EYE-SYNC Saccade Outcomes and Health/Demographic Factors in CFL Athletes

by

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Abstract

The purpose of the present study was to examine the relationship between demographic and health factors, and oculomotor functioning during baseline testing in professional athletes. Four hundred twenty-eight male athletes consented and participated in the baseline concussion assessments of the Canadian Football League (CFL). Athletes ranged from 21 to 40 years of age (M =26.44, SD =2.873), and reported a history of 0, 1, or 2+ sport-related concussions (SRCs). All athlete participants completed the Head Check questions of demographics and medical history, and the EYE-SYNC saccade test to explore how the presence of a history of concussions, Attention-Deficit/Hyperactivity Disorder (ADHD), Learning Disability (LD), age, and post-exertion influenced baseline measures of oculomotor functioning using the EYE-SYNC saccade outcomes of accuracy and precision. Correlations revealed no significant relationships between combined vertical and horizontal saccade outcomes (LeftAccuracyXY, LeftPrecisionXY, RightAccuracyXY, RightPrecisionXY) and the demographic/health variables ($p > .05$). Independent t-tests indicated no significant differences in mean saccade performance between athletes with and without ADHD and/or LD ($p > .05$). Furthermore, three-way multiple analysis of variance (MANOVA) run with age group (21-25, 26-30, 31-40) and concussion group (0, 1, 2+) revealed no main effects of age, $F(8, 844) = .914$, $p = .504$, Wilks' = .983, partial $\eta^2 = .0$) or history of concussion, $F(8, 510) = .856$, $p = .554$, Wilks' = .974, partial $\eta^2 = .013$). A one-way repeated measures analysis of variance (MANOVA) revealed no significant differences from pre- to post-exertion assessments, $F(4, 56) = .411$, $p = .800$, Wilks' = .971. The oculomotor functioning of CFL athletes at baseline, measured using the EYE-SYNC saccade task, does not appear to be influenced by a history of concussion, ADHD, LD, age, or physical

exertion. This information may help professionals with their clinical decision-making regarding the diagnosis of SRCs, and return-to-play.

Preface

This thesis represents original work completed by Bradyn Quinn Ree-Fedun. This thesis was developed as a sub-study from a larger research project, with the data for this study being collected from the Active Rehabilitation Project. The co-principle investigators included Dr. Mrazik and Dr. Naidu. Ethics approval was granted to the Active Rehabilitation Project by the University of Alberta's Research Ethics Board prior to beginning this study (Pro00073481). Dr. Mrazik supervised the research conducted for this thesis.

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Chapter One – Introduction

Sport-Related Concussions

Sport-related concussions (SRCs) represent a topic of study under the domain of mild traumatic brain injuries (mTBIs), which focuses on concussions in athletes. The Concussion in Sport Group (CISG) first established a consensus statement on the definition of SRCs in 2001, intending to establish the best practices for the diagnosis and management of SRCs (McCrory et al., 2017b). The definition and diagnostic criteria for SRCs continue to evolve, however, as SRC research progresses rapidly. This focus on SRC research has pushed researchers to develop empirically validated instruments for the assessment of SRCs, with the most common tools measuring the cognitive, emotional, and physical impairments of athletes (Harmon et al., 2019; McCrory et al., 2017b).

Oculomotor Functioning and SRCs

More recently, research has supported the development of computerized sideline assessments, with some developers focusing on eye movements and oculomotor functioning (SyncThink Inc, 2022). The visual system is sensitive to the diffuse disturbances associated with SRCs, often leading to the development of oculomotor impairments in injured athletes (Johnson et al., 2016). Therefore, tests of oculomotor functioning have been developed to identify impairments in the saccadic eye movements of athletes with a suspected SRC (SyncThink Inc, 2022). EYE-SYNC was recently cleared by the U.S. Food and Drug Administration (FDA) as an aid in the diagnosis of SRCs and is currently being used by sports organizations in the United States (SyncThink Inc, 2022). However, health/demographic variables such as a history of multiple concussions (Stephen et al., 2022), physical exertion (Lichtenstein & Merz, 2019; McGrath et al., 2013; Zwierko et al., 2019), Attention-Deficit/Hyperactivity Disorder (ADHD)

(Maron et al., 2021), and learning disabilities (LD; Moran et al., 2021) have been shown to influence oculomotor functioning. In addition, the sensitivity and specificity of ocular motor functioning have not been well established in specific populations such as professional football. At present, the American Medical Society for Sports Medicine (AMSSM) does not currently support the use of these instruments for the assessment of SRC until additional research has been done to validate the sensitivity and specificity of SRC diagnosis (Harmon et al., 2019). Oculomotor assessment tools can be completed quickly and without the need for a neuropsychologist (McCrory et al., 2017b); however, they lack the research needed to establish clinical utility (Harmon et al., 2019). Additional research is needed to determine how demographic factors and health variables affect sideline computerized oculomotor assessments.

Present Study

The purpose of the present study was to add to the current scientific literature related to oculomotor assessments in the assessment of SRCs in professional American football players. The main objective was to examine the relationship between pre-existing health conditions and oculomotor functioning in Canadian Football League (CFL) athletes. This goal was accomplished by having CFL athletes complete the Head Check medical and demographic information, and the EYE-SYNC saccade task to determine how a history of concussion, ADHD, LD, and physical exertion influenced the accuracy and precision of eye saccades during SRC baseline assessment.

Chapter Two – Literature Review

Sport-Related Concussions

Athletes are at an elevated risk for injury due to the speed and physicality involved in many sports, especially contact sports such as ice hockey, rugby, and American football. Furthermore, SRCs are a common result of head impacts (Harmon et al., 2019). SRCs are classified as mild traumatic brain injury (mTBI) and common outcomes of trauma to the brain include cognitive, psychosocial, and physical symptoms. Given that these symptoms play a role in an individual's well-being, the fields of neuropsychology and psychology have significantly contributed to a better understanding of the assessment and diagnostic process (McCrory et al., 2017b; Harmon et al, 2019). Because SRCs represent a rapidly developing area of study, additional outcome-based data is required to fill in the current gaps in knowledge (Harmon et al., 2019). To accomplish this goal, many novel assessment instruments have been developed to accelerate the SRC assessment process, including computerized measures of oculomotor functioning, which will be defined and described below. Oculomotor assessments using visual eye-tracking technology have recently been implemented into the SRC assessment protocols for college and professional athletes (SyncThink Inc, 2022). Computerized sideline assessments provide rapid neurological screenings for SRC; however, additional research is required to examine how demographic variables influence assessment outcomes (Harmon et al., 2019). The purpose of this chapter is to summarize the history of SRCs, outline the important variables associated with evidenced-based assessments of SRCs, and the role of oculomotor assessments in the assessment of SRCs.

History

The term *concussion* originates from the Latin description *concutere*, meaning “to dash together” and “shake vigorously” (Bey & Ostick, 2009). Knowledge regarding neurological impairments following a head injury has been traced back to 1700 BC when the *Edwin Smith Papyrus* described symptoms of confusion, stupor, and altered consciousness (Pearce, 2008). Further recordings of concussions were present in the 10th century when injuries due to head shaking were reported by the Persian physician, Rhazes (Rhazes, 1548). At this time, functional symptoms were reported from injuries involving headshaking without structural damage to the skull. As the knowledge of concussions advanced in the 19th century, the severity of head injuries was shown to be connected with dilation of the pupils, demonstrating the diffuse nature of concussions (Flamm, 1972). The research in this era helped to differentiate the functional consequences of concussions as separate from the structural damage caused by more severe mTBIs (Kirkland, 1972). However, the scientific community continued to lack a consensus operational definition for concussions.

To establish an operational definition of concussions within the medical community, the Congress of Neurological Surgeons agreed upon consistent diagnostic criteria in 1996 (Giza et al., 2014). This definition was not adopted by the entire scientific community but spurred further interest in the development of alternative definitions and diagnostic criteria. A consensus agreement on the definition of SRCs was not established until 2001 when the Consensus in Sport Group (CISG) gathered for the First International Symposium on Concussion in Sport (Aubry et al., 2002). At this time, the CISG emphasized the importance of uniformity in the definition of SRCs, allowing for proper accuracy and consistency of diagnosis (Webbe, 2011). This summary of the history of mTBIs demonstrates how the operational definition of concussions continues to evolve as research advances our knowledge and understanding of the injury.

Current Definition

The CISG identified SRCs to be one of the most difficult sports injuries to assess, diagnose, and manage, as the operational definitions fail to address the underlying processes responsible for the onset of symptoms (McCrory et al., 2017a; McCrory et al., 2017b). SRCs are currently a target for psychological research, and the consensus agreements on diagnostic criteria are updated frequently. The most recent CISG consensus statement on SRCs was updated in 2016, and the current definition for an SRC represents a form of mTBI that is “induced by biomechanical forces” to the head, neck, or other parts of the body, with an “impulsive force transmitted to the head” (McCrory et al., 2017b). In contrast to more serious mTBIs involving structural damage to the brain, SRCs typically produce immediate functional impairments in cognitive and neurological performance that resolve within days to weeks after the injury. The CISG recommends an immediate assessment of any athlete who is suspected to have sustained an SRC by a qualified professional. If athletes demonstrate cognitive or neurological impairments during sideline screening, the CISG recommends that a player be removed from play and undergo additional neurological testing conducted by a trained professional. Therefore, sideline assessments have become increasingly important in the identification of athletes with a suspected SRC. Vestibular ocular assessments are currently of interest to the medical and scientific community as potential tools that aid in sideline assessment (McCrory et al., 2017b).

Prevalence

According to the Centers for Disease Control (CDC; 2007), an estimated 38 million children and adolescents engage in organized sports, and 170 million adults participate in sports and physical activities annually (Langlois et al., 2006; CDC, 2007). The CDC estimates that between 1.6 million and 3.8 million SRCs occur annually in the United States; however, many go unreported as athletes may refuse to disclose their symptoms and seek the necessary medical attention (Langlois et al., 2006). Therefore, the prevalence of SRCs in the general population may not accurately represent athletes, due to the physicality and intensity of sport competition.

Recent studies have shown that between 2% and 15% of high school and college athletes involved in organized sports will sustain an SRC over the course of one season (Bretzin et al., 2018; Houck et al, 2016; Harmon et al., 2019; Kerr et al., 2017). Similarly, elite athletes are at elevated risk of sustaining SRCs, with 1302 total SRCs occurring among 1004 National Football League (NFL) athletes between the 2015 and 2019 seasons (Mack et al., 2021). Overall, 64.1% of all NFL athletes sustained a SRC within the five-year sample, with the majority of SRCs (80.3%) occurring during regular gameplay (Mack et al., 2021). An average of 243 NFL athletes sustained one SRC per season of participation, and approximately 6.8% of athletes proceeded to sustain a second concussion during the same season of play. SRC safety is improving, as the average incidence of SRCs decreased by 23% from the 2015-17 to 2018-2019 seasons, suggesting that the NFL's emphasis on concussion safety was likely responsible for the reduction in observed SRCs.

