

University of Nevada, Reno

**The use of a Virtual Reality Platform for  
Standardization of the Vestibular Ocular-Motor Screen**

A Dissertation Submitted in Partial Fulfillment

of the Requirements for the Degree of Doctor of Philosophy in Neuroscience

by

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## Abstract

Public awareness of sport-related concussion (SRC) has risen in recent history. This is evident through a couple of factors. One is the increased self-reporting of SRC. It has been estimated that 2.5 million American High School students reported having at least one SRC within the previous year. Of that same group, 1 million reported having more than one SRC.<sup>1</sup> The second factor is the development of various sports injury surveillance systems that have been implemented to track this data over the past decade. The Vestibular Ocular Motor Screen (VOMS) is a standard clinical tool for the assessment, diagnosis, and management of SRC. The VOMS consists of seven subtests that challenge the subject's oculomotor and vestibular function. The subtests are designed to elicit symptomology consistent with SRC. The current clinical protocol involves hand-held use of targets and administrator interpretation of the distances the targets are held in front of the subject. Variability among raters with this process may alter the symptom reporting from the subject and near-point convergence (NPC) measurements. This creates the potential for misdiagnosis, management, and treatment of SRC. The objective of this study is to explore a means of standardization of the VOMS among clinicians such that subjective symptomology recording is reliable in the diagnosis and management of SRC. This study consists of three experiments. Experiment one is an examination of the current clinical protocol compared to a novel prototype (PRO) and a virtual reality (VR) stimulus to determine if the latter two platforms are suitable means of standardization of the VOMS with a healthy population. The results indicate the PRO and VR elicit less symptoms but the VR had higher NPC measurements. Experiment two compares the Total Symptom Provocation Change Score (TSPCS) and Near Point Convergence (NPC) between the PRO and the VR stimuli at baseline and post-injury. Post-injury comparison data indicate no significant difference with TSPCS and NPC measurements and VR may be used with post-injury assessments. Experiment three is a direct comparison of the current clinical manual method of VOMS administration to the VR method that

includes baseline and post-injury data. This experiment also examined self-reported motion sickness. The results indicate that VR can be used to administer the VOMS despite any history of motion sickness. The goal of this study is to provide proof of concept that leads to the development of a standardized, mobile VOMS VR stimuli that can record symptoms, eye movement, measure near-point convergence (NPC), and is completely automated such that the field healthcare professional can use this platform for a quick digital relay of this information to a physician for diagnosis and management of SRC.

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## Preface

This project was initiated by a simple observation during baseline concussion assessments completed as part of a pre-season health screening for collegiate athletes. As each athlete went through the VOMS assessment, I observed that each rater's positioning of the hand-held targets varied. This made me wonder if this influenced the outcome of the VOMS assessment. I initiated a pilot study with two lab staff members (one female and one male) as raters and ten volunteer collegiate aged subjects. Each subject went through the VOMS with both raters. The raters were instructed to hold the target at what they thought was three feet apart and three feet away from the subject. The test was then paused while those distances were measured. This was specific to the smooth pursuit, horizontal and vertical saccades, and horizontal and vertical vestibular ocular reflex. Symptom scores were also recorded. The results indicated that each rater held the targets at varied distances apart and from the subject which deviated from the VOMS specified distances. The symptom scores also varied between raters with the same subject. At this point, I determined that the VOMS needed to have some form of standardization which would allow for consistent assessment between raters. This led to the development of the prototype target stand and the virtual reality stimuli. The subsequent transition to the use of the prototype and development of the virtual reality stimuli to administer the VOMS was the basis for Experiment one in this document.

The experiments in this study were based upon my following publications:

Pavilionis, Philip; Alphonsa, Sushma; Kissick, Cameron; Taylor, Madison; Moran, Ryan; Constantino, Nora; Murray, Nicholas. Vestibular/ocular Motor Screening: Evaluation Of A Novel Prototype For Injury Assessment: 2829 Board #290 May 29 9:30 AM - 11:00 AM. *Medicine & Science in Sports & Exercise* 52(7S):p 784, July 2020. | DOI: 10.1249/01.mss.0000683768.34241.c8.

Pavilionis P, Adhanom IB, Moran R, Taylor MR, Murray NG. Virtual Reality Application for Vestibular/Ocular Motor Screening: Current Clinical Protocol Versus a Novel Prototype. *Sports Health*. 2024;16(3):407-413. doi:10.1177/19417381231163158

Philip K Pavilionis, Madison Fenner, Kristen G Quigley, Isayas Berhe Adhanom, Ryan N Moran, Monique Passalacqua, and Nicholas G Murray. VOMS baseline vs post-injury: a comparison of a standardized novel prototype and a virtual reality application in sport-related concussion. SPORTSHEALTH/2024/051673 (currently under review)

## Chapter 1

### 1.1 Introduction

The inherent competitive nature of humans has been evident throughout history with the evolution of sports and physical activity. This competitiveness comes with accolades for success and the consequences of physical injury. Of the possible sport-related injuries, head injuries are one of today's most difficult to diagnose and manage.<sup>2-4</sup> Sport-related concussion (SRC) is a commonly diagnosed brain injury. Prior surveillance systems have identified a marked increase in SRCs over the past 15 years.<sup>5</sup> A study from November of 2020 comparing the prevalence of concussion among U.S. children and adolescents pointed out that reported head injuries among children increased from 3.6% to 7.0%, (ages 3-17 years), and 6.5% to 18.3% for adolescents, (ages 13-17 years).<sup>6</sup> Professional sports and its prevalence in the media has created an increased awareness of SRC in the public's eye. In 2022, the National Football League reported that there was an 18% increase in SRC among their athletes.<sup>7</sup> Despite the recent rule changes among various sports, updates in concussion management protocols, and advances in protective equipment, SRC is an ongoing health issue in physical activity and competitive sports. This health issue is compounded in that there is not a standard protocol with assessment tools that is globally accepted by the medical community to assess and manage SRC.

