SEX-RELATED DIFFERENCES IN OCULOMOTOR AND COGNITIVE CONTROL IN ASYMPTOMATIC VARSITY ATHLETES WITH AND WITHOUT A HISTORY OF CONCUSSION

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Abstract

This research examines sex-related differences in oculomotor and cognitive control in asymptomatic varsity athletes with and without a history of concussion. This study examined saccade latency, antisaccade reaction time, and cognitive tests (Stroop) using virtual reality goggles in a stationary seated position. This was administered using the Saccade Analytics© NeuroFlex® system. Data was collected from 153 varsity athletes (82 males, 71 females), including a concussion history questionnaire (64 athletes reported > 1 concussion). We observed no significant difference regardless of both sex and concussion history, varsity athletes demonstrated no differences in their saccade latency (SL), antisaccade reaction (ART) or total Stroop Error (TSE). This research suggests that athletes who have a history of concussion can fully recover and perform similar to those without a concussion history regardless of sex. Future research may aid in the development of more objective testing protocols when assessing sex-related differences in oculomotor and cognitive control.

Dedication

I would like to dedicate my work to three important people.

My siblings: Matthew and Melissa. Growing up, we always made sure that anything we did was quality first and quantity second (unless it's about food). Over many years, this lesson taught me that it's not how many goals you accomplish but the effort you put into accomplishing them.

My loving mother: Joy. You raised me with the belief that I could accomplish anything. It wasn't the "you can do anything you put your mind to" that got me to where I am today. It was you showing your unshakable love for us: being both parents for us, working long hours to provide for us, teaching us life lessons, being there to celebrate us and picking us up when we are down on ourselves. Most importantly, it was how you carried yourself, your strength as you handled some of life's obstacles, all while being respectful and caring for others around you. I believe I can achieve anything because you showed me. I only hope to live up to your legacy.

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Second, I would also like to say a thank you to both Ravneet Kalkat and Christina Amaral, without them this experience would not have been the same. Research labs are rarely known as "fun" hangouts where work is done, but both of you made that possible.

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Finally, I would like to thank Paula (my better half), I don't think it would have been possible without her encouragement to pursue research. She taught me the importance of always having a curious mind, even if it meant listening to me for hours on end.

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Terminology

Abbreviation	**Expanded word**
ART	Antisaccade Reaction Time
CBF	Cerebral Blood Flow
GCS	Glasgow Coma Scale
mTBI	Mild traumatic brain injury
PCS	Post-concussion Syndrome
RTL	Return to Learn
RTP	Return to Play
SCAT5	Sport Concussion Assessment Tool 5th Edition
SL	Saccade Latency
SRC	Sport-related concussions
TBI	Traumatic Brain Injury
TSE	Total Stroop Error
VOR	Visual Ocular Reflex
VR	Virtual Reality

Chapter 1: Introduction

Background

The familiarity and public awareness of sport-related concussions (SRC) have rapidly increased within the last decade[1]. A concussion, sport-related or not, is often identified as a form of mild traumatic brain injury (mTBI). However, the complexity of defining a concussion has been at the forefront of research, which has challenged researchers to provide an accurate definition that encompasses all aspects of injury[2]. The *Consensus Statement on Concussion in Sport* defines concussions as an injury caused by a biomechanical force from a direct or indirect blow to the head, face, neck or body[1]. The mandate of the World Health Organization (WHO) Collaborating Task Force on mild traumatic brain injury (mTBI) and acute brain injury states that an mTBI can be caused by a biomechanical force that causes a disturbance in brain function[3,4]. According to the WHO Collaborating Task Force, a diagnosis of an mTBI must include (a) one or more of the following symptoms: confusion or disorientation, loss of consciousness for 30 minutes or less, post-traumatic amnesia for less than 24 hours, and/or other neurological changes as determined by a neurophysiological assessment; and (b) a Glasgow Coma Scale (GCS) score of 13-15 after 30 minutes post-injury[4]. It is worth noting that the symptoms and GCS outlined in the WHO's definition on mTBI are also present in the Sport Concussion Assessment Tool Edition 5 (SCAT5) as outlined by the *Consensus Statement on Concussion in Sport* Group[1]. Concussions have very few visible signs within a clinical examination and are therefore diagnosed based on many patient-reported symptoms and the mechanism of injury [5]. Despite the similarities in the definitions of sport-related concussion[1] and mTBI [4] the terms are often used interchangeably which can cause confusion and a lack of consistency as concussion is often cited as one form of mTBI along its injury continuum. For the purpose of this paper, the term sport-related concussion (SRC) will be used as the definition encompasses direct and indirect forces to the head, neck, face or body which is more common in sport settings.

The incidence of SRC has been consistently increasing. A Canadian study from 2003-2013 showed a 4.4-fold increase in the frequency of emergency department and doctor visits related to concussions, with approximately 30% of all concussions being sport-related[6]. The highest incidence rate found during this time was a 5-fold increase in children and youth ages 13 to 18[6]. With Statistics Canada reporting approximately 46,000 diagnoses in 2016-2017 alone[7], there is a prominently increasing trend in concussion diagnosis within Canada. The closest estimate for mTBI cost burden in Ontario, Canada comes from a related traumatic brain injury lifetime cost of approximately 979 million to 1.22 billion[8]. Although these injuries are different in severity, this cost may only represent a fraction of the injuries reported to emergency departments across Canada relating to mTBI.

The rate of research on concussion injuries has increased over the last decade and has even been referred to as the silent epidemic by the Center for Disease Control[9]. The untethered relationship between sports, the advancement of imaging technology, research, and society has created an unprecedented ability to conduct more extensive research leading to greater access to information to the general population. Emerging research fields in cognitive neuroscience and vision science are just two examples of groups who have started to advance the discussion surrounding the effects of SRC's as well as exploring different ways to diagnose, assess and manage concussion-related symptoms in sport[10].

Pathology

Over the past decade, extensive pathophysiological research has been conducted on animal and human participants to build a foundational knowledge of symptomology for concussions. The mechanism of injury for a concussion can be explained by describing two different types of mechanical forces applied. Firstly, a linear force applied to the brain in one direction and then back in the opposite direction is known as a coup-contrecoup injury. The brain impacts the inner surface of one side of the cranium and rebounds to impact the opposite side; this type of force is often associated with an increase in cortical contusions[11]. Secondly, rotational forces applied to the brain are non-linear and can occur in the sagittal, frontal, and transverse planes. Both mechanical forces which are caused by either direct or indirect blows to the head may result in a stretch and/or shearing force applied to the axons, destabilizing the neuronal structure[11–13].

The neurometabolic cascade suggested by Giza and Hovda (2001)[14] explains the enormous effort undertaken by the brain after such an injury. The details of ionic flux demonstrate alterations in cell membranes leading to a metabolic crisis that heavily relies on adenosine triphosphate (ATP) output from the mitochondria[13]. Directly following a concussion, voltage-dependent potassium (K+) channels open because of a disruption to the neuronal membrane, leading to an influx of K+ outside the neuronal membrane. Under normal conditions, the surrounding glial cells are responsible for the reuptake of the extracellular K+. Once a large enough force disrupts the neuronal membrane, the glial cells can no longer reabsorb this influx of K+. When this process is left unchecked, it will lead to an immense excitation followed by a sweeping suppression known as spreading depolarization of the nerve cell[13]. To regain homeostasis, the cell relies heavily on ATP output from the mitochondria to initiate the active ion pumps for the reuptake of K+, leading to an energy crisis due to the substantial rapid decrease in ATP. An exponential increase follows this in waste products such as lactate. This initial elevated use of ATP, in turn, increases the amount of glucose consumption which could lead to a possible detrimental metabolic crisis in the brain. This harmful metabolic crisis affects the overall mechanism and the interconnections between cerebral blood flow (CBF), neuronal activity and cerebral metabolism.