American football is commonly played within the United States; however, it has become popular across the globe. Although the NFL and CFL play a similar game, there are distinct differences associated with the rules, the field of play, and the country of residence. Because the majority of SRC research to date has focused on NFL athletes, additional research is required to examine how SRCs present in Canadian football players. During the 1997 CFL season, 44.8% of athletes reported experiencing symptoms of an SRC and 69.6% reported multiple SRCs (Delaney et al., 2000). However, only 18.8% of athletes recognized that they had sustained a concussion. To reduce the incidence of SRCs, the CFL has introduced prevention strategies including annual concussion education seminars, concussion symptoms posters in all locker rooms, concussion spotters at each game, sideline concussion assessments, and a digital concussion platform designed to monitor the effectiveness of the league's concussion protocol (Delaney et al., 2018).

Diagnosis and Symptoms

To be diagnosed with an SRC, the following criteria must be met: a direct or indirect trauma with a force transmitted to the head, an immediate or delayed symptom presentation, an indication of a functional rather than structural brain injury, and either with or without loss of consciousness (McCrory et al., 2017b; McKeithan et al., 2019). Individuals with SRCs may present with symptoms in multiple domains of functioning. Somatic symptoms include headache, fogginess, dizziness, nausea, fatigue, blurred vision, attention problems, and sleep dysfunction (Benson et al., 2011; Kamins et al., 2017). Physical signs include amnesia, balance impairments, behavioural changes, and cognitive impairments (McCrory et al., 2017b). Psychological symptoms have been shown to include anxiety, depression, isolation, suicidal ideation, and emotional problems (Caron, 2013; McCrory et al., 2017b). SRC symptoms typically recover within a reasonably rapid period of time, yet prolonged impairments may be observed in some cases. Because the duration of recovery from SRC is influenced by variables such as age, history of concussion, history of learning and attention disorders, and other medical variables, a medical professional must analyze the athlete's medical history (Harmon et al., 2019).

In most situations, the physical and psychological symptoms caused by an SRC resolve within 1-4 weeks; however, somatic, cognitive, and emotional symptoms can linger for months after the initial injury (Harmon et al., 2019; McCrory et al., 2017b). When symptoms are present for longer than the expected recovery period, they are classified as post-concussive symptoms

(McKeithan et al., 2019). During this symptomatic period the physical, emotional, and psychological issues can interfere significantly with the individual's ability to function during day-to-day activities (Kontos et al., 2012). In addition, repeated SRCs may lead to cumulative long-term health risks (Harmon et al., 2019; Manley et al., 2017; McCrory et al., 2017b). These consequences may include impairments to neurocognitive functioning, behavioural issues, early dementia, and chronic traumatic encephalopathy. It is important to consider that the long-term symptoms that are sometimes observed in SRC patients are non-specific and may be caused by other etiologies (Harmon et al., 2019; McCrory et al, 2017b) Therefore, the objective assessment of both physical and psychological SRC symptoms is required to determine the cause of the athlete's lingering symptoms (Harmon et al., 2019).

Self-Reporting of Symptoms

As a result of the current emphasis on promoting concussion safety among American football athletes, the level of knowledge and awareness has increased among athletes and staff (Delaney et al., 2018). However, the underreporting of SRC symptoms continues to occur among youth, collegiate, and professional athletes (Clark & Stanfill, 2019; Delaney et al., 2018). Common reasons that athletes avoided disclosing their concussion symptoms are the fear of losing playing time and an underestimation of the injury's severity (Delaney et al., 2018). Therefore, it is not surprising that 54% of high school football players reported playing through headaches sustained through injury (Anderson et al., 2016). Underreporting of SRC symptoms continues to occur with professional football players, as 82.1% of CFL athletes who believed they had sustained an SRC did not seek medical attention (Delaney et al., 2018).

Stephenson and colleagues (2021) identified three key domains that contributed to an athlete's willingness to report concussion symptoms. The first domain was perceived pressures to play, including factors such as job security, the importance of the game, and athletic identity. The second domain was the interpersonal symptoms checklist, which included knowledge of concussions, normalization of symptoms, and comparison to a first concussion. The third domain was the certainty of symptoms, including self-assessment strategies, the severity of symptoms, league intervention, and teammate intervention. Although the attempt to improve concussion safety in professional sports is evident, perceived factors continue to influence athletes' decision to withhold their concussion symptoms (Stephenson et al., 2021). To reduce the importance of athletes' subjective reports, additional objective measures, including oculomotor functioning tests, are needed to provide medical professionals with objective data to aid in their clinical decision-making.

Assessment

Baseline concussion testing has become part of the standardized protocol for SRCs, and the National Collegiate Athletic Association (NCAA) recommends that all athletes complete a baseline assessment involving a symptom checklist, cognitive evaluation, and vestibular assessment (Harmon et al., 2019). The most common SRC assessment measures include screening tests which require a baseline and post-injury assessment to determine the change in functioning from pre- to post-injury (Harmon et al., 2019; Sussman et al., 2016). By establishing the athlete's standard performance while healthy, the baseline score can then be compared to a post-injury assessment to assist in the diagnosis of an SRC. If the scores collected during baseline screening assessments are not accurate, then decisions regarding the diagnosis and management of SRC symptoms may be negatively influenced. Therefore, it is essential that valid baseline data is collected to protect the health and safety of athletes with SRCs.

The similarities between attentional and oculomotor networks in the brain allow for eye-tracking protocols to be used in concussion assessments (Corbetta et al., 1998). Following an SRC, ocular impairment has been shown to occur in approximately 45% of athletes (Valovich McCleod & Hale, 2015). Over half of the neural connections in the brain are involved in visual functioning, therefore; damage to the cranial nerve may produce impairments in eye movements, such as pursuits, saccades, and convergence (Cockerham et al., 2009). Computerized oculomotor assessments have been designed to reduce the length of sideline neurological assessments and may be used as part of a comprehensive SRC assessment battery. Computerized assessment tools are desirable for sideline assessments due to their brief administration time and the difficulty of accessing registered neuropsychologists (McCrory et al., 2017b); however, the AMSSM reported that computerized and app-based assessment tools lack the research needed to establish clinical utility (Harmon et al., 2019). Further research is needed to establish the sensitivity and specificity properties of oculomotor assessments in the diagnosis and management of SRCs.

Although computerized SRC assessment tools provide additional information that may aid in the assessment and diagnosis process, they do not replace the need for a complete neuropsychological examination (McCrory et al., 2017b). Significant variance exists in how an individual athlete may respond to a suspected SRC, including the severity and duration of symptoms (Harmon et al., 2019; McCrory et al., 2017b). Therefore, no single assessment tool is available that can be used to consistently and accurately diagnose an SRC (Harmon et al., 2019). The AMSSM recommends that a multimodal battery including tests of different functions be combined to help medical professionals make their clinical decisions (Comeau & Pfeifer, 2019; Harmon et al., 2019).

Oculomotor Functioning

Part of the success in certain sports involves the ability to identify and track visual objects. Visual eye movements are required to maintain focus on moving objects (Sussman et al., 2016), and eye tracking measures allow for the assessment of neurological functions such as anticipating the temporal course and trajectory of a moving target. Saccades are rapid eye movements that redirect the fovea between two visual targets. Saccades can be reflexive to focus on an appearing object, or volitional to inhibit oneself from looking towards a distracting target. The assessment of ocular functioning through saccadic eye movements is recommended by the AMSSM as part of a physical examination for suspected SRCs (Harmon et al., 2019).

Due to the diffuse nature of SRCs, functional impairments to the cerebral and cerebellar brain regions may occur, often resulting in impaired coordination and synchronization of eye movements (Johnson et al., 2016). Therefore, video-oculography devices can be used to measure visual eye tracking in the context of SRCs (Harmon et al., 2019; Sussman et al., 2016). Precise visual eye-tracking measures that intend to assess anticipatory neural activity should monitor the pupil and corneal reflection to identify deficits in saccades, smooth pursuits, fixations, and vergence skills (Maruta et al., 2013).

EYE-SYNC (SyncThink Inc, 2022) is a computerized oculomotor assessment tool that uses a visual tracking trajectory to measure the predictive timing of dynamic visuomotor synchronization (DVS). The DVS scores between gaze and target were shown to decline significantly in individuals who had recently sustained a concussion, and the impaired scores returned to a normal range over time (Maruta & Ghajar, 2014). EYE-SYNC has been cleared by the FDA as an aid for concussion identification and diagnosis and is currently being used by American military and sports organizations (SyncThink Inc, 2022). To introduce the EYE-SYNC into Canadian sports organizations, further research is required to verify the sensitivity and specificity for use with Canadian athletes. In addition, demographic factors and pre-existing health conditions should be examined to determine their effects on oculomotor assessments (Tomczyk et al., 2021).

Variables Associated with Oculomotor Impairments

History of Concussions. The majority of athletes who experience an SRC recover fully within one to four weeks (Harmon et al., 2019, McCrory et al., 2017b); however, several studies suggested that athletes who sustained one SRC were three times more likely to sustain an additional concussion during the same athletic season (Boden et al., 2007; Guskiewicz et al., 2000). The elevated risk for multiple concussions may be explained by the force of impact, as a lower force is required to produce subsequent SRCs (Boden et al., 2007). Therefore, a history of one prior SRC is a risk factor for future SRCs, and a history of multiple SRCs is associated with additional physical, cognitive, and emotional symptoms (McCrory et al., 2017b). Because a history of multiple SRCs may lead to cumulative health issues, it is important to understand how concussion history influences cognitive and neurological functioning.

The long-term effects of multiple SRCs are controversial; however, some research has shown short-term deficits in oculomotor functioning to occur in response to repetitive sub-concussive head impacts (Stephen et al., 2022). Stephen and colleagues (2022) reported that repetitive head impacts among athletes from various contact sports led to short-term impairments in oculomotor, cognitive, and vestibular functioning. However, pre-existing variables such as ADHD and history of multiple concussions were not always controlled for. The literature supports the potential for repetitive head impacts to disrupt oculomotor functioning, creating the question of how multiple SRCs may change neurological functioning at baseline. With SRCs commonly occurring among professional football athletes (Harmon et al., 2019; Mack et al., 2021), further research is needed to determine the influence that a history of multiple SRCs has on oculomotor functioning in CFL athletes.