There are several assessment and management tools available to medical professionals. These assessment tools range from computer tests that measure cognitive function and physical reaction times to physical tests that assess an athlete's vestibular functions. Some assessment tools attempt to measure the subject's ability to visually track a moving target.<sup>8</sup> This is accomplished using several platforms that range from handheld targets to computerized applications with augmented reality. These platforms include computer-based assessments such as StimulEye<sup>9,10</sup>, RightEye<sup>11</sup>, and Oculogica's EyeBox.<sup>12</sup> StimulEye uses a smartphone app to measure pupillary light reflex (PLR) to

measure the pupil diameter over a specific time period using an algorithm to determine pupil dilation velocity and constriction latency to indicate a possible concussion.<sup>10</sup> PLR has been studied as a biomarker for concussion.<sup>13</sup> A limitation to StimulEye is the test administrator holds the phone during the use of the app and may not be able to keep it steady during the test. RightEye is a computer based assessment which tracks smooth pursuit and saccadic eye movements to identify deficits for concussion detection.<sup>11</sup> Oculogica's EyeBOX is an eye tracking system that looks to assess cranial nerve function by measuring pupil size and position over time, much like StimulEye, but with the use of a mounted mobile device which uses a camera to track eye movement. The software for this device uses an algorithm to determine based upon the subject's eye movement to determine if the subject has sustained a concussion.<sup>14</sup> Although these tools measure function of the ocular motor nerve specific to pupil and saccadic eye movement, they do not make assessments of the various other parts of the brain and cranial nerves such as the vestibular and vagus nerves. The Vestibular Ocular Motor Screen (VOMS) is a tool that enables the clinician to assess the ocular motor, vestibular, and vagus nerves upon suspicion of a SRC. This tool, developed by the University of Pittsburgh Medical Center, is the most common assessment used by most clinicians for the diagnosis of concussion.<sup>15</sup> The VOMS is comprised of seven individual tests that challenge the subject's ability to either track or focus on a target while either moving their eyes or keeping them fixed while moving the target. The tests are designed to elicit symptoms specific to a concussion. This assessment requires minimal equipment in that the clinician can simply use their fingers or use tongue depressors as targets. Additionally, they would need a metric measurement tool and a metronome app on a mobile phone. However, even with the minimal equipment on hand, the administration and interpretation of the VOMS are contingent upon a properly trained clinician. With the Resulting in the subjective reporting of symptomology during the assessment, this creates a level of uncertainty when making a diagnosis due to the possibility of the subject skewing their answers to get clearance to

return to their sports activities. With this perspective, the question that comes into focus is the possibility of creating a platform of the VOMS that would standardize the assessment among clinicians. One platform is that of a virtual reality (VR) system.<sup>16</sup> This creates several possibilities for VOMS. One, the VOMS can be standardized to ensure the targets will be in the same location each time. Two, current VR technology enables eye tracking that can be measured and compared to healthy, baseline metrics. Three, VR application development with symptom and eye tracking data that can be quickly recorded and sent to a medical professional for immediate interpretation and assessment. According to the Centers for Disease Control (CDC), "Standardization means aligning individual patient results to an unambiguous standard".<sup>17</sup> To assess the apparent ambiguity of the current clinical protocol within administrators would warrant an investigation into the methods of VOMS administration specific to the current manual protocol, use of a novel prototype, and a VR system to determine differences in symptomology and near point convergence measurements among a healthy athletic population. To address these, we will pursue the following aims:

**Aim 1:** The purpose of Aim 1 is to determine if a VR stimuli is suitable for baseline assessments. This aim will examine the difference in symptomology and near point convergence (NPC) measurements when comparing the current manual clinical method with a novel prototype and a head mounted VR system. It is hypothesized that at baseline, in a healthy athlete population, there will be no difference with symptomology and NPC measurements between use of the manual method, a novel prototype, and a VR system. No significant difference here indicates that a novel prototype and a VR stimuli can be used for baseline assessment for healthy controls.

**Aim 2:** The purpose of Aim 2 is to determine if a VR stimuli is suitable for post-injury assessment. This is addressed by examination of the use of a VR system to administer the VOMS with respect to total symptom provocation change score (TSPCS) and NPC distance at baseline and post-injury. The hypothesis is a VR system for VOMS administration compared to a novel prototype will be no different with respect to TSPCS and NPC distances. A result of no significant difference here would indicate that the VR stimuli can be used for post-injury SRC assessment.

**Aim 3:** The purpose of Aim 3 is to make a direct comparison of the current clinical protocol (Manual Administration) to the VR method to validate the use of the VR system for VOMS administration. This will include examining adolescents age groups, and those groups who self-report a history of motion sickness. It is hypothesized that the administration of the VOMS in VR will not be different with TSPCS and NPC measurements compared to the current clinical VOMS method through a randomized

administration of both stimuli. No significant differences here would indicate the VR stimuli is suitable for SRC assessment and management.

## 1.2 Background and significance

With the raised awareness and recognition of the signs and symptoms of concussion over the past 20 years, the rates of diagnosis have significantly risen.<sup>18</sup> This is particularly true of sport-related concussion (SRC). The University of Pittsburgh Medical Center's concussion statistics state that up to 3 million sport and recreation concussions occur each year with about 300,000 of those from football.<sup>19</sup> They estimate that out of every 10 concussions, 5 will go unreported. They also state that female sports of soccer and basketball make up the 2<sup>nd</sup> and 3<sup>rd</sup> most incidence of concussion among this population.<sup>19</sup> Surveillance systems for SRC rates is ongoing to this point, however, current literature points out that between 9% and 13% of all high school injuries are related to SRC.<sup>20</sup> Through the NCAA Injury Surveillance Program, a total of 3497 SRC's were reported through the academic years of 2014/15 to 2018/19. The most notable increases were in the sports of men's ice hockey, women's soccer and volleyball.<sup>21</sup> This has historically been difficult to track and collect data due to the varying methods of data collection, injury definition, and the varied methods of assessment and diagnostic tools.

## 1.3 Functional Neuroanatomy

The brain and brain stem reside within the cranial cavity and is suspended in cerebral spinal fluid (CSF). The CSF flows in and out of the cranial cavity which, along with the arteries and veins, creates a hydraulic buffer zone from the effects sudden head movements because of impacts to the head or body. This also allows the head to move freely without much effect from those resulting translational forces on the brain itself. See figure 1 below.