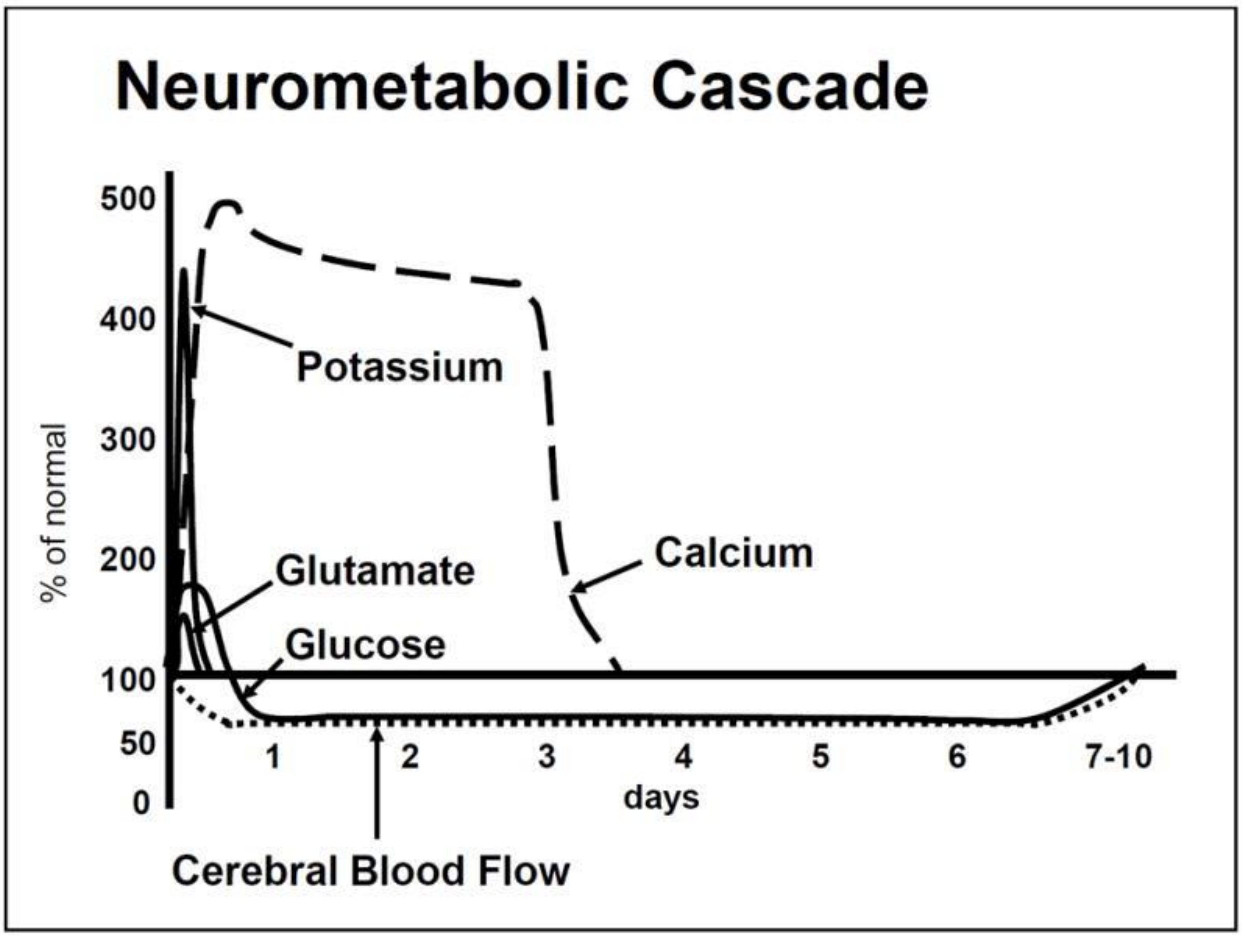


Figure 1. Time course of the neurometabolic cascade of concussion[13].

Furthermore, axonal and cytoskeletal injury caused by shearing/rotational forces leads to a further breakdown and destabilization of microtubules, ultimately leading to a dysfunction in transport and neuronal connections[14–16]. This cellular cascade impacts CBF, altering the metabolic process that is tightly coupled with neuronal activity, which may lead to widespread damage in the brain. This results in symptoms and other dysfunctions that significantly affect those who have suffered from a concussion[14,15].

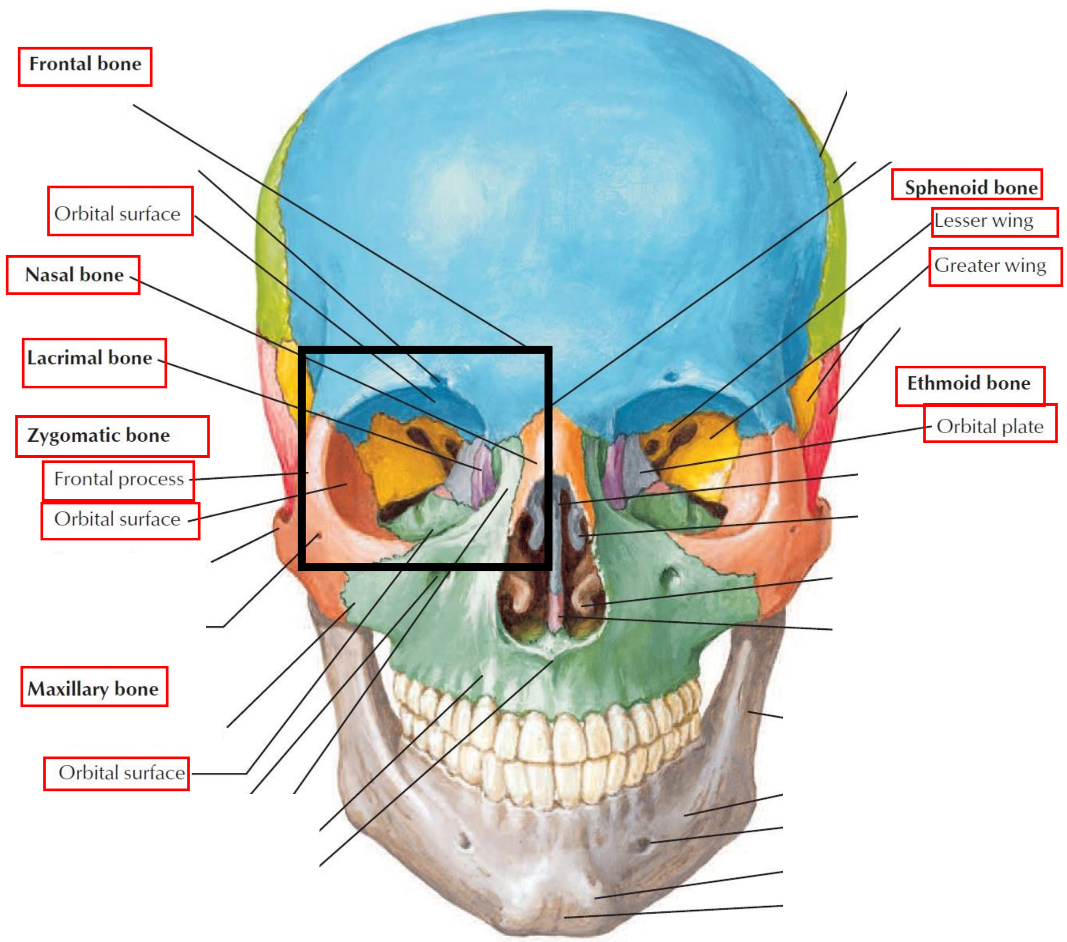
Post-concussion Syndrome

Interestingly, post-concussion syndrome PCS and persistent concussion symptoms are both used to reflect the ongoing symptoms individuals experience beyond the typical 7-14 day recovery timeline[1, 17]. Post-concussion syndrome (PCS) was outlined by the International Classification of Disease and Related Health Problems (ICD-10) and classified as having: (1) cognitive deficits and memory and/or attention and (2) at least three or more of the following symptoms: headache, dizziness, sleep disturbances and personality changes lasting for longer than three months after sustaining a concussion (ICD-10 section F0.2) Persistent post-concussion symptoms refers to post-concussion symptoms lasting longer than the expected recovery timeframe of symptoms, which typically resolved within 7-14 days[1, 17]. The term post-concussion syndrome (PCS) will be used to refer to concussion symptoms that last longer than the 3 months as outlined by the ICD-10 throughout this paper.