ADHD. ADHD is a neurodevelopmental disorder that involves difficulties with inattention, disorganization, and hyperactivity/impulsivity (American Psychiatric Association, 2022). Individuals with ADHD may present with problems listening, remaining on task, fidgeting, and remaining seated. In a 2011 position statement, the AMSSM suggested that the prevalence of ADHD among athletes may be greater than the general population, as athletes with ADHD seek out sports due to the attentional activating and reinforcing effects of physical activity (Putukian et al., 2011). Traditionally, continuous performance tests have been used to measure attention-related problems using sustained and selective attention tasks. For example, the Conners Continuous Performance Test 3rd Edition (Conners CPT; Conners, 2014) is a psychometrically sound measure of impulsivity, sustained attention, and vigilance, that is frequently used in the process of diagnosing ADHD and other attention-related disorders. The Conners CPT requires examinees to respond to the presentation of letters on a computer screen, while inhibiting their response to the target letter “X”. More recently, oculomotor assessments have been used to examine motor and cognitive control in ADHD patients, and to evaluate response to treatment (Allman et al., 2012). Reduced oculomotor functioning has been associated with atypical motor planning (Langmaid et al., 2014), slower movement preparation (Dahan et al., 2018), reduced inhibitory control (Bari & Robbins, 2013), and poor sustained attention (Goto et al., 2010). Therefore, it is important to understand how the inattentive and hyperactive symptoms of ADHD may influence oculomotor assessments in professional athletes.

Understanding how ADHD may influence SRC assessment is crucial to establishing valid and reliable assessment tools. ADHD patients often present with impaired attention and/or hyperactivity (American Psychiatric Association, 2022) and visual eye tracking assessments may be used to evaluate these deficits. The visual system includes the cortical and subcortical brain regions responsible for inhibition, planning, and motor coordination (Maron et al., 2021). Because eye movements are predictable and consistent, minor changes in oculomotor performance can be used to identify underlying problems with the neurocognitive and oculomotor systems (Maron et al., 2021).

In a recent meta-analysis, Maron and colleagues (2021) examined the differences in oculomotor control between ADHD patients and healthy controls. Eye movements included measures of saccades, fixations, and smooth pursuits using visual eye tracking. A large effect size was found for intrusive saccades during the fixation tasks and anticipatory saccades during the memory-guided saccade task. Moderate effect sizes were found for directional errors in the antisaccade task. In addition, a moderate effect size was found for anti-saccade latency and directional errors in the antisaccade gap task. However, there were no differences in smooth pursuit movements between the ADHD and healthy control groups. The researchers concluded that the intrusive directional errors in the ADHD groups were a result of impaired top-down oculomotor processing. The results of this meta-analysis indicate clear functional impairments in the eye movements of ADHD patients that can be measured using oculomotor tasks. When baseline and post-injury assessments are completed, tests of visual eye tracking abilities may provide valuable information regarding motor and executive control abilities in athletes.

Learning Disabilities. Learning disabilities (LDs) are difficulties with learning and performing academic skills, and may present as poor reading, writing, and mathematical performance (American Psychiatric Association, 2022). According to the CDC (2007), one in six American children is diagnosed with a developmental, behavioural, or LD, with LDs being one of the most common. The nature of LDs produce impairments in academic performance, which may manifest as problems with cognitive performance, such as working memory and processing speed (Chacko et al., 2013). As some of the most common SRC assessment tools measure neurocognitive performance, accounting for LDs in athletes may be an important screening procedure before baseline assessments. There is a paucity of research investigating the relationship between LDs and ocular motor functioning. Recently, LDs have been shown to influence baseline SRC assessment on measures of oculomotor functioning (Moran et al., 2021). Moran and colleagues (2021) compared the performance of thirty football and soccer athletes between the ages of 8 and 14 years with LD/ADHD to healthy matched controls. The athletes with LD/ADHD performed significantly worse on SRC baseline tests of vestibular and oculomotor functioning and oculomotor performance, compared to their matched controls. Specifically, the athletes with LD/ADHD reported greater symptom provocation during tests of eye movements and demonstrated worse saccades, convergence, vestibular ocular reflex (VOR), and visual motion sensitivity. As LDs and ADHD may negatively influence SRC assessment scores at baseline, additional research exploring the relationship between pre-existing health conditions and oculomotor performance in athletes is required.

Physical Exertion. Optimal neurocognitive performance is required for athletes to maintain high visual attention and rapid object identification. Therefore, it is likely that their oculomotor skills are more developed than non-athletes (Zwierko et al., 2019). However, oculomotor functioning in healthy athletes was found to decrease following strenuous physical activity (Zwierko et al., 2019). Following incremental treadmill running to exhaustion, skilled soccer athletes demonstrated increased saccade duration and decreased average saccade velocity on a visual search task. Compared to non-athletes, exercise-induced fatigue led to a greater reduction in gaze efficiency for the athlete group. The researchers concluded that physical effort may lead to reduced oculomotor functioning in athletes. The presence of oculomotor and cognitive deficits in athletes following physical exertion creates the opportunity for invalid SRC assessment scores. If SRC assessments are completed immediately after a practice or game, temporary post-exertion impairments in neurocognitive functioning may skew or invalidate test results. Additional research is required to determine how physical exertion influences other computerized SRC assessments in elite athletes.

Present Study

As discussed above, numerous demographic and health characteristics create the possibility of impaired neurological and cognitive functioning athletes (Bari & Robbins, 2013; Dahan et al., 2018; Goto et al., 2010; Langmaid et al., 2014; Maron et al., 2021; Moran et al., 2021; Stephen et al., 2022; Zwierko et al., 2019). For professional athletes, impairments to oculomotor functioning create the opportunity for inaccurate SRC assessments, and invalid baseline testing may alter clinical decision-making. The current study seeks to examine the relationship between demographic and health variables, and computerized oculomotor assessments in professional football athletes. To accomplish this, CFL athletes completed the Head Check health and demographic questions and the EYE-SYNC assessment to determine how the pre-existing health characteristics correlated with EYE-SYNC saccade scores, and how much variance in oculomotor performance is accounted for by the presence of pre-existing health factors. In addition, the effect of physical exertion was examined to determine if post-exertion assessments, compared to at rest, lead to reduced visuomotor abilities. The present study will contribute to the scientific literature by exploring how computerized oculomotor assessment tools are impacted by a history of multiple concussions, and whether a history of concussion, ADHD, LD, and physical exertion exacerbate oculomotor impairments. By identifying the role that these variables play in visual eye-tracking abilities, the health and safety of athletes can be improved by ensuring that league-mandated testing and return-to-play protocols are being followed.

Objective 1

The first objective is to examine the relationship between a history of concussions measured using the Head Check health information, and oculomotor functioning measured using the EYE-SYNC saccade tasks.

Hypothesis 1. It is expected that a statistically significant correlation will exist between a history of concussions and the accuracy and precision of eye movements during EYE-SYNC saccade tasks.

Objective 2

The second objective is to compare the accuracy and precision of eye movements during EYE-SYNC saccade tasks between athletes with a history of concussion, ADHD, and LD, and those without.

Hypothesis 2. It is expected that a statistically significant difference will exist between the presence of a history of concussions, ADHD, and LD, and the mean accuracy and precision of eye movements during EYE-SYNC saccade tasks.

Objective 3

The third objective is to examine the relationship between post-exertional testing and oculomotor functioning measured using the EYE-SYNC saccade tasks.

Hypothesis 3. It is expected that a statistically significant difference will exist between pre- and post-exertion scores, measured using the accuracy and precision of eye movements during EYE-SYNC saccade tasks.

Chapter Three – Method

This chapter provides an overview of the research methods used in the present study. This includes a description of the research design, key terms, participants, measures, statistical analyses, data collection, and ethics.

Participants

All participants included in the present study were members of one of the nine CFL clubs across Canada. Data was collected from CFL athletes during the 2021 season, providing a good representation of the total CFL athlete population. All active CFL athletes that were fit to participate in baseline medical testing were approached to participate in the study, with 644 completing the EYE-SYNC baseline testing. Athletes with "fair" and "good" EYE-SYNC scores were included in the analysis. 33 athletes provided "poor" or incomplete baseline scores and were removed from the analysis. If multiple assessments were provided for the same participant, only the first assessment was included. As a result, 87 duplicate baseline scores were removed. To merge the athlete EYE-SYNC and Head Check data files, a Microsoft Excel VLOOKUP code was used to match data from the same athletes. As a result of the potential misspelling of athlete names, the VLOOKUP code was unable to match 97 athletes, and they were removed from the analysis. The final sample size of athletes who completed the EYE-SYNC baselines and were included in the analyses was 428. Seventy athletes were selected to participate in the post-exertional testing. The post-exertional scores from 7 athletes were removed due to "poor" data, and 3 duplicate cases were removed. Overall, a total of 60 athletes were included in the final post-exertional analysis.

Inclusion Criteria

1. Consent and permission received from the CFL.

2. Demographic, health data, and EYE-SYNC baseline information were collected at the beginning of/during the 2021 season.

Exclusion Criteria

1. Not cleared to participate in medical baseline testing by a team medical professional.
2. Poor, duplicate, or missing EYE-SYNC data.

Key Terms

The present study's use of the term "concussion" and "sport-related concussion" were according to the CISG's 2016 consensus agreement (McCrory et al., 2017b). The criteria for a "history of multiple concussions" were greater than one prior concussion. In addition, the diagnostic criteria for "ADHD" and "LDs" were taken from the DSM-5 (American Psychiatric Association, 2022). The term "athlete" was used to describe the population of active CFL athletes.

Research Design and Data Collection

The present study used a cross-sectional retrospective design with data being collected from active CFL athletes during the 2021 season. All athletes involved in this study participated in the CFL's mandated medical evaluations, and health/demographic data was collected in accordance with these guidelines. The EYE-SYNC assessment tool had not been utilized by the CFL prior to the 2021 season; therefore, the oculomotor data was collected after the outset of the 2021 season. The Head Check and EYE-SYNC data were collected electronically by team athletic therapists and trained graduate students. The EYE-SYNC technology used an integrated stimulus presentation-eye tracking apparatus (SyncThink Inc, 2022) with which eye movements were recorded at 500 Hz using infrared video-oculography while the head was stabilized by placing the athlete's elbows on a table while holding the device against their face. To examine the impact of physical exertion on ocular movement metrics, post-exertion assessment data were collected after a regular practice that occurred on a separate day from baseline testing.

Independent Variables

Demographic and Health Information

Athlete information was obtained from Head Check, a computerized database containing demographic and health information for all players in the CFL. The variables of age, history of concussion, ADHD, and LD were obtained from the Head Check database. ADHD and LD were coded as “2” if they were present in the participants, or “1” if they were not present. History of concussions was grouped to account for the number of prior SRCs, with “0” representing no prior SRCs, “1” representing one prior SRC, and “2” representing 2 or more prior SRCs. Three age groups were created for athletes within the ranges of 21-25, 26-30, and 31-40 years of age. The age groups of 31-35 and 36-40 were combined due to the low number of athletes above the age of 31 years.

Physical Exertion

EYE-SYNC baseline assessments were completed during a resting state and following the physical exertion of team practice. Pre- and post-exertion test scores will be examined to determine if post-exertion leads to significantly different accuracy and precision of saccade scores.