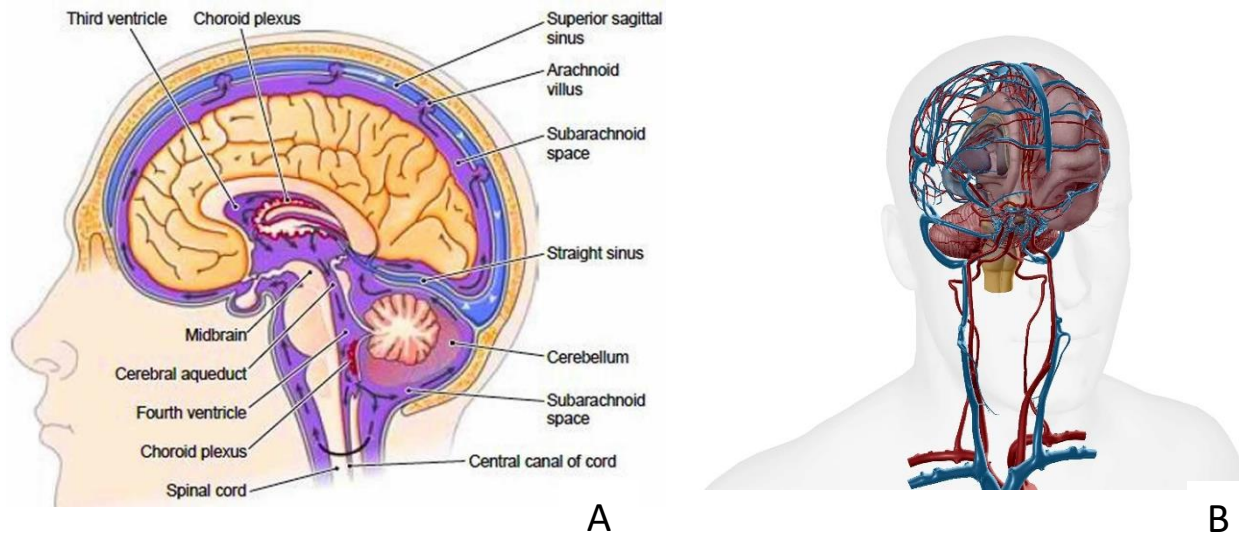


Figure 1: A: The flow of cerebral spinal fluid within the cranial cavity. B: The arteries and veins within and surrounding the brain tissue creates a hydraulic pad that protects the brain tissue from damage due to movement under normal daily activity.<sup>22,23</sup>

#### The Cranial Nerves:

The Cranial Nerves comprise of 12 nerve roots that originate sequentially from caudal and ventral brainstem (See Figure 2) They consist of the olfactory, optic, oculomotor, trochlear, abducens, trigeminal, facial, vestibulocochlear, glossopharyngeal, vagus, accessory, and hypoglossal nerves. This part of the central nervous system, when functioning properly, enable the senses of smell, sight, eye movement, facial and mandibular mobility, head orientation and balance, stylopharyngeus and pharyngeal constrictor muscle motor function, thoracic and abdominal viscera function, upper trapezius and sternocleidomastoid motor control, and muscle mobility of tongue.<sup>24</sup>

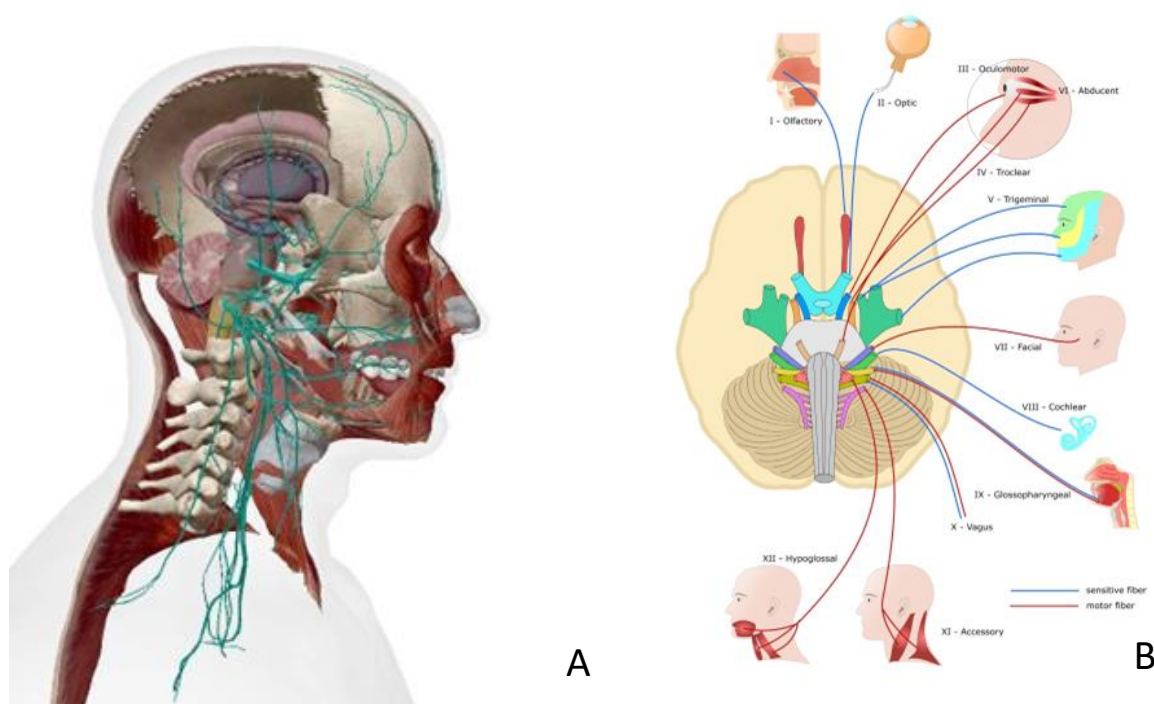


Figure 2: A- the cranial nerves are identified in green.<sup>23</sup> B- The cranial nerves organization and function.<sup>24</sup>

#### 1.4 SRC Mechanisms

The mechanism of a SRC can occur in several ways which are not always a blow to the head. More often, the mechanism is some form of violent collision sustained by the athlete where the head and neck cannot buffer this force. For example, an athlete may be knocked to the ground without any head impact at the time of collision with another athlete. It is upon either impact with the other athlete or the impact of the athlete hitting the ground or both that the brain is subject to the coup-contrecoup or whiplashing effect such that brain is subject to the sloshing within the cranial cavity. Depending on the direction of the force, various parts of the brain are affected in the form of diffuse axonal shearing. This initiates a metabolic cascade which results in a series of ionic and metabolic imbalances in the brain tissue that can prolong the recovery period.<sup>25</sup> Physiologically, this mechanism causes damage to the frontal lobe (cognitive function), the cerebral cortex (motor function), the temporal lobe (short term

memory, equilibrium), Wernicke's Area (spoken language, comprehension), and the Occipital lobe (sight and image recognition). Other areas of the brain and nervous system are also subject to this "whiplash" mechanism. They include the Cerebellum (Coordination of movement, balance, equilibrium) and the brain stem (Midbrain, Pons, Medulla Oblongata) where most of the Cranial nerves emanate from. The Optic nerve, (which originates from the cerebrum), the Oculo-motor nerve, the Vagus nerve and the Vestibulocochlear nerve function are assessed within the VOMS.