Research conducted by Ellis et al. (2015)[15] helped advance our understanding of concussion injury and rehabilitation by introducing classifications of post-concussion syndrome based on the metabolic crisis and cluster of present physiologic, vestibulo-ocular and cervicogenic symptoms. The physiological classification is described as having persistent alterations in neuronal depolarization, cellular metabolism, and cerebrovascular physiology, with predominant symptoms including persistent headaches, dizziness, nausea, fatigue, light, and sound irritability[15]. The cervicogenic classification is an isolated mechanoreceptive, nociceptive and proprioceptive dysfunction within the cervical spine, with predominant symptoms including dull headaches and occipital headaches activated by activity that relies on neck stability[15]. The vestibulo-ocular classification is an isolated dysfunction of the central and peripheral components of the vestibulo-ocular neurological sub-system, with predominant symptoms of mild to moderate headache and eye strain[14]. These three classifications help categorize (PCS), allowing practitioners to access objective research regarding symptomology that may aid in their recovery programs.

Vision and oculomotor related impairments following concussion

Vision-related deficits are common in SRC injuries, due to the anatomical location of the eyes and cranial nerves (CN). Coupled with the common coup-contrecoup mechanism and rotational forces experienced in SRC[16], cranial nerves that are relevant to vision-related deficits (optic, oculomotor, trochlear and abducens) are located just behind the orbital socket. The orbital socket that houses the eye is formed by seven different bones to help form each of the borders. The roof of the orbit consists of the lesser wing of the sphenoid bone and orbital surface of the frontal bone. The lateral wall is comprised of the frontal process of the zygomatic bone, greater wing of the sphenoid bone and the zygomatic bone. The medial wall is created by the sphenoid body, orbital plate of the ethmoid bone, lacrimal bone, and nasal bone and the floor is formed by the orbital surface of the maxillary bone and zygomatic bone. The cranial nerves pass through various foramen and fissures formed by the intricate bony architecture of the orbital socket, leaving them susceptible to damage.



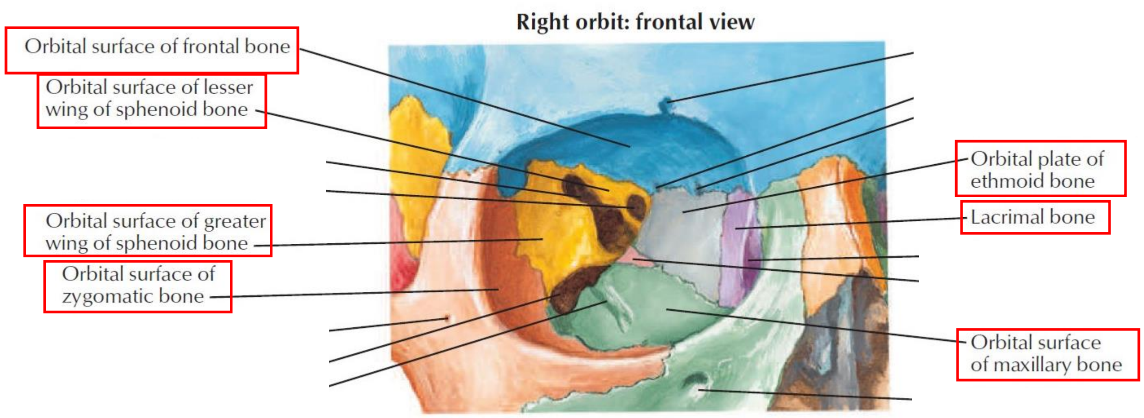


Figure 2 – Bony anatomy of the orbit of the eye[18] .

Visual processing is one of the most complex integrations of neural connections throughout the brain. The visual system is comprised of the sensory and central nervous systems, which are responsible for: light reception, coloured vision, stereopsis, motion perception, pattern recognition, accurate visual motor coordination (fixation, saccades and smooth pursuits), accommodation, pupil control, acuity and blinking. This paper will only discuss the relationship of oculomotor control and cognition as they relate to SRC history, particularly since the occipital cortex is the primary visual cortex for processing visual information as our dominant sense. The specific complex physiological processes of vision can be found in *The Principles of Neural Science* by Kendel and Schwartz [19] as an additional resource.

Saccade

An accurate and timely diagnosis of concussion is vital to ensure a safe and complete recovery. One of the most investigated objective measurements in concussion vision research is saccades[20]. Saccades are rapid eye movements (in any direction) that enable quick and accurate scanning from one object to another[16]. Saccade testing requires patients to move their eyes back and forth between two objects that the practitioner is holding. Concussions can significantly impact these eye movements and can negatively change them even after symptom resolution[21]. A dysfunction throughout the visual and oculomotor control system can lead to increased symptom aggravation. Oculomotor impairment and symptoms may include diplopia (double vision), difficulty reading, headache, eye strain, blurred vision, and problems scanning[22,23]. A recent study has identified that professional athletes have a higher diagnosis of diplopia after acute concussions than their healthy control counterparts, lending evidence for additional sensitive oculomotor testing[24].

Murray et al. (2019)[21] examined participants with SRC and found a decrease in saccadic skills compared to a healthy control group. This study was completed using a Wii Fit board and a mounted monocular eye-tracking tool[17]. Those who had a SRC demonstrated a significant increase in saccade amplitude and velocity when compared the healthy group. An increase in amplitude and velocity results in more extensive and faster eye movements, leading to decreased accuracy and control. These findings align with others who have seen similar results with changes in amplitude, velocity and accuracy of saccades[20,25–27].

Eye-tracking technology can recognize additional details related to cognition and oculomotor control after sustaining a concussion. While Kelly et al. (2019)[28] demonstrated no significant difference in saccades between concussed and healthy control groups, interestingly, when participants were asked to indicate the direction of a stimulus, the concussed participants performed slower than the control group. These results may be due to the complex cognitive processes required to bring perception and action together. Saccades are a basic eye movement and can be overlooked as an objective tool in diagnosing a concussion. Using eye-tracking technology can increase the objectivity of the practitioner’s diagnosis, as well as helping return the athlete to sport in a safer manner.

Antisaccade

One of the complex visual movement skills that measure oculomotor function and cognition together is antisaccades. Antisaccades, which are the inhibition of a regular saccadic movement, can be evaluated as early as 24 hours after a concussion to help with diagnosis[29].

Antisaccade studies have linked executive control to multiple brain regions, including the frontal and parietal lobes, frontal and supplementary eye fields, which have shown to inhibit saccadic movements[30]. The core principle of these tests is that it requires the participant to use higher-order automatic response inhibition and attentional control by moving their eyes in the opposite direction of the normal saccadic movement to the peripheral target stimulus. Simply, antisaccades use a wide range of brain areas to complete an uncomplicated task of moving the eyes in the opposing direction of a stimulus.

Concussion research has consistently demonstrated significant differences in amount, duration, accuracy and velocity of antisaccades when comparing healthy controls to those with brain injuries such as concussions. This suggests antisaccades can be used as a biomarker for concussion as a reliable and valid measure[26,29,31]. A meta-analysis conducted by Mani et al (2018)[32] objectively measured oculomotor research related to both mTBIs and TBIs. The studies included in the analysis found that antisaccades could supplement traditional neuropsychological testing, which is typically completed for all concussion baseline testing. Moreover, analysis on antisaccade assessments demonstrated how antisaccades could be a proxy neural marker for cognitive impairment[28].

D'Amico's (2016)[29] unpublished dissertation found that participants who had sustained a concussion had inadequate oculomotor control, with the most significant difference in antisaccade ability. D'Amico (2016)[27] administered the antisaccades task on athletes 24 to 48 hours post-concussion. By using eye-tracking technology to determine gaze position, athletes were reported to have longer antisaccade durations when compared to healthy and matched controls[27]. Others have found similar findings with antisaccade testing with significant differences in latency to target, inhibition control, mean error rate and impaired motor accuracy[25,27,30,31,33–37]. These results confirm the need to pursue athlete specific antisaccades concussion protocols and further investigate additional cognitive impairments.