Dependent Variables

EYE-SYNC

By measuring saccadic eye movements, EYE-SYNC uses oculomotor assessment data to aid in the diagnosis of SRCs (SyncThink Inc, 2022). EYE-SYNC provides objective neurological data that can be used as part of a medical professional’s clinical decision-making regarding rehabilitation and return to play following an SRC (SyncThink Inc, 2022). In 2021, the FDA cleared EYE-SYNC as an aid to concussion diagnosis, and the technology is currently being used by American sports organizations to help identify the presence of SRC in their athletes (SyncThink Inc, 2022). EYE-SYNC's oculomotor assessment battery includes measures of smooth pursuit, saccade, vestibular-ocular reflex (VOR), and vestibular-ocular reflex cancellation (VORx). Each individual test can be completed in approximately 60 seconds, with the duration of the full test battery being 2-5 minutes.

Data were obtained by the EYE-SYNC system which includes virtual reality goggles with embedded eye tracking sensors and a high-performance tablet (see Figure 1). Each participant

holds the virtual reality device in front of their eyes while seated on a table to ensure the device remains steady. The examiner completes a calibration process with the participant in which the participant fixates on an orange dot in the middle of the screen. Subsequently the participant

Figure 1.

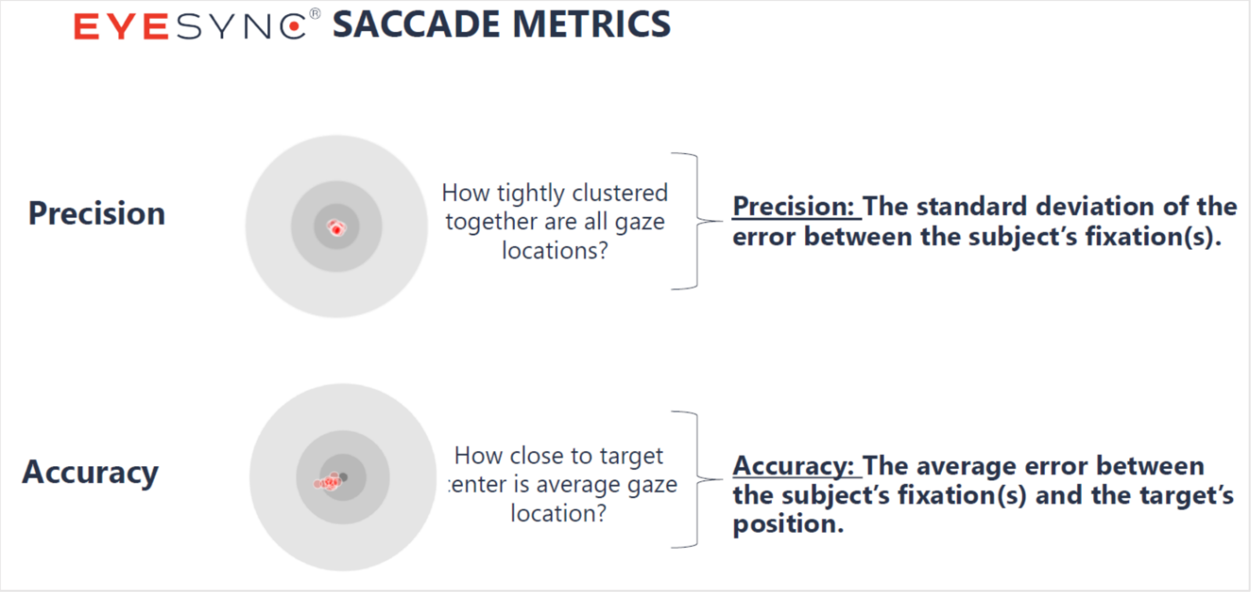
SYNC-THINK System and EYE-SYNC Device

follows the orange dot with their eyes to nine different targets on the screen to ensure the participant understands the task and that they are actively tracking the orange dot. The participant's eye movements can be followed by the examiner to ensure that the participant is understanding the task and can follow the orange dot. The saccade trial begins with the participant fixating on the orange dot located in the middle of the screen. Subsequently, the orange dot moves back and forth to specified targets in the left and right visual fields. The task requires the participant to follow the moving orange target back and forth for 30 seconds. The test is repeated a second time and the system selects the best performance. The automated software algorithm analyzes the eye position versus the target over the assessment time and produces visual synchronization measures. The present study recorded the saccade tasks to simplify speed and ease of administration. The saccade test required the participant to track a visual target as it moved rapidly between horizontal locations.

Saccades. The amount of error and variance in millimeters (mm) during visual synchronization with a fixated target (saccade) was recorded to identify the quality of performance. The participant's quality of saccades was generated by incorporating the accuracy and precision of eye movements for both the left and right visual fields. EYE-SYNC automatically selected the eye with the higher quality performance and used the data from the selected eye in the results. Accuracy was defined as the average error distance between the participant's fixations and the target's position, and this metric was used to represent how close the average gaze fixation was to the target's location (see Figure 2). Low accuracy would lead to fixations that are far from the target location, while high accuracy would produce fixations that are centered on the target's location. Precision was defined as the standard deviation of the error between the participant's fixations, and this metric was used to represent the consistency of the athlete’s gaze fixations in relation to the target. Low precision would lead to scattered fixations, while high precision would lead to tightly clustered fixations. EYE-SYNC outputs accuracy and precision for the X and Y axes, along with a combined XY metric. The accuracy and precision of the athletes’ fixations during the saccade tasks were measured (in mm), with accuracy measuring the distance between the fixations and target location, and precision measuring the standard deviation (in mm) between all fixations. The present study used the four saccade outcomes (LeftAccuracyXY, LeftPrecisionXY, RightAccuracyXY, RightPrecisionXY) as estimations of the athletes’ oculomotor functioning at baseline. LeftAccuracyXY represents the combined saccade accuracy of the X and Y axis for the athlete’s left visual field, while RightAccuracyXY represents the combined accuracy of the X and Y axis for the athlete’s right visual field. LeftPrecisionXY represents the athlete’s combined saccade precision on the X and Y axis for the left visual field, while RightPrecisionXY represents the combined precision on the X and Y axis for the right visual field. Overall, these four saccade outcomes were used to assess the performance quality during the EYE-SYNC saccade tasks.

Figure 2.

Precision and Accuracy Measures of Saccadic Movements



How tightly clustered together are all gaze locations?

Precision: The standard deviation of the error between the subject's fixation(s).

How close to target enter is average gaze location?

Accuracy: The average error between the subject's fixation(s) and the target's position.

The present study's use of the EYE-SYNC tool was intended to provide additional information regarding the use of computerized oculomotor assessments in the assessment of SRCs for CFL athletes. Specifically, the effects that a history of concussion, ADHD, and LD had on EYE-SYNC saccade outcomes were examined. Finally, the influence that physical exertion had on the athlete's eye movements was examined to explore how post-exertion performance may alter the EYE-SYNC saccade outcomes.

Statistical Analysis

Pearson correlations were completed to determine the statistical relationship between a history of concussions, ADHD, LD, age, and the four outcome measures on the EYE-SYNC saccade tasks (LeftAccuracyXY, LeftPrecisionXY, RightAccuracyXY, RightPrecisionXY).

Independent t-tests were used to compare the saccade outcome means between the athletes who had ADHD and/or LD and those who did not. To compare the saccade outcome means across the concussion group and age group levels, a three-way multiple analysis of variance (MANOVA) was used. The four mean saccade outcomes were compared across age groups (21-25, 26-30, 31-40) and concussion groups (0, 1, 2+).

A one-way repeated measures MANOVA was used to explore the relationship between the saccade outcomes with the influence of physical exertion (pre- and post-exertion). A repeated measures MANOVA was deemed appropriate for this analysis due to the same athletes completing both baseline (pre-exertion) and post-exertion assessments. Therefore, this study's use of a repeated measures MANOVA will help identify the variance in EYE-SYNC saccade outcomes that are accounted for by the independent variable of assessment type: pre- and post-exertion testing. All statistical analyses were conducted using IBM Statistics, Version 28.

Because the present study is using retrospective data to evaluate how baseline EYE-SYNC saccade outcomes were influenced by pre-existing factors in CFL athletes, the purpose of this analysis was not to predict future EYE-SYNC performance (e.g., linear regression). Therefore, the selected analyses were deemed appropriate for exploring the relationship between health/demographic variables and saccade outcomes. For the post-exertion analysis, a repeated measures design uses the participants as their own controls and individual differences are considered, therefore; unsystematic error is reduced.

Ethics

This project was granted ethics approval prior to this study by the Research Ethics Board at the University of Alberta (Pro00073481). To be included in this study, the athletes were asked to sign a consent form that outlined the purpose of the study, committee requirements, and the risks and benefits of the study. In line with CFL regulations, all athletes completed baseline testing (which included the Eye-Sync and Head Check) prior to beginning their CFL season.

Chapter Four – Results

The purpose of the present study was to retrospectively examine the relationship between the four independent variables (history of concussions, ADHD, LD, and physical exertion) and the four outcome variables (LeftAccuracyXY, RightAccuracyXY, LeftPrecisionXY, RightPrecisionXY). Next, the outcome means were compared across group levels to identify any differences in saccade performance across the history of concussion, ADHD, LD, and post-exertion groups. This chapter describes the assumptions of Pearson correlations, independent samples t-tests, one-way repeated measures MANOVA, three-way MANOVA, and the results of the statistical analysis.

Assumptions

Before conducting the Pearson correlations, t-tests, three-way MANOVAs, and repeated measures MANOVA, the assumptions were examined in SPSS. The data met the assumptions of having a continuous dependent variable (saccade outcomes), independent variables with multiple groups (concussion group, age group, ADHD, and LD), and independence of observations. The independent variables were measured on a dichotomous scale (LD, ADHD) and an ordinal scale (concussion group and age group). The dependent variables (LeftAccuracyXY, RightAccuracyXY, LeftPrecisionXY, RightPrecisionXY) were measured on a continuous scale.

Outliers were identified using boxplots and extreme values tables generated from SPSS. Although there is concern regarding the presence of outliers in the saccade outcomes, they were explained by the purpose of this study. Due to the large number of athletes contained in this sample (N = 428), the data is expected to be representative of all CFL athletes. These variables are important for identifying the influence that the examined independent variables have on the saccade outcomes. Therefore, the outliers are needed to accomplish the objectives of this study.

The Shapiro-Wilk test for normality indicated that the saccade outcome data were not normally distributed ($p < 0.5$). However, the sample was comprised of healthy CFL athletes without current SRC symptoms; therefore, a normal distribution was not expected. For this reason, the data were included in the study.