## 1.5 Current Clinical Protocol

The current protocol of concussion management is multifaceted. This involves assessment of cognitive, neurological, and vestibular function. Ideally, athletes are screened prior to participation with a healthy state baseline assessment in these areas. The specific assessments are completed via the use of a computerized neuro-cognitive assessment as is the case with the IMPACT Test.<sup>26</sup> In addition, a neuro-vestibular test is also applied, commonly done using Tandem Gait.<sup>27-29</sup> The Tandem Gait assessment involves the athlete walking in an heel-to-toe pattern along a 3 meter length line. They walk down and back on the line with a 180 degree turn at the far end. Usually, 6 trials are performed with 3 of the 6 trials involving a dual task of counting backwards by sevens or responding to a number given to them as to whether the number is odd or even.<sup>30</sup> These assessments are standardized and are easily replicated among different administrators. Another current clinical assessment is the VOMS. The VOMS assesses symptom provocation of the vestibular and ocular system via a series of subtests.<sup>15,31</sup> This includes evaluating smooth pursuits (SP), horizontal and vertical saccades (H-Sacc, V-Sacc), near-point convergence (NPC), horizontal and vertical vestibular/ocular reflex (HOR, VOR), and visual motion sensitivity (VMS). The specific parameters for each subtest are:

**Pretest:**

The subject is in a seated position and the stimuli is stationed 3 feet away (the administrator uses handheld, 14-point targets). The subject is asked to give a number rating of the severity of the following symptoms: headache, dizziness, fogginess, and nausea. An 11-point Likert Scale (Zero=not present to 10=extreme) to determine symptom severity at the beginning and after each sub-test.

**Smooth Pursuit (SP):**

The SP subtest involves a moving target in which the subject is instructed to keep their head still while tracking the target with their eyes in an “H” pattern that covers 3 feet horizontally and 3 feet vertically.

**Horizontal Saccades (H-Sacc)/Vertical Saccades (V-Sacc):**

The H-Sacc and V-Sacc subtest is accomplished by instructing the subject to keep their head still while they use their eyes to look alternately at two horizontally placed targets held 3 feet apart to the beat of 180 beats per minute (BPM) for a total of 10 repetitions (1 repetition is when their eyes fixate at either target and then transfer their eyes to the opposite target). This is repeated with the targets now held in a vertical position.

**Near Point Convergence (NPC):**

For the NPC subtest, the subject is given a handheld target with the instruction to keep their head still and hold the target at an arms-length distance to start. They are then instructed to focus on the target with their eyes while moving the target towards their nose. They are instructed to stop moving the target when they see two targets. At this point, the distance from the target to their nose is measured in centimeters (cm). An additional two trials are repeated, and the subsequent measurements are recorded and averaged.

**Horizontal Vestibular Ocular Reflex (H-VOR)/Vertical Vestibular Ocular Reflex (V-VOR):**

The H-VOR is completed by having the subject focus on a target being held three feet from their seated position. They are instructed to rotate their head laterally from side to side at the rate of 180 bpm while focusing on the target. One complete rotation is when they move their head from one side to the other. The subtest is stopped with they complete 10 rotations. The V-VOR is the same as the H-VOR, but the subject is instructed to nod their head vertically.

**Visual Motion Sensitivity (VMS):**

For the VMS subtest, the subject is instructed to stand. They are given a target in which they are told to hold at arm's length from their head at about the level of their nose. They are instructed to rotate their head, extended arm, and torso from one hip to the other at a rate of 50 bpm for 10 rotations (1 rotation is going from one hip to the other) while focusing on the target. Traditionally, the VOMS is administered using the clinician's fingers on each hand or two tongue depressors with a 14pt. black dot at one end, a metronome application, and a metric linear ruler.

Due to the minimal equipment required and ease of use, it is an ideal tool in any clinical, field, or sideline setting. The administration and interpretation of the VOMS relies heavily upon appropriately trained personnel and subjective symptom reporting. For example, the horizontal saccades component of the VOMS requires the eyes to travel between two fixed positions for 10 rapid repetitions at exactly three feet away from the patient, one and a half feet to the right and the left of the patient's midline. At the successful conclusion of this task, the patient rates their overall headache, dizziness, nausea, and fogginess. These exact locations of the administrator's fingers or implementation device are intended to create a gaze angle of 30°. <sup>15</sup>

The ImpACT Test and the Tandem Gait assessment have a high reliability. The ImpACT Test reliability has been studied extensively.<sup>32-34</sup> One particular longitudinal study used intraclass correlation coefficients (ICC's) of composite scores ranging from 0.47 (95% confidence interval, CI [.38, .54]) to 0.83 (95% CI [.81, .85]). These numbers from a study completed by Brett, et al (2017) were done over a 2-year period in which little change was seen with the five sets of validity criteria.<sup>32</sup> The Tandem Gait had a high interrater reliability for single task (ICC [3,1] = 0.95, 95% CI = 0.90, 0.97, p<0.001) and dual task (ICC [3,1] = 0.98, 95% CI = 0.95, 0.99, p<0.001).<sup>29</sup> The VOMS is the only assessment that involves neuro-vestibular and ocular-motor function. The results other than the NPC are merely subjective and if not monitored or gauged correctly, the results may be skewed upon further bouts of testing among different clinicians. If the distance the eye must travel is not consistent, it will subsequently alter the gaze angle along with potentially changing the overall symptoms reported.<sup>35,15,36</sup> It is important to properly administer the exam to ensure an appropriate diagnosis and management when dealing with an injury as critical as SRC.

Studies have examined the reliability and validity of the VOMS.<sup>37-39</sup> These studies results are based upon the results of the VOMS given repeatedly over time with respect to false positive rates, levels of agreement, and total symptom scores. Few mention the personnel that administer the tests and there is no mention of any variability of symptom reporting or NPC variation among administrators. It would be logical at this point to examine the current clinical manual method and explore ways to standardize the VOMS between administrators to have similar reliability and validity as the ImpACT and the Tandem Gait assessments.