Cognition recovery assessment

There is a need to further investigate the relationship between previous concussions and the development of cognitive impairment in a non-invasive and practical manner. Historically, this topic has been motivated by postmortem research of athletes with a history of high impact exposures such as football or boxing[38,39]. Research on SRC has highlighted the public's perception of the irreversible damage after repetitive head impacts[40]. In non-sports related traumatic brain injuries (TBI), investigations found an increased risk of cognitive impairment and dementia, the higher the severity of injury[40].

Subjective reports with respect to neuropsychological test results are not supported in the literature. There exists a disparity in subjective and objective test results, which adds a need for more sensitive cognitive testing[41–43]. One of the most common tools used to assess SRC is the SCAT 5[1]. The tool is typically reviewed every four years to reflect new research being conducted on the current definition of SRC, in addition to signs and symptoms of acute concussions, current research regarding general and sideline evaluation guidelines, removal from play guidelines and graduated return to sport (RTS) and return to learn (RTL) strategies[1]. In reviewing the gradual 6-stage RTS strategy of the SCAT 5, cognitive-specific elements of return to activity are mentioned first within Stage 1 by stating there should be a "gradual reintroduction of work/school activities" as the targeted goal[1]. Stage 4 indicates "exercise, coordination, and increased thinking" as its targeted goal[1]. Interestingly, Stages 2 and 3 of the protocol do not incorporate a cognitive component, which ignores the complexity of the neurocognitive element of rehabilitation. In contrast, within SCAT5 the Return To Learn (RTL) strategies are vastly different from its RTS portion, with no incorporation of physical strategies. This may reflect a missed opportunity to address a more comprehensive approach to RTS and RTL strategies. Creating more detailed RTS and RTL guidelines that incorporate both the physical and cognitive elements of recovery will emphasize the importance of an athlete's full physical and cognitive recovery even after athletes report full symptom resolution. Moreover, tools such as ImPACT Neurocognitive test and the King-Devick test are dominant modalities in assessing concussions at baseline with athletes. However, they lack accuracy in assessing physiological performance with a neurocognitive load, something that is specific to both practice and game environments in all sport and physical performance.

Stroop

The Stroop task is a neurocognitive evaluation that integrates multiple brain areas (frontal-parietal and temporal areas, white matter and midbrain) to assess several different cognitive domains, such as cognitive flexibility, selective attention, interference response and reaction to cognitive pressure[44–48]. The Stroop task itself requires regions within the brain to interact with one another, demonstrating the ability to use the task as a tool to evaluate neurocognitive function after a concussion[44,45,48,49]. This interaction primarily involves processing stimuli and triggers the visual cortex and frontal-parietal networks[49].

During the Stroop task, participants are asked to complete three conditions. In the first condition, participants see coloured words (e.g., "red" printed in black ink) and are instructed to read the word aloud. In the second condition, they see a neutral array of letter colour pairs (e.g., "X's" printed in green ink) and are instructed to name the colour of the ink. In the final condition, participants see incongruent word colour pairs (the word "red" printed in blue ink) and are instructed to name the colour of the ink in which the word is written[46]. The Stroop task is meant to create a disturbance between the athletes' perception and action. These disruptions are caused by the inhibition of executive function control active during the task. Athletes who are acutely concussed may experience decreased performance due to the increase in cognitive load presented[50] .

Returning an athlete to play after a concussion primarily relies on the ability to perform at a high enough cognitive demand for their sport while asymptomatic. In recent years, research has shown that athletes actively under-report symptoms and have the ability to falsify their baseline and post-injury neurocognitive tests during concussion assessment[51,52]. Black et al. (2017)[53] found a significant difference between reporting of physical symptom recovery and cognitive recovery, where the time for symptom resolution was six days, and cognitive recovery was 11 days[49]. The falsification and intentionally not performing at maximal effort at baseline can lead to a higher risk of reinjury and create a potential for worsening symptoms post-injury[51]. Importance should be placed on testing the cognitive function of student-athletes with specific goals of returning to learn first. Ideally, using measures that coincide with academic performance, such as attention, could yield more accurate objective results. The current literature on explicitly testing the Stroop task and SRC is limited. Additionally, given the current knowledge and tools, it may be beneficial to digitize the Stroop task using eye-tracking technology to eliminate errors that may be caused by external factors (e.g., visual and auditory distracting stimuli).

Sex-related differences in concussion assessment

Currently, research is limited regarding concussion history differences between sexes. Research relating to oculomotor and cognitive abilities in athletes with a history of concussion is also under-reported. Moreover, research completed within these realms is conducted in isolation. Comparing the cognitive abilities and oculomotor skills of athletes with a history of concussion taking sex into account is crucial in order to advocate for better and more accurate assessment and recovery tools.

Sex-related differences in concussion reporting

Females have shown to be at a higher risk of incurring a SRC relative to males, even in sex-comparable sports[54,55]. Furthermore, sex-related differences in concussion reporting show that both high school and college level female athletes are more likely to report more baseline concussion symptoms. Most notably, females are more likely to report difficulty concentrating and problems with hearing/vision post-injury[56]. During the acute phase of post-concussion symptoms there was no significant difference between sexes in total symptom score when using the SCAT2[56,57]. Although, it has been stated that males reported more post concussion symptoms when compared to females, this may be due to sampling bias, where the majority of athletes evaluated in the studies above were football players.

Sex-related differences in oculomotor function

Recently a study completed by Sufrinko et al. (2018)[58] investigated sex related differences in athletes following a SRC but found no significant difference in horizontal saccades (p=0.67). Most antisaccade research in sport-related concussion has divided participants into control and concussion cohorts versus exploring sex-related differences[59,60]. Research that has evaluated antisaccade differences between sexes reported females had higher error rates in antisaccade performance when compared to males [56] but this research is limited to healthy participants so it does not capture differences related to SRC.

Sex-related differences in Stroop Task

The Stroop task is used as a neuropsychological test that assesses executive functioning skills. Research regarding specific sex-related differences on the Stroop task are infrequent. It was first reported by Dr. Stroop that women perform better on the colour condition, whereas both sexes completed the word condition equally[61]. These initial results have been supported by research over the years[62–66], however, inconsistencies in sample size, age and methodologies have rendered sex related differences inconclusive. As recent as 2000 David, Pelotte and Lewis[67] demonstrated that specific sex-related differences are not significant after reviewing previous research from that decade. Furthermore, a systematic review completed by Scarpina & Tagini (2017)[68] outlined different versions of the Stroop task, reporting that none of these different versions created can fully address the Stroop Effect (inhibiting the interference from the incongruent stimuli). This brings to question previous research on the Stroop task and sex-related differences. The measurement of speed and accuracy are imperative to correctly detect the Stroop effect. If athletes strictly use speed as the parameter, it will incorrectly assess accuracy as they will be completing each item for total amount instead of correctness, which therefore limits the incongruency protocol that was set out. The measure of accuracy is completed through error rate as it is an indicator of inhibiting control[69]. Therefore, both accuracy and speed are indicative of outcome performance and should be tested together. Within the Stroop task there is a potential for a speed-accuracy trade-off; which is the common dilemma of deciding between two competing demands[69].

In summary, there are many knowledge gaps around the lingering effects of SRC on cognitive and oculomotor abilities, and any sex-related differences in these effects. The present research study addresses this gap in a cross-sectional cohort study described in the following chapter.

Chapter 2: Manuscript

Introduction

The increase in incidence rates in North America's traumatic brain injuries may be due to increased knowledge, exposure rates or access to information about these types of injuries[6,7,70]. This increasing trend shines light on the ever-growing burden placed on healthcare systems. It is essential to understand that concussions, which are a form of mild traumatic brain injury (mTBI), are multifaceted injuries requiring further research to better understand their complexity. Although the incidence of brain injuries (concussions and mTBI) has an increasing trend, most of these injuries resolve within 7-14 days[15]. Approximately 20% of those who have suffered any kind of brain injury have persistent symptoms that last longer than three weeks, prolonging recovery even further[14].