The three-way MANOVA assumptions of having a continuous dependent variable, independent categorical variable groups, and independence of observations were achieved through study design. A linear relationship between the dependent variables for each group of the independent variable was confirmed using a scatterplot. There was no evidence of multicollinearity between saccade outcomes as assessed by Pearson correlation ($r < 0.9$). Shapiro Wilk's test of normality confirmed that the saccade outcomes were not normally distributed across concussion groups and age groups ($p < .05$). This finding was expected given the large representative sample of healthy CFL athletes. Levene's test of homogeneity of variances was not significant for the four saccade outcomes ($p > .05$), satisfying the assumption of homogeneity of variances.

For the one-way repeated measures MANOVA, the assumptions of two or more continuous dependent variables (LeftAccuracyXY, RightAccuracyXY, LeftPrecisionXY, RightPrecisionXY) and one independent variable with two or more categorical independent groups (pre- and post-exertion) were achieved based on study design. An adequate sample size was collected for the baseline/pre-exertion group and post-exertion group ($N = 60$). The presence of a linear relationship between the dependent variables (saccade outcomes) for each related group of the independent variable (pre-post exertion) was confirmed using a scatterplot matrix.

Pearson Correlation

A Pearson correlation was conducted to determine whether the independent variables of concussion, ADHD, LD, and age were significantly correlated with the four outcome variables of saccade accuracy and precision (see Table 6). There was a significant and positive correlation found between each of the four saccade outcomes (LeftAccuracyXY, RightAccuracyXY, LeftPrecisionXY, RightPrecisionXY), which supported the use of these saccade variables as an overall measure of oculomotor functioning. A significant and positive relationship was found between concussions and age, suggesting that the number of concussions increases along with age in CFL athletes. In addition, a significant positive relationship was found to exist between the variables of ADHD and LD. This finding was expected given the overlap between LD and ADHD within the Head Check database. Surprisingly, no significant correlations were found between concussions, ADHD, LD, age, and the four saccade outcomes. In accordance with these findings, there was no need to add any of the variables as covariates in the relationship between the history of concussions and the saccade outcomes. Instead, the difference in mean oculomotor performance across variable group levels was explored.

T-Tests and Three-Way MANOVAs

T-tests were used to compare the means of the four saccade outcomes across athletes with reported ADHD and/or LD, and those without a history of these difficulties. Three-way MANOVAs were used to compare the mean saccade outcomes across the three age groups (21-25, 26-30, 31-40), and the three concussion groups (0, 1, 2+).

ADHD

An independent samples t-test was used to determine if there were differences in the four mean saccade outcomes between athletes with and without ADHD. There was no significant difference between the athletes with and without ADHD on LeftAccuracyXY, (95% CI, -.113 to

.221), t(71.735) = .645, p = .521, LeftPrecisionXY, (95% CI, -.060 to .114), t(76.092) = .620, p = .537, RightAccuracyXY, (95% CI, -.124 to .253), t(68.201) = .684, p = .497, and RightPrecisionXY, (95% CI, -.004 to .156), t(81.998) = 1.891, p = .062. The presence of ADHD symptoms in the CFL athletes did not lead to significantly different means of oculomotor performance, measured using the four EYE-SYNC saccade outcomes.

LD

An independent samples t-test was used to determine if there were differences in saccade outcomes between athletes with and without LDs. There was no significant difference between the athletes with and without a LD on LeftAccuracyXY, (95% CI, -.120 to .317), t(33.951) = .918, p = .365, LeftPrecisionXY, (95% CI, -.095 to .317), t(33.344) = .543, p = .590, RightAccuracyXY, (95% CI, -.444 to .164), t(31.502) = -.940), p = .354, and RightPrecisionXY, (95% CI, -.195 to .087), t(32.602) = -.777, p = .443. The presence of LDs in the CFL athletes did not lead to significantly different means of oculomotor performance, measured using the four EYE-SYNC saccade outcomes.

History of Concussion

A three-way MANOVA was run with the three concussion groups (0, 1, 2+) and four saccade outcomes (LeftAccuracyXY, LeftPrecisionXY, RightAccuracyXY, RightPrecisionXY). The results of the MANOVA were not significant, with no main effect of concussion group on the combined saccade outcomes. F(8, 510) = .856, p = .554, Wilks' Lambda = .974, partial η^2 = .013. The number of previous concussions in the CFL athletes did not lead to significantly different means on the four EYE-SYNC saccade outcomes.

Age

A three-way MANOVA was run with the three age groups (21-25, 26-30, 31-40) and four saccade outcomes (LeftAccuracyXY, LeftPrecisionXY, RightAccuracyXY, RightPrecisionXY). The results of the MANOVA were not significant, with no main effect of age group on the combined saccade outcomes. F(8, 844) = .914, p = .504, Wilks' Lambda = .983, partial $\eta^2 = .009$. The age group of the CFL athletes did not lead to significantly different mean saccade outcomes.

One-Way Repeated Measures MANOVA

Physical Exertion

The present study used a repeated measures MANOVA to determine whether there was a statistically significant difference in the EYE-SYNC saccade outcomes combined over the two points in time (pre- and post-exertion). Therefore, in this experiment the saccade outcomes were assessed using four dependent variables (LeftAccuracyXY, RightAccuracyXY, LeftPrecisionXY, RightPrecisionXY) and the independent variable was physical exertion assessment with two related groups (pre- and post-exertion). The baseline scores were taken as pre-exertion performance. The two groups are related because all athletes that completed the post-exertion assessments first completed the baselines, therefore; each athlete included in the analysis had eight scores: one for each of the four dependent variables at pre- and post-exertion time points.

The result of the one-way repeated measures MANOVA was not statistically significant, suggesting that there was no difference in the combined EYE-SYNC saccade outcomes between the pre- and post-exertion assessments (see Table 7). Because the results of the repeated measures MANOVA were not statistically significant, there was no need to conduct post hoc analyses. These findings indicate that the EYE-SYNC saccade outcomes of accuracy and precision appear to be unaffected by physical exertion.

Objective 1

The first objective of the present study was to explore the relationship between the history of concussions and the four EYE-SYNC saccade outcome measures. Pearson correlations were calculated between concussions, ADHD, LD, age, and the four saccade outcomes (LeftAccuracyXY, RightAccuracyXY, LeftPrecisionXY, RightPrecisionXY). The correlations revealed no significant relationships between any of the four independent variables and the four saccade outcomes. Although a significant positive correlation was found to exist between the variables of age and concussions, and ADHD and LD, the presence of these factors did not influence the saccade accuracy and precision outcomes. Therefore, the results of the correlation rejected the hypothesis that a significant positive relationship would exist between the predictor variables and the saccade outcomes (see Table 6).

Objective 2

The second objective of this study was to examine the differences in mean saccade outcomes between the athletes with ADHD, LD, and history of concussions, and those without these difficulties. This second objective was addressed through independent samples t-tests and MANOVAs. Based on the scientific literature described in Chapter 2, it was hypothesized that the presence of these health factors would lead to significantly lower saccade outcomes at baseline. However, the results of the analyses revealed no significant differences in mean saccade outcomes between the athletes with a history of concussion, ADHD, or LD. In addition, the mean saccade performance did not differ significantly between the three athlete age groups. Overall, the hypothesis for the second objective of this study was not confirmed for any of the pre-existing health/demographic variables.

Objective 3

The third objective of the present study was to determine if physical exertion influenced the CFL athletes' performance on the outcome of the EYE-SYNC saccade accuracy and precision scores. To test this relationship, a one-way repeated measures MANOVA was conducted using the two levels of physical exertion (pre- and post-exertion) as the independent variable, and four dependent variables (LeftAccuracyXY, RightAccuracyXY, LeftPrecisionXY, RightPrecisionXY). The results of the repeated measures MANOVA revealed that there was no significant difference between the combined saccade outcomes of accuracy and precision between pre- and post-exertional tests, $F(4,56) = .411$, $p = .800$, Wilk's Lambda = .971, partial $\eta^2 = .009$. Therefore, the hypothesis of objective three was not confirmed, and it was determined that post-exertional testing did not lead to significantly different EYE-SYNC saccade scores compared to baseline.

Table 1.

Number of Participants With/Without Health Variables by Age Group

Age	ADHD+	ADHD-	LD+	LD-	HoC0	HoC1	Hoc2+
21-25	25	159	13	171	72	14	7
26-30	26	180	14	192	85	37	21
31-40	4	34	3	35	12	10	3
Total	55	373	30	398	169	61	31

Note. Age Group (Age), Participants with Attention/Deficit-Hyperactivity Disorder (ADHD+), Participants without Attention/Deficit-Hyperactivity Disorder (ADHD-), Participants with Learning Disability (LD+), Participants without Learning Disability (LD-), History of No Previous Concussions Group (HoC0), History of 1 Previous Concussion Group (HoC1), History of 2+ Previous Concussion Group (HoC2+).

Table 2.

Descriptive Table of Variables for ADHD Groups

	ADHD	N	Min	Max	M	SD	Skewness		Kurtosis	
LeftAccuracyXY	**no**	373	.249	4.010	1.023	.615	2.088	.163	5.617	.325
	yes	55	.377	2.549	1.036	.590	1.272	378	.717	.741
LeftPrecisionXY	**no**	373	.112	2.042	.504	.335	1.904	.163	4.168	.325
	yes	55	.201	1.431	.499	.295	1.722	.378	3.112	.741
RightAccuracyXY	**no**	373	.209	4.176	1.030	.625	1.964	.163	5.152	.325
	yes	55	.317	4.658	1.079	.744	3.122	.378	13.647	.741
RightPrecisionXY	**no**	373	.082	1.786	.526	.340	1.512	.163	2.046	.325
	yes	55	.110	1.331	.504	.285	1.220	.378	1.533	.741

Note. Number of participants (N), Minimum Statistic (Min), Maximum Statistic (Max), Mean (M), Standard Deviation (SD).

Table 3.

Descriptive Table of Variables for LD Groups

	LD	**N**	**Min**	**Max**	**M**	**SD**	**Skewness**		**Kurtosis**	
LeftAccuracyXY	**no**	398	.249	4.010	1.022	.609	2.050	.156	5.414	.312
	yes	30	.359	2.549	1.056	.642	1.169	.524	.380	1.014
LeftPrecisionXY	**no**	398	.112	2.042	.502	.326	1.921	.156	4.444	.312
	yes	30	.201	1.431	.521	.380	1.640	.524	1.639	1.014
RightAccuracyXY	**no**	398	.209	4.176	1.020	.610	1.971	.156	5.365	.312
	yes	30	.461	4.658	1.263	.963	2.670	.524	8.688	1.014
RightPrecisionXY	**no**	398	.082	1.786	.523	.336	1.508	.156	2.070	.312
	yes	30	.186	1.331	.526	.286	1.256	.524	2.080	1.014

Note. Learning Disability (LD), Number of participants (N), Minimum Statistic (Min), Maximum Statistic (Max), Mean (M), Standard Deviation (SD).

Table 4.