## Chapter 2

### 2.1 Pilot Study: current protocol vs novel prototype

An observation of the current clinical protocol produced a question to the variation of administration of the VOMS between raters. Per protocol, the targets shown to the patient for each of the seven tests must be held a specified distance from the patient and a specified distance apart if there are two targets involved. Through this observation, it was determined that these parameters vary among raters in their perception of the specified distances (3 feet) in which the targets the subject was instructed to focus on varied among different administrators. These altered distances that the eye must travel during smooth pursuits and saccades could influence symptom reporting. To address this issue, a novel prototype was developed (See Figures 3 & 4) to keep the targets at the proper distance during the VOMS. Thus, the purpose of this study was to examine the differences in the VOMS using the traditional method (TRAD) versus using a clinical prototype (PRO) within 72 hours of a sport-related concussion. It is hypothesized that there will be no difference between the TRAD and PRO methods.

### 2.2 Methods

The participants included 22 NCAA Division 1 athletes with a diagnosed SRC. 11 athletes (Female = 4, Male = 7, average age = 19 years) completed the VOMS assessment using the TRAD method and 11 SRC (Female = 4, Male = 7, average age = 22 years) completed the VOMS using the PRO method. For the TRAD method, the raters arm position was not controlled, and each trained rater was asked to administer the exam normally. For the PRO, it consisted of an adjustable, vertical pole affixed to a tripod stand with a leg of the stand that extended to 36 inches. At the upper end of the vertical pole, a second pole was affixed via a pivot clamp. The length of this pole was 36 inches with 2 white 14-point markers affixed to either end. (See Figure 3) One end of this part of the prototype contained a secondary pole that had a slide rule device that can be extended out to the end of the nose when aimed at the face to

allow for the measurement for NPC. (See Figure 4) All SRCs were assessed within 72 hours post-injury. Mann-Whitney U tests assessed the differences between both methods of assessment for total symptom severity changes and NPC distance.



Figure 3: The VOMS prototype target stand. A: a mobile, 36-inch cross piece with white, 14-point targets at each end. This arm is adjustable to a horizontal or vertical position. B: adjustable vertical arm allows for adjustment to the height of the subject's nose. C: measured distance of 36 inches to get the correct distance from the subject's nose to the target stand. D: a sliding measure that extends to the subject's nose for near point convergence measurement. The slide measure has a 30 cm tape on it. An additional sliding target (See Figure 4) is used on the slide measure for the near point convergence test.



Figure 4: The sliding target used to measure near point convergence for the VOMS prototype. The subject's nose is placed on the orange pad at the end of the slide measure. The subject then holds the sliding target. While focusing on the 14-point target, they move it towards their nose. At the point they see two targets, they are instructed to stop, and the measurement is taken. This is repeated three times. A symptom assessment is taken after the 3rd trial.

## 2.3 Results

The results indicate that using the TRAD method (average=12±8 symptoms severity) elicited a significantly greater amount of change score symptom severity when compared to the PRO (average=5±4 symptoms severity;  $p=.016$ , Cohen's  $d=1.1$ ). However, no significant difference was noted on NPC between TRAD (average=8.5±7.1cm) and PRO (average=13.1±9.8cm;  $p=.32$ , Cohen's  $d=0.6$ ).

## 2.4 Discussion

The purpose of this pilot study was to examine the differences in the VOMS with the use of the current clinical method versus using a novel prototype as a means of standardization among raters. The hypothesis here was there would not be any difference between the TRAD and the PRO methods. The results are that the TRAD method had higher symptom scores compared to the PRO method. This could be related to the variability of the distance between the targets by the rater. Another possibility of the higher symptom scores is the distance of the rater from the subject among raters in the TRAD method. As the case with the saccades, the VOMS protocol stipulates the placing the targets 3 feet apart<sup>40</sup> and the subject is tasked with alternating looking at each target with their eyes to the beat of 180 bps. As the subject attempt this, their eyes should be moving 30 degrees from the midline in each direction.<sup>15,41</sup> Variation as where the targets held by the rater would affect this 30 degree range and subsequently alter the symptomology report by the subject. As indicated from the results, there was no significant difference was seen between the TRAD and the PRO methods with NPC. This can be attributed to the fact that the NPC test for both the TRAD and the PRO method involved the subject holding the target as they brought it towards the end of their nose. The only difference was the measurement device was built into the prototype in the PRO method but still produced the same results as the TRAD method. NPC was measured in the TRAD method by the rater holding a ruler up to the subject's nose and target to get this measurement.

## 2.5 Conclusion

The TRAD elicited a greater change in symptom severity, but no changes were observed in NPC compared to the PRO method. A standardized measurement tool may reduce the distance that the eyes travel during the assessment which could elicit fewer overall symptoms on the VOMS and avoid human error due to subjective evaluation and varying target placement among test administrators.

## Chapter 3

### 3.1 Standardization of VOMS administration at baseline.

The validity and reliability of the VOMS compared to other common concussion assessment tools has been explored.<sup>37</sup> The VOMS should be part of a comprehensive battery of assessments when screening for SRC.<sup>37</sup> Prior research has made inferences to the reliability of the VOMS itself to aid in the diagnosis and management of SRC and having an “acceptable” false positive rate.<sup>39</sup> A false positive in the VOMS would result from the subject reporting symptom scores that higher than the established clinical cutoff (TSPCS higher than 2 and NPC distances greater than 5cm) when they do not have a concussion.<sup>39,40</sup> Few studies have examined the variability of symptomology and NPC measurements of the VOMS between administrators.

### 3.2 Man vs Pro vs VR at Baseline

The study included 688 NCAA Division I healthy student-athletes who were a convenience sample that consisted of three groups. The first group was made up of 111 (female=47, male=64, average age=21 years) who completed the manual VOMS (MAN), 365 healthy young adults (female=157, male=211, average age=21 years) who completed the VOMS administered with a novel prototype (PRO), and 212 healthy young adults (female=78, male=134, average age=20 years) who completed the VOMS administered with the virtual reality system (VR). All participants were free of existing or prior diagnosed neurological injury, (including SRC), attention deficit hyperactivity disorder, learning disabilities, non-corrected vision impairment, motion sickness (within the past 6-months), and any lower extremity injury that can impair the ability to stand upright as determined by self-report. All participants were individual observations collected at pre-participation physicals. All participants provided written informed consent to the study procedure, which was approved by the University’s Institutional Review Board, prior to enrollment into the study. The VOMS was administered at a western American university campus.