The terms "mTBI" and "concussion" have been used interchangeably throughout research, often causing confusion and a lack of consistency in the literature. Dating as far back as 1966, the Congress of Neurological Surgeons proposed a definition for concussion: “a clinical syndrome characterized by immediate and transient impairment of neural function, such as alteration of consciousness, disturbance of vision, equilibrium, etc., due to mechanical forces”[71]. The development of a strong representative definition continues under the mandate of the World Health Organization (WHO) Collaborating Task Force on mTBI and acute brain injury which states that an mTBI can be caused by a biomechanical force that causes a disturbance in brain function[3,4,72]. Similarly, the latest *Consensus Statement on Concussion in Sport*, defines concussions as an injury caused by a biomechanical force from a direct or indirect blow to the head, face, neck, or body[1]. Having a unified definition for both mTBI and concussion will help better define research objectives such as treatment protocols, rehabilitation strategies and accuracy of diagnosis.

It is increasingly evident that concussions commonly affect widespread areas of the brain, including the frontal-parietal, temporal, white matter, midbrain, and brainstem[50]. Deficits in these areas could affect, among other things, cognitive functions (e.g., attention), executive functions (e.g., task management), and oculomotor abilities (i.e., eye movements), all of which are crucial for everyday life activities. With the advancement of technologies and increased patient education about concussion assessments and detection within the last decade[73], it should be relatively straightforward to diagnose and treat concussions accurately. Unfortunately, this is not always the case; instead, there is a lack of practical, objective tools to help guide practitioners with precise assessment and diagnostic metrics.

In assessing concussions, the oculomotor system and associated cognitive functions are often overlooked. Due to its extensive connections throughout the brain, the oculomotor system can be more susceptible to head injuries[74]. Current vision research in concussion is helping to achieve more accurate and objective methods of assessing and diagnosing dysfunction in the visual and oculomotor systems, in conjunction with cognitive functions. Areas under investigation include speed and accuracy of oculomotor skill related to cognitive functions such as memory, attention, impulse control, and decision making[75].

The primary purpose of the Stroop task, an example of a test used to assess the brain's integrative networks, is to create and resolve the interference paradigm created during the final stage of the task[46]. By causing a distraction to the athlete's automatic perception, it becomes difficult for those who are experiencing concussion symptoms to manage the increased cognitive load[50], therefore decreasing the athlete's overall performance on the test. The difference in the time it takes to see the item and execute the correct response can help to determine the severity of symptoms and visual recovery outcomes[20,23,25,30,75–77]. Athletes rely on the ability to perform at an elite level both physically and cognitively, therefore one of the components of returning a varsity athlete to play is their performance on the neurocognitive component of the concussion assessment.

The objective of this cross-sectional cohort study was to assess the sex-related differences of cognitive function (Stroop Task), oculomotor control (saccades) and a combination of these two domains (antisaccade performance) for asymptomatic varsity athletes with and without a history of concussion. Furthermore, we examined the differences in Saccades, Antisaccade and Stroop by sex and concussion history. The outcome variables that were measured were: saccade latency (SL), Antisaccade Reaction Time (ART) and Total Stroop Error (TSE). Outcome variables were compared with both exposure variables (sex and history of concussion). Our hypothesis is that varsity athletes with a history of concussion will have a significantly more impaired performance in Stroop and Antisaccade tasks when compared to healthy varsity athletes, and no significant difference in less strenuous tasks such as saccades. The effect of sex on performance and its interaction with concussion history is an exploratory measure in the current study.

Methods

Participants

In this cross-sectional cohort study, data was collected from 174 varsity athletes from York University's Keele St. campus before the 2019-2020 varsity season. All athletes were required as part of the pre-season participation protocol to complete concussion baseline testing. All participants in this study were 18 years of age or older and had either (a) no reported history of concussion (No Hx), or, (b) had a previous history of concussion (Hx) as diagnosed by a physician. The study used virtual reality (VR) goggles; consequently participants were excluded if: (a) they were currently experiencing a concussion (within 72 hours post-injury); (b) they had previously diagnosed or undiagnosed eye conditions such as amblyopia, colour blindness, (c) suffer from visual epileptic seizures; or (d) were experiencing severe cervical dysfunction or balance impairment. At the time of testing, all athletes were reported to be healthy and were not diagnosed with a current concussion, and athletes with a previous history of concussion were defined as asymptomatic in accordance with the current return to play protocol guidelines[1]. The study protocol was approved by the Human Participants Review Sub-Committee, York University's Ethics Review Board.

Table 1 *Participant demographics and characteristics (N=153)*

Variables	Male	Female	Total
N (%)	82 (53.6)	71(46.4)	153 (100)
M Age (*SD*)	20.50 (1.85)	19.76 (1.60)	20.13 (1.76)
History of Concussion (%)	31 (37.8)	33 (46.5)	64 (41.8)

Note. M = Mean; N = Total; SD = Standard Deviation.

Equipment

The FOVE Virtual Reality headset was used to administer the Saccade Analytics © vision software NeuroFlex®. This software program was delivered through a Dell G5 15 gaming laptop. Participants completed a series of predetermined visual tasks (saccades, antisaccades & Stroop) as programmed by the vision software NeuroFlex®. A digitized version of the Stroop task[61] was programmed into the software specifically for this study by the Saccade Analytics engineering team.

Measures

Saccades Latency (SL)

The saccades latency task was 1 minute and 30 seconds in length and was measured in milliseconds. At 500 millisecond time points, participants were shown a dot (i.e., target) in the middle of the screen, which appeared at one of 12 predetermined locations. Participants are instructed to move their eyes as fast as possible to the target without moving their head (Figure 3).

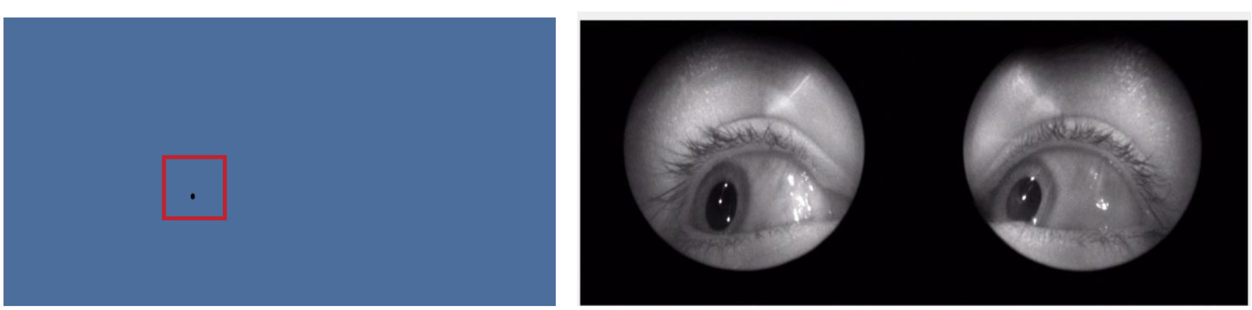


Figure 3 - *Saccade latency task*

Antisaccades Reaction Time (ART)

The antisaccade reaction time task was 3 minutes long and again measured in milliseconds. During the task, participants looked in the opposite direction of the stimuli presented. At first, there was a dot in the middle of the screen showing where to keep the gaze fixed. After a predetermined time of 250 - 500 milliseconds (unknown to the participant), the dot disappeared and was replaced with a subsequent dot in either the right or left periphery. Then another dot appeared in the correct spatial location where participants should have positioned their eyes (i.e. opposite direction of the original dot). They were then instructed to follow the current dot as it slowly glides to the centre again (Figure 4).