Descriptive Table of Variables for Age Groups

	Age	**N**	**Min**	**Max**	**M**	**SD**	**Skewness**		**Kurtosis**	
LeftAccuracyXY	**21-25**	184	.249	3.287	1.017	.568	1.549	.250	2.859	.495
	26-30	206	.349	4.010	1.033	.619	2.168	.203	6.167	.403
	31-40	38	.301	3.412	.983	.644	2.150	.383	5.320	.750
LeftPrecisionXY	**21-25**	184	.112	2.042	.508	.341	1.979	.250	4.812	.495
	26-30	206	.117	1.806	.485	.312	1.985	.203	4.659	.403
	31-40	38	.157	1.638	.555	.341	1.443	.383	1.988	.750
RightAccuracyXY	**21-25**	184	.209	3.610	1.061	.657	1.636	.250	3.328	.495
	26-30	206	.303	4.658	1.032	.656	2.663	.203	10.010	.403
	31-40	38	.319	2.595	1.037	.527	1.328	.491	2.497	.953
RightPrecisionXY	**21-25**	184	.110	1.654	.562	.363	1.268	.250	1.042	.495
	26-30	206	.082	1.786	.492	.300	1.745	.203	3.628	.403
	31-40	38	.161	1.608	.557	.337	1.179	.383	1.267	.750

Note. Age (Age), Number of participants (N), Minimum Statistic (Min), Maximum Statistic (Max), Mean (M), Standard Deviation (SD).

Table 5.

Descriptive Table of Variables for Concussion Groups

	No. of SRCs	N	Min	Max	M	SD	Skewness		Kurtosis	
LeftAccuracyXY	**0**	169	.249	3.785	1.045	.592	1.827	.187	4.133	.371
	1	61	.321	4.010	1.052	.720	2.151	.306	5.383	.604
	2+	31	.366	1.855	.858	.436	1.148	.421	.111	.821
LeftPrecisionXY	**0**	169	.112	2.042	.519	.344	1.878	.187	3.986	.371
	1	61	.137	1.789	.483	.323	1.876	.306	4.042	.604
	2+	31	.184	1.219	.457	.251	1.538	.421	2.094	.821
RightAccuracyXY	**0**	169	.209	4.658	1.050	.645	2.191	.187	7.446	.371
	1	61	.303	3.199	1.009	.610	1.693	.306	2.835	.604
	2+	31	.455	4.176	1.025	.708	3.194	.421	12.965	.821
RightPrecisionXY	**0**	169	.082	1.654	.525	.332	1.416	.187	1.792	.371
	1	61	.141	1.786	.529	.344	1.498	.306	2.221	.604
	2+	31	.199	1.608	.497	.315	2.181	.421	5.321	.821

Note. History of Concussion Groups (No. of SRCs), Number of participants (N), Minimum Statistic (Min), Maximum Statistic (Max), Mean (M), Standard Deviation (SD).

Table 6.

Pearson Correlations Table

	Left Accuracy	Left Precision	Right Accuracy	Right Precision	SRC	ADHD	LD	Age
LeftAccuracyXY	1	.688**	.606**	.373**	-.078	-.031	-.043	.017
LeftPrecisionXY	-	1	.296**	.302**	-.068	-.027	-.027	.041
RightAccuracyXY	-	-	1	.642**	-.022	-.035	.058	.004
RightPrecisionXY	-	-	-	1	-.020	-.077	.041	-.035
Concussions	-	-	-	-	1	-.052	.041	.178*
ADHD	-	-	-	-	-	1	.442**	-.025
LD	-	-	-	-	-	-	1	.003
Age	-	-	-	-	-	-	-	1

Note. Pearson Correlation (PCorr), Attention Deficit/Hyperactivity Disorder (ADHD), History of Concussion Groups (Concussions), Learning Disability (LD), Age Groups (Age), EYE-SYNC Saccade Left Accuracy (LeftAccuracy XY), EYE-SYNC Saccade Left Precision (LeftPrecision XY), EYE-SYNC Saccade Right Accuracy (RightAccuracy XY), EYE-SYNC Saccade Right Precision (RightPrecision XY).

*$p < .05$

**$p < .01$

Table 7.

Description of Pre- and Post-Exertion Variables

Outcome	**Pre-exertion**		**Post-exertion**	
	M	*SD*	*M*	*SD*
LeftAccuracyXY	1.035	0.492	1.034	0.614
LeftPrecisionXY	0.546	0.331	0.519	0.357
RightAccuracyXY	1.028	0.705	1.007	0.475
RightPrecisionXY	0.524	0.353	0.559	0.324

Note. Mean (M), Standard Deviation (SD), EYE-SYNC Saccade Left Accuracy (LeftAccuracyXY), EYE-SYNC Saccade Left Precision (LeftPrecisionXY), EYE-SYNC Saccade Right Accuracy (RightAccuracyXY), EYE-SYNC Saccade Right Precision (RightPrecisionXY).

Chapter Five – Discussion

As research concerning SRCs progresses, the importance of appropriate assessment and diagnostic procedures is further emphasized. Numerous SRC assessment tools exist; however, the importance of objective assessment data requires the development of novel assessment tools and protocols. Despite the potential for sideline oculomotor assessments to provide rapid and objective SRC information, limited research exists to support the accuracy and reliability of their use within professional sports. As multiple health characteristics have been shown to impair oculomotor functioning (Bari & Robbins, 2013; Dahan et al., 2018; Goto et al., 2010; Langmaid et al., 2014; Maron et al., 2021; Moran et al., 2021; Stephen et al., 2022; Zwierko et al., 2019), additional research is needed to determine how these factors may affect the SRC assessment protocols of professional athletes.

The purpose of this study was to explore the relationship between pre-existing health/demographic factors and the accuracy and precision of EYE-SYNC saccade tasks during the baseline testing of professional athletes. To accomplish this goal, CFL athletes completed the EYE-SYNC saccade test, and athlete health and demographic information was obtained from the Head Check database. The objectives of this study were to examine the relationship between pre-existing health factors and EYE-SYNC saccade outcomes, compare saccade performance based on the presence of health difficulties, and examine the influence that physical exertion had on saccade performance. Through these objectives, this study sought to help contribute to the applied use of sideline oculomotor assessments among CFL athletes. Furthermore, this study was intended to promote future research to improve SRC assessment and diagnostic protocols, by introducing potential health factors during baseline testing.

Objective 1

The results of the correlations revealed no significant relationships between the pre-existing health variables and the EYE-SYNC saccade outcomes. Based on the literature reviewed in Chapter 2, it was hypothesized that the presence of ADHD, LD, and a history of concussion would be associated with significantly lower oculomotor performance within CFL athletes. However, the results of the correlations indicated that no significant relationship existed.

Significant positive relationships were found to exist between each of the four saccade outcomes, suggesting that the saccade accuracy and precision were effectively measuring a similar construct of oculomotor functioning. Another significant and positive relationship was found between the variables of age group and concussion group, indicating that the risk of sustaining an SRC increases with age. As the number of head impacts can be assumed to rise along with time spent playing professional sports, the positive relationship between age and history of concussion is not surprising. Overall, the results of the correlations suggest that the EYE-SYNC saccade scores at baseline were not significantly correlated with the athletes' history of concussions, ADHD, LD, and age.

Objective 2

Despite the lack of correlations between the athlete's health characteristics and saccade outcomes, the potential for group differences to occur between athletes with and without these difficulties remained a possibility. The second objective of this study was to explore the differences in mean saccade accuracy and precision between the athletes with and without the examined health factors. To accomplish this goal, independent t-tests were used to compare the four mean saccade outcomes between the athletes with ADHD and/or LD, and those without these difficulties. The results of the comparison of means revealed no significant difference in any of the four saccade outcomes between the athletes with ADHD and/or LD, and those without. Based on the examined literature (Bari & Robbins, 2013; Dahan et al., 2018; Goto et al., 2010; Langmaid et al., 2014; Maron et al., 2021; Moran et al., 2021), it was expected that the presence of ADHD and/or LD would lead to poorer oculomotor performance on the EYE-SYNC saccade tasks. However, the results of the analyses revealed no difference in saccade accuracy and precision between the groups of athletes with and without attention and learning difficulties.

One possible explanation for this finding is the brief administration time of the EYE-SYNC saccade tasks. With some of the most common symptoms of ADHD being inattention and distractibility, it was expected that athletes with attention difficulties would struggle to follow and predict the movement of the visual target. Because the administration time of the saccade task was approximately 60 seconds in duration, this may not have been long enough to observe the athletes' attention-related symptoms. The results of Maron and colleagues (2021) meta-analysis suggested the presence of impaired oculomotor performance in individuals with ADHD symptoms, particularly in regard to saccade inhibition. However, the duration of eye tracking measures used in the examined studies was not described. The brief nature of the EYE-SYNC saccade task, and the fact that it was novel to the athletes, may have maintained their focus on the task at hand. Therefore, a longer saccade task, or the entire EYE-SYNC test battery, may be beneficial for identifying the effects that ADHD and LD have on oculomotor performance.

To examine the differences in average saccade performance between the levels of concussion group and age group, three-way MANOVAs were conducted. The results of the analyses revealed no significant differences in saccade performance across the three concussion groups (0, 1, 2+) and age groups (21-25, 25-30, 31-40). The present study's hypothesis that significant differences in EYE-SYNC saccade performance would occur between athletes with no history of concussion and those with multiple concussions was not confirmed. This study recorded the number of previous concussions sustained by the athletes, however, the amount of time passed since the latest injury was not examined. Each of the athletes who participated in baseline assessments was confirmed to have fully recovered from any prior SRC; therefore, the baseline saccade outcomes were assumed to be a measure of healthy functioning.

The lack of significant differences in saccade performance between athletes with no history of concussions and those with multiple concussions may be a result of the healthy population of athletes. Because no saccadic deficits were observed in athletes with a history of concussions, these results indicate that the athletes made good recoveries from their prior SRCs without lingering oculomotor difficulties. This finding is encouraging, as the CFL athletes in the present study appear to return to full health upon recovering from prior SRCs. Another explanation may be the present study's use of baseline data without also examining post-injury data. The cumulative effects of multiple SRCs may only be observable in immediate post-injury assessments. Furthermore, the baseline assessments only identified the athletes' oculomotor performance at a single point in time. With multiple SRCs being associated with additional physical, cognitive, and emotional symptoms (McCrory et al., 2017b) the time needed to return to baseline oculomotor functioning following an SRC may differ in athletes with a history of multiple concussions. Future research should examine the oculomotor performance of elite athletes at baseline, post-injury, and follow-up assessments during recovery.