### 3.3 Methods

The MAN mode was used according to the current clinical protocol as previously described. The PRO was also used in this period, again, according to the protocol described earlier in this text. The VOMS protocol administered in VR was conducted with an HTC Vive Pro Eye Head Mounted Display (HMD) with a diagonal focus of vision (FOV) of 110-degree, a refresh rate of 90Hz, a combined resolution of 2880×1600 pixels, six degrees of freedom (DoF) for position and orientation tracking, and adjustable interpupillary (IPD) and focal distances. Before beginning the exam, the participant's nose length was measured and recorded to account for HMD being mounted onto the head. The headset was powered by an Acer Predator gaming laptop with a 7th Generation Intel Core i7 Quad-Core processor with 16GB of memory and NVIDIA GeForce GTX 1070 graphics card running Windows 10. The HTC VIVE 2.0 Hand Controller was used to receive input from participants to start the stimuli moving towards them and stop the stimuli when ocular convergence was lost (image splitting into two objects) during the NPC test and to re-create the target object during the VMS component of the VOMS. The Unity3D engine version 2019.1.6 and the Unity3D VR plugin - SteamVR - version 1.7 was used to develop the VOMS stimuli in which the VOMS protocol was simulated in a VR environment.

### 3.4 Data Analysis

The methods of evaluating VOMS symptoms have been published extensively<sup>35,42,43,15,31</sup> and in this study the total symptom provocation<sup>31</sup> was calculated by summing the total number of increased symptoms from baseline (pre-test) for each VOMS item. In addition, each VOMS subtest total reported symptoms were individually evaluated. All symptom data were taken verbally from the subject before

each device administration, and after each VOMS sub-test while NPC was collected using the various measurement tools and further analyzed.

### 3.5 Statistical Analysis

Before any analyses, the data were examined for normalcy and influential skewness. All the VOMS variables were not normally distributed, thus nonparametric assessments were applied. Thirty Mann-Whitney U tests were conducted to compare baseline symptoms, change score, and each subtest total symptoms of the VOMS (SP, H\_Saccades, V\_Saccades, NPC change, H\_VOR, V\_VOR, VMS, and NPC average) by device (MAN, PRO, VR). Furthermore, Mann-Whitney U tests were computed to examine sex differences to compare baseline symptoms, change score, and each subtest of the VOMS by device. Cohen's d effect sizes were calculated as small ( $d=0.20$  to  $0.49$ ), medium ( $d=0.50$  to  $0.79$ ) and large ( $d\geq 0.80$ ).<sup>44,45</sup> All tests were conducted using Statistical Package for the Social Sciences (SPSS, IBM Inc. Armonk, NY, 2020, v 28.0.0.0). An alpha level of 0.05 was set a priori. No alpha level corrections were applied as all the statistical analyses were planned.

### 3.6 Results

#### 3.6.1 At Baseline with Symptom Provocation

MAN (average= $0.446\pm 1.165$ ) had significantly more symptoms than the PRO (average= $0.163\pm 0.644$ ;  $p=0.006$ , Cohen's  $d=0.31$ ) and the VR (average= $0.161\pm 0.933$ ;  $p=0.001$ , Cohen's  $d=0.27$ ), with no significant difference between the PRO and VR ( $p=0.317$ , Cohen's  $d=0.01$ ). Overall change score symptoms were significantly greater using the MAN (average= $0.396\pm 1.081$ ) when compared to the PRO (average= $0.128\pm 0.427$ ;  $p=0.005$ , Cohen's  $d=0.33$ ) and the VR (average= $0.170\pm 0.903$ ;  $p<0.001$ , Cohen's  $d=0.31$ ). This trend continued for each subtest of total symptoms except no significant differences were noted between the PRO and VR for any symptom

provocation (see Appendix Table 1). The number of false positives for the overall change score ( $\geq 2$  change score) and subtest total symptoms ( $\geq 2$ ) were consistently highest in the MAN (average=7.6%, range=4.5 to 9%) followed by VR (average=2.9%, range=1.4 to 3.3%) and the lowest with the PRO (average=1.5%, range=0.3 to 1.9%) (see Appendix: Table 1).

### 3.6.2 At Baseline with Near Point Convergence

The results of the NPC average measurement suggest that the VR produced (average= $2.99 \pm 0.684$ cm) significantly greater NPC distance than MAN (average= $2.91 \pm 3.35$ cm  $p < 0.001$ , Cohen's  $d = 0.03$ ) and PRO (average= $2.21 \pm 1.81$ cm;  $p < 0.001$ , Cohen's  $d = 0.57$ ) conditions. The MAN and PRO were not significantly different ( $p = 0.975$ , Cohen's  $d = 0.26$ ). The number of false positives ( $> 5$ cm) were 20.7% during the MAN, 7.9% during the PRO, and 0% during the VR (see Appendix: Table 1).

### 3.7 Conclusion

The administration of the VOMS with a VR platform may be a tool that can improve the collection of symptomology and NPC data without excessive symptom provocation. While the VR had higher NPC, the scores were still below the clinically acceptable threshold of  $< 10.0$ cm. The differences in the NPC measurements should be noted but may be a result of variability in the sample and the difference in measurement (ocular mid-point vs bridge of nose). The asymptomatic VR testing is aimed at determining if VR would be a viable tool for assessment. The novel concept of using VR would require the development and distribution of the combination of software and hardware. Thus, it would take time to make this available to most of the practitioner population. A solution would be to develop a phone app that works with a simple, low-cost VR HMD. Advances in technology in this area will enable healthcare providers to share important diagnostic data in the assessment and management of SRC. Additional research on the methods of secure data transfer among healthcare providers (i.e., athletic trainers and sports medicine physicians) needs exploration for the implementation of the VR platform

and VOMS administration. Its application to the symptomatic population is the next step in this ongoing study.

## Chapter 4

### 4.1 Standardization of SRC assessment at baseline and post-injury

The current clinical VOMS protocol manual method is the most used to date. The interpretation of the target distances creates variability between raters. There is some research that used a modified version of VOMS along with the Sport Concussion Assessment Tool3 (SCAT)<sup>46</sup> as an expedited means of assessment during sport competition. The study by Ferris, et al, (2022) recommends using only four of the 7 tests within the VOMS due to the oculomotor and vestibular redundancies. This streamlined version of the VOMS would only include smooth pursuits, horizontal saccades, horizontal VOR, and VMS.<sup>46</sup> However, this modification still involves a clinician holding targets at their estimated distances.