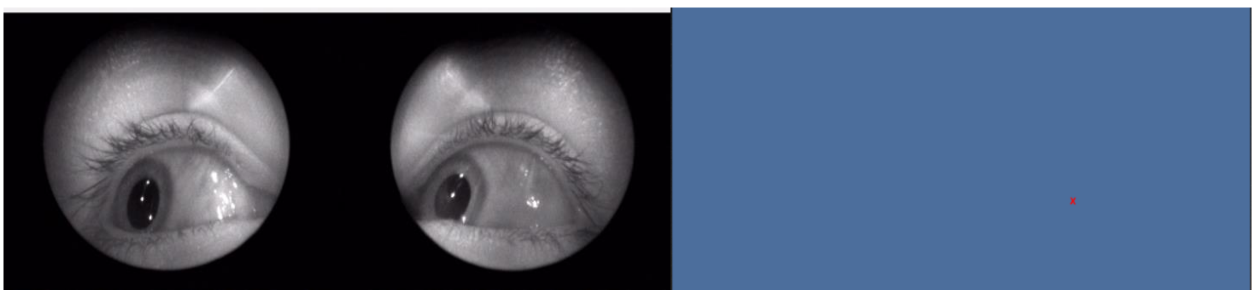


Figure 4 *- Antisaccade reaction time task*

Stroop Task

A modified digital version of the Stroop task[57] was administered through the VR goggles. The 2 minute and 25-second task measured correct and incorrect responses (Total Stroop Error; TSE) and was comprised of three different conditions; each condition was 45 seconds in length and was presented in consecutive order. The researcher was present to advance the program through each section and to record all incorrect responses. The first section of the task was word recall. Participants were asked to say the *colour of the word* written in white ink aloud (Figure 5.0). After participants responded, the researcher continued to advance to the next image until the condition was complete. During the second condition, participants were asked to repeat a similar task; however, they were instructed to name the *colour of the sequence of five "X" 's* that appear ("XXXXX") (Figure5.2). In the final condition, participants were instructed to say the *name of the colour they saw* and not the word printed. (Figure 5.3). For instance, if the word "Blue" appeared in yellow ink, the correct response would be : "Yellow," . The total task collection was automatically counted by the software and incorrect responses are collected after each condition by the researcher.

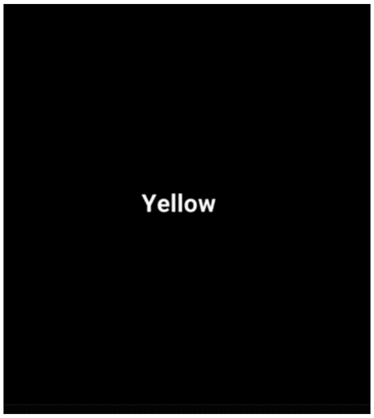


Figure 7.0 *- Stroop word condition*

Figure 7.1 *- Stroop colour condition*

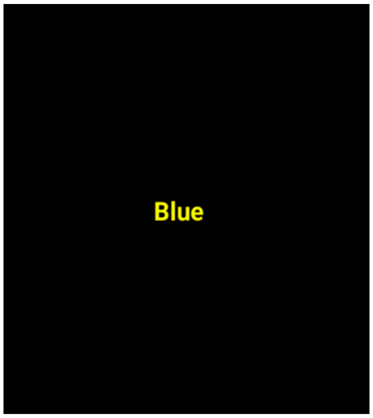


Figure 7.2 *- Stroop combined condition*

Procedure

FOVE VR Calibration Test

Before task administration for every participant, both the Saccade Analytic© NeuroFlex® software and FOVE VR goggles were calibrated to ensure normalized data. The ground was used as a universal baseline for the axis of movement within the VR goggles and software. The VR headset was then placed on the participant's head with straps adjusted accordingly, as determined by the participant's comfort level. Each participant underwent a separate visual calibration test to determine if they could continue with the procedure. A participant would pass if they were able to sustain visual fixation on a green dot for three seconds or more on each of the five different visual fields (up, down, left, right and center). The calibration dots would decrease in size within each of the five fields to assess accuracy of fixation. A participant would fail if too much head movement was detected, the participant's eyes were unable to fixate longer than three seconds, or if their eyes were unable to sustain stable fixation as dots decreased in size. Once the initial calibration was complete and participants passed the visual calibration, they were permitted to continue with the rest of the testing protocol.

Data Analysis

Statistical analyses were performed using the Statistical Package for the Social Science Version 26 (SPSS, 2018). The Shapiro-Wilk test was used to evaluate the normality of continuous demographic and outcome variables. Demographic statistics as outlined in Table 1 were conducted on the exposure variables: sex and concussion history (Hx) and outliers were removed. Descriptive analyses (mean, ± SD) found in Table 3 were conducted on the outcome variables: SL, ART and TSE. An independent samples t-test was used to determine significant interaction between exposure variables. Outcome variables were then separated into four different cohorts by sex and Hx/No Hx of concussions (Male No Hx, Female No Hx, Female Hx, Male Hx). A one-way analysis of variance (ANOVA) was used to compare the four separate groups by each outcome variable. A Bonferroni between groups correction was applied to determine differences for all variables. A linear regression analysis was performed to determine differences in variability in adjusted exposure variables (concussion Hx and sex) by outcome variables (saccade latency, antisaccade reaction time and total Stroop error). All significance levels were $p < 0.05$ to protect from type 1 error.

Results

A total sample population of 174 varsity athletes were recruited at the baseline pre-season testing for the study. There were 21 athletes excluded from the data analyse; seven met exclusion criteria for the study, one experienced a system malfunction, four athletes were considered outliers and nine were missing data on intake forms (previous concussion history or sex).

Table 2 *Excluded participant data*

Excluded Data	Total (n=21)
Undiagnosed Strabismus	2
Colour blindness	2
Amblyopic	2
Balance impairment	1
System malfunction	1
Outliers	4
Incomplete forms	9

Note. Excluded participant data, which include participants who met the exclusion criteria, extreme outliers and those with incomplete forms and system malfunctions.

An independent samples t-test showed no significant interactions between sex and concussion history [t(151) = -1.082, p = 0.28] among all participants for all outcome. Further analysis using a one-way ANOVA was performed, resulting in no significant differences found for SL [F(3,137) = 0.245, p = 0.865], ART [F(3,138) = 0.146, p = 0.932] and TSE [F(3,145) = 1.66, p = 0.178] between sex and concussion history. This was completed using all four cohort groups (male no hx, female no hx, male history, female hx) (Table 3)

Stroop task variable

Further statistical analysis using the Bonferroni post hoc test of TSE revealed there was no significant difference between females Hx (*M* = 0.81, *SD* = 1.046) and males Hx (*M* =1.50, *SD*= 1.50), *M* = 0.69, *SE* = 0.34, *p* = 0.26. A linear regression indicated that there was no significant effect between sex when adjusted for concussion history and TSE variables, Male No Hx (β = 0.111, p = 0.713), Female No Hx (β = -0.075, p = 0.793). Interestingly, Females with a Hx of concussion showed a trend toward a significant difference in the Stroop task, suggesting females with a history of concussion performed less errors (β = -0.566, p = 0.063), compared to males with no history of concussion shown in Table 4.

Table 3 - *Outcome measure descriptives and one-way ANOVA in saccade latency, antisaccade RT, Total Stroop Error by sex and concussion history*

Outcome Measure	No Hx Group		Hx Group		*F*	*p*
	Male *M* (*SD*)	Female *M* (*SD*)	Female *M* (*SD*)	Male *M* (*SD*)		
Saccade Latency (msec)	0.21 (0.03)	0.20 (0.01)	0.20 (0.16)	0.21 (0.02)	0.26	0.865
Antisaccade (RT)	0.47 (0.10)	0.47 (0.11)	0.47 (0.13)	0.46 (0.09)	0.14	0.932
Stroop						
Words	46.7 (4.09)	49.6 (4.90)	50.6 (5.18)	52.2 (4.54)		
Colour	44.6 (3.56)	44.5 (3.98)	45.5 (4.16)	45.7 (4.98)		
Combined	34.4 (3.82)	35.4 (3.46)	37.2 (4.64)	35.6 (5.33)		
Total	128.7 (9.59)	129.51 (10.2)	133.2 (12.2)	133.6 (12.6)		
Stroop Errors						
Words	0.04 (0.19)	0.03 (0.16)	0.00 (0.00)	0.03 (0.18)		
Colour	0.24 (0.48)	0.38 (0.76)	0.23 (0.56)	0.42 (0.80)		
Combined	1.12 (1.25)	0.89 (0.84)	0.58 (0.77)	1.03 (1.16)		
Total	1.37 (1.47)	1.30 (1.18)	0.81 (1.05)	1.48 (1.48)	1.62	0.178