Objective 3

The third objective of this study was to examine the influence that physical exertion had on the EYE-SYNC saccade outcomes. The one-way repeated measures MANOVA indicated that there was no difference in combined saccade accuracy and precision outcomes between the pre- and post-exertion groups. Therefore, the EYE-SYNC saccade tasks appear appropriate for the assessment of athletes immediately following practice or game participation. This finding is important for the practicality of the EYE-SYNC tool, as follow-up assessments can be completed immediately following practice or game participation, even if baselines were completed while athletes were at rest. With one of the main advantages of computerized sideline SRC assessments being the speed of administration, this finding supports its use as a sideline assessment for suspected SRCs that occur during gameplay. This finding is applicable to in-game SRC sideline testing, as physical exertion does not appear to significantly alter the athletes' saccade scores from baseline. Therefore, baseline and follow-up assessments may be completed after practice or game participation without altering the reliability and validity of oculomotor functioning.

The post-exertion findings suggest that in a healthy population of CFL athletes, there are no observable consequences of physical exertion on saccadic performance. This finding is encouraging, as the absence of post-exertional deficits in oculomotor functioning may be used as additional information in the diagnosis of SRCs. If healthy CFL athletes do not demonstrate poorer oculomotor performance following physical exertion, the presence of post-exertion deficits may be an indication of an SRC or other neurological concerns.

This study's physical exertion findings contradict those observed by Zwierko and colleagues (2019), who found that oculomotor functioning in athletes decreased following physical exercise to exhaustion. In their experiment, the athletes ran on a treadmill to exhaustion before immediately completing the oculomotor tests (Zwierko et al., 2019). Each athlete's exhaustion was measured using blood lactate concentrations, heart rate, and oxygen consumption. The present study's post-exertion assessments were completed after a standard team practice; however, it cannot be determined whether the CFL athletes had exercised to exhaustion, or how much recovery time they were allowed before completing the EYE-SYNC saccade task. Furthermore, the athletes' response to physical exertion may differ during recovery from a recent SRC (McGrath et al., 2013; Lichtenstein & Merz, 2019). Future research should explore the effects of physical exertion on CFL athletes while controlling for the amount and intensity of exercise, along with the duration of recovery. In addition, the effects of physical exertion on oculomotor performance during recovery from an SRC should be explored in CFL athletes.

Strengths and Limitations

The inclusion and exclusion criteria of this study ensured that the sample of CFL athletes completed the EYE-SYNC saccade tasks while healthy at baseline. Therefore, the sample of 428 examined athletes can be expected to represent the normal CFL population well. Although this standardization is a strength of the study, the focus on baselines limited the analyses to healthy performance without examining post-injury or follow-up assessment data. To address this limitation, it is suggested that post-injury assessments of oculomotor functioning be administered to all CFL athletes who sustain an SRC during the season. Another limitation of the present study was the decision to retain outliers in the sample. Due to the nature of the study and the population examined, it was determined that a normal distribution of oculomotor performance was not expected for healthy CFL athletes. Because of the non-significant results in the present study, it is unlikely that the exclusion of outliers would have changed the findings significantly. Another limitation is the small sample of athletes who completed the post-exertion assessments (N = 60) compared to the baseline (N = 428). Future research should consider administering post-exertion assessments to all CFL athletes who completed baseline examinations to generalize these findings to the entire CFL population.

The present study examined the EYE-SYNC saccade test in isolation without including the additional measures of smooth pursuit, vestibular-ocular reflex (VOR), and vestibular-ocular reflex cancellation (VORx). At present, the limitations of time for professional athletes are a challenge as parameters from the Collective Bargaining Agreement between the CFL and the Player's Association limit how much additional time a player can devote to non-football activities. An advantage of the EYE-SYNC assessment tool is that it can be completed in 2-5 minutes; however, the administration of the saccade test in isolation required approximately 60 seconds. Therefore, this brief administration time may not have been long enough to observe differences in oculomotor functioning across the independent variables. Finally, a strength of this study was the use of objective data without relying on athletes' subjective symptom reports. This process reduced the potential for athlete bias to alter assessment data.

Conclusions and Future Directions

The findings of this study indicated that the CFL athletes' baseline oculomotor functioning, measured using the EYE-SYNC saccade task, was not influenced by the health and demographic variables of history of concussion, ADHD, LD, age, and physical exertion. This suggests that the number of previous concussions and the presence of ADHD and/or LD do not need to be controlled for during baseline measures of oculomotor performance. In addition, there was no significant difference in saccade outcomes between pre- and post-exertion assessments. Therefore, this finding suggests that athletes may be tested following practice or game participation without the need to return to the at-rest state of the baseline assessments. This information may allow CFL athletes with a suspected SRC to be tested immediately on the sidelines using the EYE-SYNC tool.

These findings indicate that the observed healthy population of CFL athletes did not suffer from prolonged oculomotor deficits upon recovery from previous SRCs. In addition, the influence of ADHD, LD, and physical exertion does not appear to alter the baseline saccadic performance of healthy CFL athletes. These results are encouraging, as they support the conclusion that CFL athletes are recovering fully from prior SRCs, and healthy athletes are not negatively affected by pre-existing health difficulties.

Future studies examining SRCs in CFL athletes should consider administering the additional EYE-SYNC tests of smooth pursuit, VOR, and VORx to obtain a comprehensive measure of oculomotor functioning. The administration of the saccade task in isolation may not have been sensitive enough to identify subtle differences in oculomotor performance between the examined groups of athletes. In addition, future research should strongly consider the examination of post-injury and follow-up data to determine the effects that a history of concussion, ADHD, LD, and physical exertion have on the recovery of CFL players from an SRC.

Overall, the tools for assessing and diagnosing SRCs in professional athletes have advanced significantly over recent years. The introduction of computerized oculomotor tools into the SRC protocols of professional sports teams creates exciting possibilities for protecting the health of athletes. Sideline measures of oculomotor functioning provide the potential for important objective data without relying solely on subjective symptom reports; however, additional research is required to explore the many factors that can influence oculomotor functioning in professional athletes. To integrate novel SRC assessment tools, such as EYE-SYNC, into the consensus statements of SRC safety, the role of health and demographic variables should continue to be explored. The present study, and future research examining the use of computerized oculomotor SRC assessments in professional athletes, could help establish the reliability and validity of these assessment tools.

References

Allman, A. A., Ettinger, U., Joober, R., & O'Driscoll, G. A. (2012). Effects of methylphenidate on basic and higher-order oculomotor functions. *Journal of Psychopharmacology*, *26*, 1471–1479. https://doi.org/10.1177/0269881112446531

American Psychiatric Association. (2022). *Diagnostic and statistical manual of mental disorders* (5th-TR ed.). https://doi-org.ezproxy.frederick.edu/10.1176/appi.books.9780890425596

Anderson, B. L., Gittelman, M. A., Mann, J. K., Cyriac, R. L., & Pomerantz, W. J. (2016). High school football players' knowledge and attitudes about concussions. *Clinical Journal of Sport Medicine*, *26*, 206-209. https://doi.org/10.1097/JSM.0000000000000214

Aubry, M., Cantu, R., Dvorak, J., Graf-Baumann, T., Johnston, K., Kelly, J., Lovell, M., McCrory, P., Meeuwisse, W., & Schamasch, P. (2002). Summary and agreement statement of the first International Conference on Concussion in Sport, Vienna 2001. *The Physician and Sportsmedicine*, *30*, 57-63. https://doi.org/10.3810/psm.2002.02.176

Bari, A., & Robbins, T. W. (2013). Inhibition and impulsivity: Behavioral and neural basis of response control. *Progress in Neurobiology, 108,* 44-79. https://doi.org/10.1016/j.pneurobio.2013.06.005

Benson, B. W., Meeuwisse, W. H., Rizos, J., Kang, J., & Burke, C. J. (2011). A prospective study of concussions among National Hockey League athletes during regular season games: The NHL-NHLPA Concussion Program. *CMAJ*, *183*, 905–911. https://doi.org/10.1503/cmaj.092190

Bey, T., & Ostick, B. (2009). Second Impact Syndrome. *West J Emerg Med. 10,* 6-10. Retrieved from https://escholarship.org/uc/item/5x03f3tx

Boden, B. P., Tacchetti, R. L., Cantu, R. C., Knowles, S. B., & Mueller, F. O. (2007). Catastrophic head injuries in high school and college football athletes. *American Journal of Sports Medicine*, *35*, 1075–1081. https://doi.org/10.1177/0363546507299239

Bretzin, A. C., Covassin, T., Fox, M. E., Petit, K. M., Savage, J. L., Walker, L. F., & Gould, D. (2018). Sex differences in the clinical incidence of concussions, missed school days, and time loss in high school student-athletes: part 1. *The American Journal of Sports Medicine*, *46*, 2263-2269. https://doi.org/10.1177/0363546518778251

Caron, J. G., Bloom, G. A., Johnston, K. M., & Sabiston, C. M. (2013). Effects of multiple concussions on retired national hockey league players. *Journal of Sport and Exercise Psychology*, *35*, 168-179. https://doi.org/10.1123/jsep.35.2.168

Centers for Disease Control and Prevention. (2007). Nonfatal traumatic brain injuries from sports and recreation activities--United States, 2001-2005. *Morbidity and Mortality Weekly Report*, *56*, 733-737. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm5629a2.htm

Chacko, A., Uderman, J., Feirsen, N., Bedard, A. C., & Marks, D. (2013). Learning and cognitive disorders: multidiscipline treatment approaches. *Child and Adolescent Psychiatric Clinics, 22,* 457-477. https://doi.org/10.1016/j.chc.2013.03.006

Clark, R., & Stanfill, A. G. (2019). A systematic review of barriers and facilitators for concussion reporting behavior among student athletes. *Journal of Trauma Nursing*, *26*, 297-311. https://doi.org/10.1097/JTN.0000000000000468

Cockerham, G. C., Goodrich, G. L., Weichel, E. D., Orcutt, J. C., Rizzo, J. F., Bower, K. S., & Schuchard, R. A. (2009). Eye and visual function in traumatic brain injury. *J Rehabil Res Dev*, *46*, 811-818. https://www.coulditbemyeyes.com/wp-content/uploads/2015/08/Cockerham-eye-and-visual-function-after-TBI-2009.pdf

Comeau, D., & Pfeifer, N. (2019). Diagnosis of concussion on the sidelines. *Seminars in Pediatric Neurology, 30*, 26-34. https://doi.org/10.1016/j.spen.2019.03.005

Conners, C. K. (2014). *Conners continuous performance test 3rd edition manual*. Toronto: Multi-Health Systems.

Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., Linenweber, M. R., Peterson, S. E., Raichle, M. E., Van Essen, D. C., & Shulman, G. L. (1998). A common network of functional areas for attention and eye movements. *Neuron, 21*, 761-773. https://doi.org/10.1016/S0896-6273(00)80593-0

Dahan, A., Ryder, C. H., & Reiner, M. (2018). Components of Motor Deficiencies in ADHD and Possible Interventions. *Neuroscience, 378,* 34-53. https://doi.org/10.1016/j.neuroscience.2016.05.040

Delaney, J. S., Caron, J. G., Correa, J. A., & Bloom, G. A. (2018). Why professional football athletes chose not to reveal their concussion symptoms during a practice or game. *Clinical Journal of Sport Medicine*, *28*, 1–12. https://doi.org/10.1097/JSM.0000000000000495

Delaney, J. S., Lacroix, V. J., Leclerc, S., & Johnston, K. M. (2000). Concussions during the 1997 Canadian Football League season. *Clinical Journal of Sport Medicine, 10*, 9-14. https://doi.org/10.1097/00042752-200001000-00003

Flamm, E. S. (1972). The dilated pupil and head trauma 1517–1867. *Medical History*, *16*, 194-199. https://doi.org/10.1017/S0025727300017610

Giza, C. C., & Hovda, D. A. (2014). The new neurometabolic cascade of concussion. *Neurosurgery*, *75*, 24-33. https://doi.org/10.1227/NEU.0000000000000505

Goto, Y., Hatakeyama, K., Kitama, T., Sato, Y., Kanemura, H., Aoyagi, K., Sugita, K., & Aihara, M. (2010). Saccade eye movements as a quantitative measure of frontostriatal network in children with ADHD. *Brain and Development*, *32*, 347–355. https://doi.org/10.1016/j.braindev.2009.04.017

Guskiewicz, K. M., Weaver, N. L., Padua, D. A., & Garrett, W. E. (2000). Epidemiology of Concussion in Collegiate and High School Football Athletes. *The American Journal of Sports Medicine, 28,* 643-50. https://doi.org/10.1177/03635465000280050401

Harmon, K. G., Clugston, J. R., Dec, K., Hainline, B., Herring, S., Kane, S. F., Kontos, A. P., Leddy, J. L., McCrea, M., Poddar, S. K., Putukian, M., Wilson, J. C., & Roberts, W. O. (2019). American Medical Society for Sports Medicine position statement on concussion in sport. *British Journal of Sports Medicine*, *53*, 213-225. http://doi.org/10.1136/bjsports-2018-100338

Houck, Z., Asken, B., Bauer, R., Pothast, J., Michaudet, C., & Clugston, J. (2016). Epidemiology of sport-related concussion in an NCAA Division I Football Bowl Subdivision sample. *The American Journal of Sports Medicine*, *44,* 2269-2275. https://doi.org/10.1177/0363546516645070

Johnson, B. P., Lum, J. A. G., Rinehart, N. J., & Fielding, J. (2016). Ocular motor disturbances in autism spectrum disorders: Systematic review and comprehensive meta-analysis. *Neuroscience and Biobehavioral Reviews, 69,* 260-79. https://doi.org/10.1016/j.neubiorev.2016.08.007

Kamins, J., Bigler, E., Covassin, T., Henry, L., Kemp, S., Leddy, J. J., Mayer, A., McCrea, M., Prins, M., Schneider, K. J., McLeod, T. C. V., Zemek, R., & Giza, C. C. (2017). What is the physiological time to recovery after concussion? A systematic review. *British Journal of Sports Medicine, 51,* 935-40. https://doi.org/10.1136/bjsports-2016-097464

Kerr, Z. Y., Roos, K. G., Djoko, A., Dalton, S. L., Broglio, S. P., Marshall, S. W., & Dompier, T. P. (2017). Epidemiologic measures for quantifying the incidence of concussion in national collegiate athletic association sports. *Journal of Athletic Training*, *52*, 167-174. https://doi.org/10.4085/1062-6050-51.6.05

Kirkland, T. (1792). *A Commentary on Apoplectic and Paralytic Affections: And on Diseases Connected with the Subject*. W. Dawson.

Kontos, A. P., Elbin, R. J., Schatz, P., Covassin, T., Henry, L., Pardini, J., & Collins, M. W. (2012). A revised factor structure for the post-concussion symptom scale: Baseline and postconcussion factors. *American Journal of Sports Medicine*, *40*, 2375–2384. https://doi.org/10.1177/0363546512455400

Langlois, J. A., Rutland-Brown, W., & Wald, M. M. (2006). The Epidemiology and Impact of Traumatic Brain Injury A Brief Overview. *J Head Trauma Rehabil, 21,* 375-8. https://doi.org/ 10.1097/00001199-200609000-00001

Langmaid, R. A., Papadopoulos, N., Johnson, B. P., Phillips, J. G., & Rinehart, N. J. (2014). Handwriting in Children With ADHD. *Journal of Attention Disorders*, *18*, 504–510. https://doi.org/10.1177/1087054711434154

Lichtenstein, J. D., & Merz, Z. C. (2019). Post-exertion neuropsychological testing in the management of sport-related concussion. *Psychological Injury and Law*, *12*, 146-154. https://doi.org/10.1007/s12207-019-09350-0

Mack, C. D., Solomon, G., Covassin, T., Theodore, N., Cárdenas, J., & Sills, A. (2021). Epidemiology of concussion in the National Football League, 2015-2019. *Sports Health*, *13*, 423-430. https://doi.org/10.1177/19417381211011446

Manley, G., Gardner, A. J., Schneider, K. J., Guskiewicz, K. M., Bailes, J., Cantu, R. C., Castellani, R. J., Turner, M., Jordan, B. D., Randolph, C., Dvořák, J., Alix Hayden, K., Tator, C. H., McCrory, P., & Iverson, G. L. (2017). A systematic review of potential long-term effects of sport-related concussion. *British Journal of Sports Medicine, 51,* 969-77 https://doi.org/10.1136/bjsports-2017-097791

Maron, D. N., Bowe, S. J., Spencer-Smith, M., Mellahn, O. J., Perrykkad, K., Bellgrove, M. A., & Johnson, B. P. (2021). Oculomotor deficits in attention deficit hyperactivity disorder (ADHD): A systematic review and comprehensive meta-analysis. *Neuroscience and Biobehavioral Reviews, 131,* 1198-1213. https://doi.org/10.1016/j.neubiorev.2021.10.012

Maruta, J., & Ghajar, J. (2014). Detecting eye movement abnormalities from concussion. *Progress in Neurological Surgery*, *28*, 226–233. https://doi.org/10.1159/000358786

Maruta, J., Heaton, K. J., Kryskow, E. M., Maule, A. L., & Ghajar, J. (2013). Dynamic visuomotor synchronization: quantification of predictive timing. *Behavior Research Methods, 45*, 289-300. https://doi.org/10.3758/s13428-012-0248-3

McCrory, P., Feddermann-Demont, N., Dvoøák, J., Cassidy, J. D., McIntosh, A., Vos, P. E., Echemendia, R. J., Meeuwisse, W., & Tarnutzer, A. A. (2017a). What is the definition of sports-related concussion: A systematic review. *British Journal of Sports Medicine*, *51*, 877–887. https://doi.org/10.1136/bjsports-2016-097393

McCrory, P., Meeuwisse, W., Dvořák, J., Aubry, M., Bailes, J., Broglio, S., Cantu, R. C., Cassidy, D., Echemendia, R. J., Castellani, R. J., Davis, G. A., Ellenbogen, R., Emery, C., Engebretsen, L., Feddermann-Demont, N., Giza, C. C., Guskiewicz, K. M., Herring, S., Iverson, G. L., … Vos, P. E. (2017b). Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*, *51*, 838–847. https://doi.org/10.1136/bjsports-2017-097699

McGrath, N., Dinn, W. M., Collins, M. W., Lovell, M. R., Elbin, R. J., & Kontos, A. P. (2013). Post-exertion neurocognitive test failure among student-athletes following concussion. *Brain Injury, 27*, 103-113. https://doi.org/10.3109/02699052.2012.729282

McKeithan, L., Hibshman, N., Yengo-Kahn, A., Solomon, G. S., & Zuckerman, S. (2019). Sport-Related Concussion: Evaluation, Treatment, and Future Directions. *Medical Sciences*, *7*, 44. https://doi.org/10.3390/medsci7030044

Moran, R. N., Wallace, J., Murray, N. G., & Covassin, T. (2021). Effects of attention deficit hyperactivity disorder and learning disability on vestibular and ocular baseline concussion assessment in pediatric athletes. *Applied Neuropsychology: Child*, *10*, 276-282. https://doi.org/10.1080/21622965.2019.1683453

Pearce, J. M. S. (2008). Observations on concussion: A review. *European Neurology*, *59,* 113–19. https://doi.org/10.1159/000111872

Putukian, M., Kreher, J. B., Coppel, D. B., Glazer, J. L., McKeag, D. B., & White, R. D. (2011). Attention deficit hyperactivity disorder and the athlete: an American Medical Society for Sports Medicine position statement. *Clinical Journal of Sport Medicine, 21*, 392-400. https://doi.org/0.1097/JSM.0b013e3182262eb1

Rhazes, A. Lutetiae ex officina. Rome: R Stephan, 1548.

Stephen, S. J., Hasman, L., Goldenberg, M., Merchant-Borna, K., Kawata, K., Mannix, R., Bazarian, J. J., Stephen, M., Hasman, M., Goldenberg, M., Merchant-Borna, D., & Bazarian. (2022). Short-Term Neurologic Manifestations of Repetitive Head Impacts

Among Athletes: A Scoping Review. *J Head Trauma Rehabil*. https://doi.org/10.1097/HTR.0000000000000767

Stephenson, D. W. H., Kinsella, E. A., Holmes, J. D., & Johnson, A. M. (2021). Canadian Football League players' reporting of concussion symptoms. *Forum: Qualitative Social Research, 22.* Retrieved from https://www.qualitative-research.net/index.php/fqs/article/download/3615/4718?inline=1

Sussman, E. S., Ho, A. L., Pendharkar, A. V., & Ghajar, J. (2016). Clinical evaluation of concussion: The evolving role of oculomotor assessments. *Neurosurgical Focus*, *40*. https://doi.org/10.3171/2016.1.FOCUS15610

SyncThink Inc. (2022). https://syncthink.com/

Tomczyk, C. P., Anderson, M., Petit, K. M., Savage, J. L., & Covassin, T. (2021). Vestibular/Ocular Motor Screening Assessment Outcomes After Sport-Related Concussion in High School and Collegiate Athletes. *Journal of Athletic Training, 56*, 1285-1291. https://doi.org/10.4085/1062-6050-0588.20

Valovich McLeod, T. C., & Hale, T. D. (2015). Vestibular and balance issues following sport-related concussion. *Brain Injury, 29*, 175-184. https://doi.org/10.3109/02699052.2014.965206

Webbe, F. (2011). *The handbook of sport neuropsychology*. Springer Publishing Company.

Zwierko, T., Jedziniak, W., Florkiewicz, B., Stępiński, M., Buryta, R., Kostrzewa-Nowak, D., Nowak, R., Popowczak, M., & Woźniak, J. (2019). Oculomotor dynamics in skilled soccer players: The effects of sport expertise and strenuous physical effort. *European Journal of Sport Science*, 19, 612-620. https://doi.org/10.1080/17461391.2018.1538391