As previously mentioned, advancements in technology enable the use of mobile phone apps, VR and Augmented Reality (AR) environments, systems that involve a form of vestibular assessment, or combinations of the afore mention platforms comprise the assortment of assessment tools that are being made available to clinicians.<sup>47</sup> Some platforms infer that a diagnosis can be made through visual eye tracking measurements and/or pupil response. A review of the technology that involves eye tracking with SRC are specific to smooth pursuits and/or saccadic eye movement as a measurement for concussion diagnosis and management.<sup>48</sup> Each of these platforms varied in the metric that was being measured as well as sampling frequencies. A platform that has recently been cleared by the Food and Drug Administration (FDA) uses a combination of horizontal and vertical saccades as well as smooth pursuits as an aid for diagnosis of a SRC. The platform called “EyeBOX” (Oculogica, New Richmond, WI) uses an algorithm that compares a subject’s eye tracking recording from a stimuli created within their propriety equipment. From this algorithm, a report is generated that indicates a deficit with eye

movements. This is a means of standardization, but this requires their equipment to be on hand for the clinician. Of the technology available today, all require additional expensive equipment and a medical office visit.<sup>16</sup> This VR platform of the VOMS can be modified to work as a phone app and use a simple, inexpensive VR headset to administer the test, record symptoms and NPC, and possibly collect eye movement data. This VR-VOMS system can be designed to send the data to a secure cloud drive that the physician or qualified medical professional can review the data to help make a timely and efficient diagnosis.

#### 4.2 VOMS Standardization: a comparison of a novel prototype and a VR stimuli:

The next step in this progression was to compare the total symptom provocation change score (TSPCS), NPC, and each individual sub-test from the VOMS protocol between the novel prototype and the VR system at baseline (BAS) and post-injury (PI) assessment. The hypothesis is that the novel prototype and the VR application will be no different with TPSPC and NPC scores from baseline to post-injury.

#### 4.3 Methods:

##### **Use of a novel prototype (PRO):**

394 Division I athletes (Female=154, Male=211; avg. age=20.8±1.4 years) completed the VOMS baseline (BAS) concussion assessment. 29 Division I athletes (Female=18, Male=11; avg. age=20.6±1.4 years) completed the VOMS within 72 hours of a diagnosed with a concussion by the university team physician per university concussion management protocol. The novel prototype as described in Section 2.2 was used to administer the VOMS. Symptom ratings of headache, nausea, dizziness, and foginess were recorded at pre-test and subsequently after every sub-test.

**Use of a virtual reality stimuli for VOMS administration (VR):**

511 Division I athletes (Female=223, Male=288; avg. age=20.9±6.6 years) completed the VOMS baseline (BAS) concussion assessment. 22 Division I athletes (Female=10, Male=12; avg. age=21.1±1.3 years) completed the VOMS in VR within 72 hours of a diagnosed with a concussion by the university team physician per university concussion management protocol. The VOMS was administered via the VR stimuli as described in chapter 3. All participants had prior written informed consent specific to the study procedure per the approved University's Institutional Review Board as indicated prior to enrollment into the study. The participants were also screened for any prior history of motion sickness for prior use of an HMD VR system. Both PRO and VR stimuli were administered at a western US university.

Baseline VOMS for both stimuli was administered as part of the pre-participation athletic healthcare screening. The Post-injury VOMS for both stimuli was administered within 72 hours of the suspected or diagnosed SRC. Each participant in baseline and/or post-injury reported subjective symptoms using an 11-point Likert scale (0- symptom not present to 10-stop test, symptom so severe that subject needs immediate medical assistance). The symptoms being rated were headache, dizziness, nausea, and fogginess. This was completed before the test began (pre-test) and following each of the seven tests (smooth pursuit (SP), horizontal/vertical saccades (H-Sacc/V-Sacc), near point convergence (NPC), horizontal/vertical vestibular ocular reflex (H-VOR/V-VOR), and visual motion sensitivity (VMS)) of the VOMS.

#### 4.4 Data Analysis

Average symptom score for each stimuli and sub-test was calculated along with the respective standard deviation. TSPCS was calculated by adding the total number of provoked increased symptoms

from pre-test to completion of all seven tests. The TPSCS were then averaged, a standard deviation was calculated as well. The three trials of NPC distances were averaged.

#### 4.5 Statistical Analysis

The data was examined for normalcy and any skewness, it was determined that the VOMS variables were not normally distributed. Thus, a series of Mann-Whitney U tests were completed using Statistical Package for the Social Sciences (SPSS, IBM Inc. Armonk, NY, 2020, v 28.0.0.0) to compare the change score, pre-test symptoms, each VOMS subtest symptoms, and VOMS NPC measurement for the following comparisons of the PRO and the VR conditions of the VOMS:

*PRO Baseline vs VR Baseline (see Appendix, Table 2)*  
*PRO Baseline vs PRO post-injury (see Appendix, Table 3)*  
*VR Baseline vs VR post-injury (see Appendix, Table 4)*  
*PRO post-injury vs VR post-injury (see Appendix, Table 5)*

p-values along with Cohen's d effect sizes were calculated for symptoms scores and NPC averages for each comparison above and associated symptom score sub-tests within each condition. The Alpha level was set at 0.05 a priori.

#### 4.6 Results:

Using clinical cutoff scores for TPSCS ( $\geq 2$ )<sup>47</sup> and NPC ( $\geq 5\text{cm}$ )<sup>48</sup>, comparisons could be made between the conditions listed in Section 4.5. The results of the comparisons are that at baseline, the PRO was statistically significant different with change score ( $p=.022$ ), pre-test symptoms ( $p=.004$ ), NPC distance ( $p<.001$ ), smooth pursuits ( $p<.001$ ), horizontal saccades ( $p<.001$ ), and vertical saccades ( $p=.013$ ) when compared to the VR. No other significant differences were observed with the remaining sub-tests. See Appendix Table 2 for all descriptive and statistical data.

There was a significant difference with all sub-tests ( $p < .001$ ) except for smooth pursuit ( $p = .092$ ) for PRO baseline to PRO SRC post-injury. See Appendix Table 3 for all descriptive and statistical data for PRO baseline to PRO SRC post-injury comparisons.

There was a significant difference change score, pre-test symptoms, and all subtests ( $p < .001$ ) for VR baseline to VR SRC post-injury except NPC measurement ( $p = .657$ ). See Appendix Table 4 for all descriptive and statistical data for VR baseline to VR SRC post-injury comparisons.

Lastly, there was no significant difference between PRO and VR for SRC post-injury across the change score, pre-test symptoms, any subtest symptoms, and NPC measurement. See Appendix Table 5 for all descriptive and statistical data for PRO vs. VR SRC post-injury comparisons.