Note. N =153; Hx = History of concussion; RT = Reaction Time.
* p = <0.05

Table 4 *- Associations between outcome measures (saccade, antisaccade and Stroop) and exposure variables (sex and Hx)*

Group	Saccade Latency			Antisaccade RT			Total Stroop Error		
	β	95% CI	p	β	95% CI	p	β	95% CI	p
Constant	0.207	0.200 to 0.214	0.00*	0.468	0.437 to 0.498	0.00*	1.373	1.005 to 1.740	0.00*
Male Hx	-.001	-.012 to 0.009	0.822	-0.009	-0.060 to 0.041	0.710	.111	-0.485 to 0.708	0.713
Female No Hx	-0.003	-0.013 to 0.007	0.538	0.003	-0.044 to 0.050	0.901	-0.075	-0.641 to 0.490	0.793
Female Hx	-0.004	-0.015 to 0.007	0.436	0.006	-0.045 to 0.058	0.805	-0.566	-1.162 to 0.030	0.063^{+}

Note. N = 149; RT = reaction time; We examined the predictor values of sex and concussion history by saccade latency, antisaccade RT and Total Stroop Error.
$^{+}$ trending toward significance
* p = <0.05

Discussion

Our primary findings demonstrate that regardless of both sex and concussion history, varsity athletes demonstrated no differences in their saccade latency (SL), antisaccade reaction (ART) or total Stroop Error (TSE). This study was tailored to examine the difference between athletes with a history of concussion and athletes without a history of concussion to evaluate if oculomotor or cognitive deficits are present after recovery. It is reasonable to suggest from the results presented here that athletes who have a concussion history perform similarly to athletes with no history, suggesting they had recovered at the time of testing. Furthermore, these results suggest no significant differences in oculomotor or cognitive abilities between the sexes, regardless of concussion history.

Our hypothesis for this study is that varsity athletes with a history of concussion will have a significantly more impaired performance in Stroop and Antisaccade tasks when compared to healthy varsity athletes. Furthermore, the effect of sex on performance and its interaction with concussion history is an exploratory measure. There was only a trend found in that females with a history of concussion performed slightly fewer errors in the Stroop task than their male counterparts. A larger sample size may have reported a significant difference in females with a history of concussion performing better than males with no history on this task. Our results support those of Braun et al. (2013)[78], who found that those with a previous history of sport-related concussion also showed no significant difference in oculomotor function or learning effect among collegiate student-athletes. Our findings are not consistent with others, however, these studies examined acutely concussed athletes demonstrating a significant difference in saccade and antisaccade velocity and reaction time [20,21,25–29]. Specifically, many other studies investigating saccade and antisaccade reactions in athletes found those with an acute concussion demonstrated significant differences in performance compared to their non-concussed counterparts[20,21,25–29]. For example, Kelly et al. (2018)[79] reported significant differences in saccades and reaction time between concussion and control groups. Differences in findings among all studies may be related to sample size, timing and severity of concussion, as well as time since concussion[20,21,25–29]. Further research is needed to understand the complexities of sex-related differences associated with previous concussions and concussion recovery in student-athletes.

Our primary purpose for using the Stroop task was to create an interference paradigm for the athletes[46]. By causing a distraction to the athlete's perception, it becomes difficult for those experiencing concussion symptoms to manage an increased cognitive load[50], therefore decreasing the athlete's overall performance on the test. Although our findings show a lack of significance in this area, this could be related to a potential speed/accuracy trade-off between the sexes. Males completed more items within the time allotted, while females performed fewer errors. This suggests that males had an increase in performance speed which led to a decrease in accuracy, while females had a decrease in performance speed and higher accuracy. Regardless of history of concussion, males and females had similar results on all outcome measures. Though this may indicate sex-related differences in the speed-accuracy trade off, concussion history does not factor in sex's ability to perform on the Stroop task. The lack of significant findings between those with and without a history of concussion may also indicate the athletes in this study with a history of concussion had all recovered from their injury.

Returning an athlete to play after a concussion primarily relies on performing at a high enough cognitive demand for their sport while asymptomatic. In recent years, research has shown that athletes actively under-report symptoms to falsify their baseline and post-injury neurocognitive tests during concussion assessment[51,52,80]. Black et al.[53,81] found a significant difference between reporting of physical symptom recovery and cognitive recovery, where the time for symptom resolution was six days, and cognitive recovery was 11 days[53]. The falsification and intentionally not performing at maximal effort at baseline can lead to a higher risk of reinjury and create a potential for worsening symptoms post-injury [51,80]. Importance should be placed on testing the cognitive function of student-athletes with specific goals of returning to learn first. Using measures that coincide with academic performance, such as attention, could yield more accurate objective results. The current literature on explicitly testing the Stroop task and sport-related concussion is limited and requires more exploratory research to determine if it can play a role in helping to more accurately identify when an athlete has fully recovered cognitively. These findings aid in the growing research on concussion rehabilitation, demonstrating that athletes are able to recover to previous abilities in SL, ART and TSE regardless of sex and concussion history.

Limitations

As with many studies, there were limitations to the current concussion study. One limitation was data collection; the sample included convenience sampling that was drawn from the York University Varsity Athletics Program. The athletes preparticipation form only asked about previous sport-related concussions; therefore, previous types of head injuries not related to the athlete's participation in their sport may have gone unreported. Future research should look at collecting all related head injury data.

Furthermore, the reliability of data collection is another limitation of this study. The reporting of errors for the Stroop task was done manually because of the novel method of the Stroop task. To address this in the future, researchers should automate error reporting within the software system to increase reliability.

Additionally, the concussion intake form collected was reported subjectively; therefore, inconsistencies in how many diagnosed concussions could have differed from the actual amount the athlete had actually experienced. The study was a part of pre-season baseline testing; consequently, concussion history was taken from their pre-participation intake forms.

Conclusion

In conclusion, regardless of sex or concussion history, varsity athletes showed no significant differences when performing saccades latency, antisaccade reaction time or total Stroop error. These findings suggest that those with a history of concussion do not suffer from long term oculomotor or cognitive deficits. The lack of sex-related differences in oculomotor and cognitive functions suggests that both males and females with no history of concussion have similar abilities in saccade latency, antisaccade reaction time and Stroop accuracy to those with a history of concussion. This study demonstrated the similarities in sexes by evaluating athletes with a history of concussion against those without a history, using VR goggles to accurately determine visual and cognitive performance. This research represents a starting point for improving the metrics for safe and timely return to activity, a fundamental goal for student-athletes. Given the prolonged recovery required when individuals experience successive concussions and the grave outcomes associated with chronic traumatic encephalopathy, the prevention of reinjury is imperative.

Chapter 3: Discussion & Conclusion

Discussion

The purpose of this study was to investigate sex-related differences using VR goggles and NeuroFlex® software to track oculomotor (saccades and antisaccades) and cognitive (Stroop) abilities in asymptomatic varsity athletes with and without a history of concussion. The recent attention on concussions in sport has highlighted sex-related differences that exist in brain structure and function after a concussion injury[55,82]. Structural and functional sex-related differences could impact the overall evaluation of concussion assessments, diagnosis, prevention strategies, rehabilitation and management of symptoms. For example, females have demonstrated greater interhemispheric communication by engaging several different brain areas (superior prefrontal and mid-inferior temporal) for a single task which suggests more robust connections between both hemispheres[82]. Furthermore, it has been reported that females' corpus callosum and concentration of grey matter are notably different than males[55]. Research recently completed by Ng et al. (2017)[83] demonstrated that an increased strain on the corpus callosum was likely the cause of a reduction of attention, reaction time and working memory after an mTBI[78], which may be a factor in differences in symptom reporting between the sexes. Our study did not find statistically significant sex-related differences when comparing oculomotor and cognitive abilities in varsity athletes regardless of a history of concussion. This may be because the study compared athletes with a history of a concussion and not acutely concussed athletes. In addition to testing athletes with a history of concussion, timing of when the concussion occurred was also unknown and could have varied significantly. Variables such as length of time, severity and recovery time of the initial injury were not explored in this study and therefore could have contributed to the difference in findings relative to other studies. Previous research conducted on SRC and sex differences examined athletes who have been acutely concussed and timing since concussion ranging from 48 hours to 10 days post-concussion injury[56,84]

Oculomotor Skills

Oculomotor skills post-concussion have demonstrated impaired functioning[20], however, it is still unclear whether there are sex-related differences in oculomotor function after concussion injury. Within the current study no significant differences were found between athletes with or without a history of concussion as well as between sex. There have been many studies examining differences in oculomotor abilities which have found significant deficits in saccades and antisaccades post-concussion injury [29,34–36,76,85–88,89], however, the majority of these studies focus entirely on acutely concussed patients making the results challenging to compare to those who have recovered.

