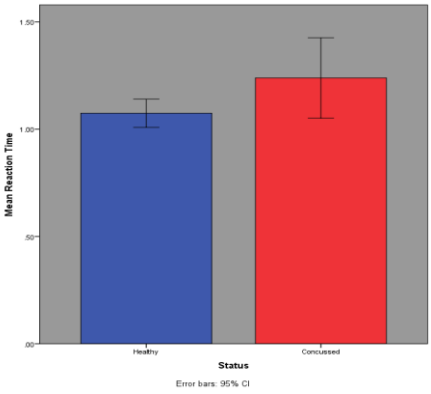

Figure 1: Mean reaction time (milliseconds) values for healthy and concussed participants. Error bars represent 95% confidence intervals.

There was a statistically significant difference in mean reaction times between healthy and concussed participants, t(7.578)=2.342, p=.049. As illustrated in Figure 2, the mean dual task count on the number of passes in the concussed group (M=1.43, SD=0.656) was lower than the mean dual task count in the healthy controls (M=2.26, SD=0.787).

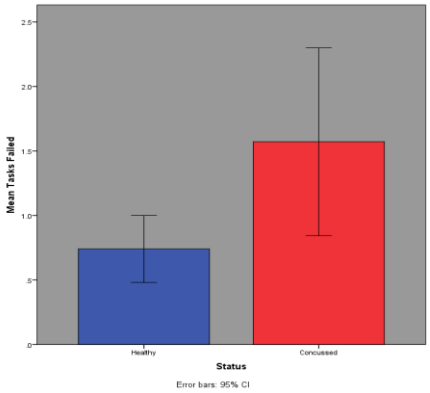

Figure 2: Mean dual task pass rates for healthy and concussed participants. Error bars represent 95% confidence intervals.

There was also a statistically significant difference in mean dual task passes between the healthy and concussed participants, t(8.914)=2.558, p=.031.

DISCUSSION: These preliminary results highlight important differences in both reaction time and ability to respond to secondary dual task cues in a driving environment between concussed participants and normal healthy controls. With respect to human attention network models, concussed drivers appeared to experience deficits in the orienting network. Orienting network deficits resulted in difficulty with locating cues within a known space before a target or symbol was shown (Ponsford & Kinsella, 1992; Stuss et al., 1989; Spikman, Zomeren, & Deelman, 1996). This potentially affected on the concussed participants' ability to locate the dual task markers and respond correctly in the required amount of time. Deficits in executive control networks, as seen in the concussed participants, led to difficulty determining and acting on stimuli relevant to the current task, such as dual task markers, amidst background stimuli irrelevant to the test (Ponsford & Kinsella, 1992; Stuss et al., 1989). This may have led to the discrepancy in reaction times during the various traffic scenarios and vehicle/pedestrian incursions when compared to the normal healthy sample. During the course of data collection, only one concussed participant had to drop out due to nausea and dizziness demonstrating that this protocol was relatively safe and well tolerated by the patient population. While these findings were statistically significant, it is important to note that reaction times and dual task fails may have been affected by mood, attentiveness, motivation, and the relative health of the subjects. This study is limited by the broad and subjective nature of concussion. The subjective symptoms reported by the concussed participants varied. These varied symptoms, combined with the wide-ranging time frame since injury may have lead to a large range of scores for both reaction time and dual task pass rates as more participants were tested.

CONCLUSION: The purpose of this study was to compare driver reaction time and dual tasking ability in concussed and normal healthy populations in a simulated driving environment. These

preliminary results revealed statistically significant differences between the groups for both reaction times and dual task pass rates. These results are consistent with previous literature reporting reaction time and dual task deficits for concussed individuals in non-driving environments. Furthermore, these results are in accordance with the deficits concussed individuals experience in the orienting and executive control networks as indicated by the human attention network model. Understanding the effect concussion has on safe driving ability is the first step to creating a standardized guideline for clinicians to use when assessing concussed patients and determining if they are fit to drive. Standardized guidelines would also benefit individual patients by ensuring both their own safety and that of others sharing the road. This research also assists in opening an avenue for future research to explore relationships between brain injury reconstruction techniques using kinematic measures and driving ability. Future research will include more concussed participants to strengthen the results of the study and equalize the number of participants in each group.

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