Research conducted by Cochrane et al. (2019)[90] and Kelly et al. (2018)[79] focused on oculomotor function and reaction times in athletes with and without a concussion. They found deficits in both saccades and antisaccades in athletes who had sustained a concussion. Within our study we observed no significant difference in athlete's oculomotor abilities with or without a history of concussion. The reason may be because those athletes who have had previous concussions have fully recovered from their concussion symptoms, which supports our findings as athletes with a history of concussion had similar results to athletes without a history of concussion. It should be noted that the majority of athletes who sustain a concussion recover typically between 7 -14 days [14,15,91]. Another possible reason for our findings to show no difference between history and no history of concussion may be due to the oculomotor system not being affected after the athlete sustained the concussion. Athletes in general have a higher oculomotor and cognitive motor skill level than the general population[92]. Having only tested varsity athletes at baseline it is possible that these athletes performed at a higher baseline skill level, or perhaps experienced an increased ability to compensate for any residual deficits. This means we may not be able to see oculomotor deficits in athletes because they are more skilled and perform above average within the task. Additionally, the oculomotor testing within the VR goggles may not be sensitive enough to detect difference within concussion history athletes, or even differences between sexes. Heitger et.al[25,26] used the IRIS infrared limbus tracker for both saccades and antisaccades at a testing distance and hertz similar to our study (5 to 15 degrees for saccades and antisaccade testing and 200Hz) respectively. Yet they found significant differences within their study population because of the timing of concussion (10 days post-injury). The oculomotor task in our study used VR goggles and NeuroFlex® software which was administered after the athletes have recovered from their SRC and were asymptomatic.

Therefore, this equipment may be best utilized during the early stages of concussion symptoms as well as early stages of recovery for better detection. Future studies should investigate the accuracy and efficacy of using VR goggles to detect oculomotor deficits in athletes who are suffering from a sports-related concussion.

Stroop and speed accuracy trade off

The use of computerized neurocognitive tests for SRC are widely used to help return athletes to sport. The reliability of these cognitive tests have been studied[93,94], with common issues such as length of testing time, availability of testing, ease of use and cost being some of the limiting factors testing the neurocognitive functions concussion. Neurocognitive concussion testing assesses specific tasks that are modified from traditional neuropsychological testing. Visual memory, concentration, reaction time and visual processing speed are some of the paradigms that have been proven sensitive for SRC diagnosis[95]. Our current study used the Stroop task as a neurocognitive evaluation to assess differences in athletes with a previous history of concussions. We chose to evaluate TSE by combining errors from all three conditions and found no difference between athletes with or without history of concussion or sex. We also found no significant difference when adjusting for sex and concussion history. These results may be because the athletes had fully recovered from the cognitive component of the SRC. Again, it is important to address that athletes have a higher cognitive baseline skill level comparatively[92], therefore the difference in results could be because athletes performing the Stroop task completed it faster and more accurately than the average population. One of the reasons for using the Stroop task in our study was the visual application and the executive functioning interference paradigm. Another reason for using the Stroop task for our study was its ability to be digitized[96]; to our knowledge this was the first time it has been used outside of military research for athlete populations, specifically history of concussion athletes. Having the Stroop task digitized into the software and displayed into the VR system decreased any visual distraction that may otherwise be present during a computerized version of the Stroop task.

Interestingly, this unique application for neurocognitive evaluation gave the research team the ability to address the potential for a speed-accuracy trade-off. Although it is was not directly measured within this study because the history of concussion group was no longer symptomatic, there may be some evidence that males and females demonstrate this potential for a trade-off in order to enhance performance which will be addressed within the next section of this discussion. Efforts should be made to standardize the Stroop task for concussion assessment and rehabilitation. From our results we found no difference in TSE regardless of history of concussion or sex, suggesting it is entirely possible that all athletes with a history of concussion completely recovered. Therefore, standardizing the timing of the evaluation is very important, and could lead to more effective RTL and RTS outcomes. It might be best to administer this test early in the recovery stages of a concussion. A study exploring the differences between a digitized VR version of Stroop and computerized version should also be completed to further validate the effectiveness of this type of objective cognitive testing. Future efforts should investigate the sex-related differences within the general population compared with athletes to determine if participation in sport is a factor.

Sex-related differences

Investigating sex-related differences in varsity athletes with a history of concussion involves athletes who have been cleared to return to play (RTP) and return to learn (RTL). Athletes, regardless of sex, who have sustained a concussion should undergo some type of RTP or RTL protocol that ensures the safety of the athlete once they return. Varsity athletes have a high level of performance cognitively as well as physically within their sport, which requires an increase in attention and concentration in order to achieve their desired athletic goals[86]. Research has shown that females recover differently than males after a concussion[97], and have even considered sex as a factor of poor outcome after concussion[98]. Differences in females' greater number of symptoms, timing of reported symptoms, cognitive difficulties and length of time of recovery have also been reported[54,97,93,94]. A study completed by Sufrinko et al (2017)[58] demonstrated that concussed females had slower reaction times when testing the vestibular ocular reflex (VOR). Additionally, studies on post-concussion cognitive performance investigated differences in neurocognitive ability between sex found that females exhibited a lower performance on visual memory when compared to males[94,100]. Contrary to the previous studies, our research did not yield any significant difference between sex and oculomotor or cognitive abilities. However, our research did yield an interesting trend when examining the TSE and sex, showing the potential for a speed-accuracy trade-off between males and females. Current literature shows that speed-accuracy trade-off is apparent between healthy males and females. Research completed by Bianco et al. (2020)[91] found that healthy males demonstrated reduced cognitive preparation; conversely, females performed more accurately and more consistently when completing a simple task response and discriminative task response. Evidence of the speed accuracy trade-off is present within the current study, although not statistically significant; males with a history of concussion performed more items per condition than females, while also performing more errors than females. It is possible that the sample size for our study was not large enough to find a significant effect within the speed-accuracy trade-off between sexes. Additionally, the timing of the initial diagnosis of SRC was not currently evaluated within the current study and may be a more critical factor in identifying such sex-related differences.

Future research should explore adding supplementary cognitive load throughout the RTP protocol to evaluate more sports-specific concentration and attention abilities. The current study demonstrated the ease of use and portability as well the cost-effective nature of adding cognitive load using VR goggles on asymptomatic varsity athletes with and without a history of concussion. Furthermore, research should look to explore sex-related oculomotor and cognitive differences in acutely concussed athletes to validate the use of VR goggles as a tool for concussion assessment and rehabilitation. These future directions may help identify more specific recovery processes and improve the timeline for recovery from concussion injuries.

Conclusion

Although there have been great strides to understand how brain trauma affects the different sexes, there is still more research needed to help provide objective results for the diagnosis of sex-specific differences in sport-related concussions. Within our study we examined sex-related differences between asymptomatic varsity athletes with and without a history of concussion through saccade latency, antisaccade reaction time and total Stroop error. We found no statistically significant differences between saccade latency, antisaccade and total Stroop error regardless of sex and previous history of concussion. This research suggests that athletes who have a history of concussion are able to fully recover and perform similar to those without a concussion history.

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