#### 4.7 Conclusion

These data provide proof of concept that the VR system can be administered at BAS and PI. In a study done by Tomczyk, et al. (2021), athletes were assessed within 72 hours of SRC using the current manual clinical protocol. They found that most of their sample had total symptom scores greater than the clinical cutoff ( $\geq 2$ ) for all TSPCS. This study did not assess NPC measurement, rather only focused on the symptom score of NPC. The PI symptom scores for NPC were less than the clinical cutoff scores.<sup>46</sup> This could make a case for the VR results as there was not a significant change for NPC measurement from BAS to PI. The results specific to the VR TSPCS are consistent with the Tomczyk study with respect to TSPCS.<sup>49</sup>

The diagnosis and management of SRC, the assessments should be consistent among clinicians.<sup>4,39,50</sup> VOMS with a VR stimuli provides a means to standardize the test among clinicians.<sup>51,52</sup> Overall, this study provides a case that symptom reporting through VOMS administration is consistent with a novel prototype and a VR stimuli following SRC. There were some subtle differences in NPC distance measurement between the PRO and VR stimuli, but the NPC may not be a sole indicator of SRC

with post-injury assessment. Further study of this aspect of the VOMS is warranted. The comparison data of the PRO and VR stimuli provide proof of concept that the VR system can be administered at PI without additional symptoms and may be a valid form of standardization of the VOMS. Further evaluation of the VR stimuli to administer the VOMS would involve a comparison in a similar fashion to the current clinical method of administering the VOMS.

## Chapter 5

### 5.1 The Manual Method vs the Virtual Reality Method: Baseline to Post-Injury

MAN vs VR with random administration:

Throughout this project, it has been demonstrated that 1) there is a need to standardize the VOMS with some type of tool to reduce false positive rates, 2) the VOMS can be safely administered in virtual reality in a healthy population compared to other modalities, 3) the VOMS in VR appears to not provoke the symptoms of those with a concussion outside normal reference values. However, a need exists to evaluate if the VOMS in VR exacerbates the symptoms relative to the manual method for those with a concussion.

Previous examination of the VOMS has been explored by comparing the test-retest reliability to other clinical SRC tools such as the Balance Error Scoring System (BESS) or the King Devick (K-D) test.<sup>37</sup> There has been some research examining the use of VR for concussion assessment. One study looked at the use of VR for SRC assessment with horse jockeys.

The assessment tool labeled “CONVERT” used eye tracking to assess visual processing speed in addition to manual reaction time while collecting decision-based data to make assessments on central nervous system performance after a SRC. The CONVERT assessment uses a VR experience of a horserace as the stimuli (see Figure 5). This study through the development of CONVERT had a high test-retest reliability compared to other test batteries.<sup>53</sup>

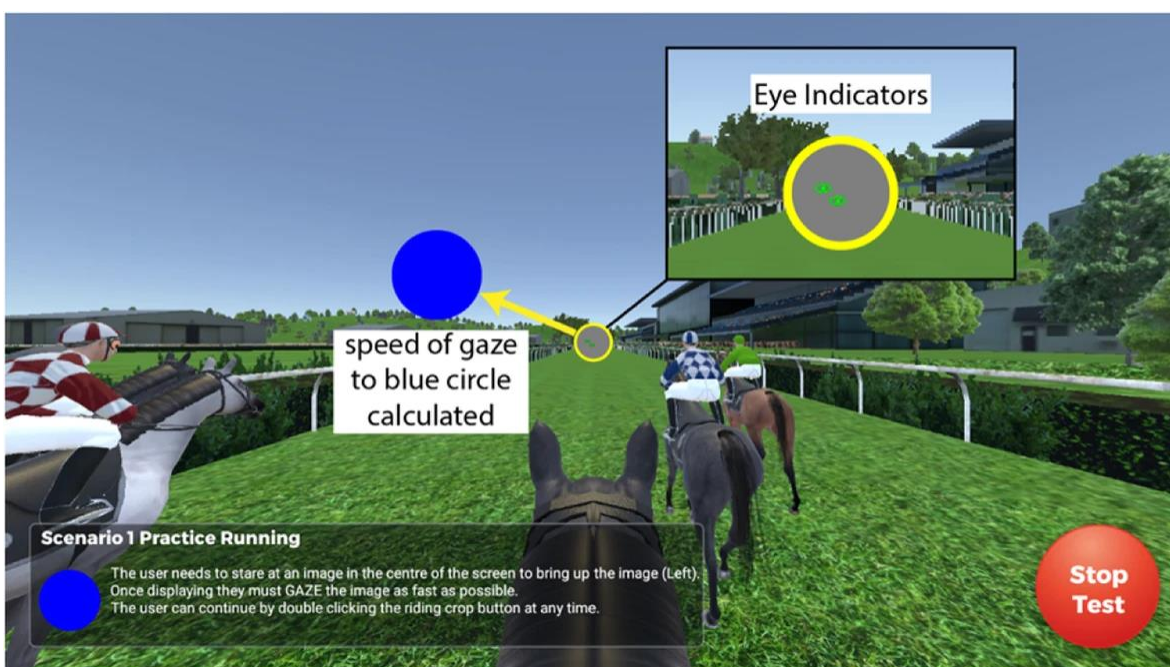


Figure 5: an example of the CONVERT stimuli. A head mounted display unit is used along with a controller to measure responses as well as collect saccadic eye movements and speed of gaze during the simulated horse race.<sup>48</sup>

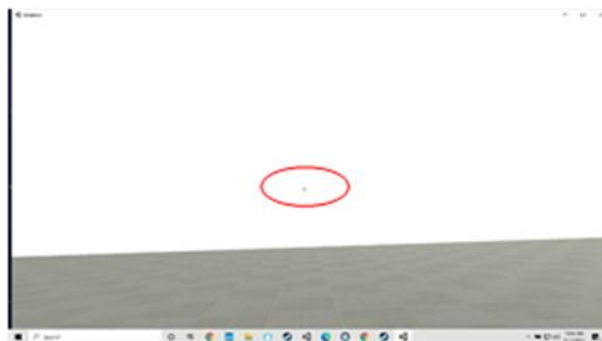
Other studies have examined test order<sup>54</sup> as well as minimal detectable change and false positive rates.<sup>35</sup> To this date, minimal research has been conducted with respect to increasing accuracy and minimizing false-positive rates among administrators. One recent study examined the VR-VOMS stimuli with respect to symptom provocation and eye tracking was explored looking at the use of several machine learning strategies for SRC detection. This on-going study has only looked at the smooth pursuit (SP) and visual motion sensitivity (VMS). So far this study using machine learning models has shown a 99.9% true positive rate with respect to symptom provocation when compared to the current clinical

manual method data.<sup>51</sup> Before any additional research is conducted using eye tracking, it is important to verify that the VOMS in VR does not provoke more symptoms than the manual method for those with a concussion.

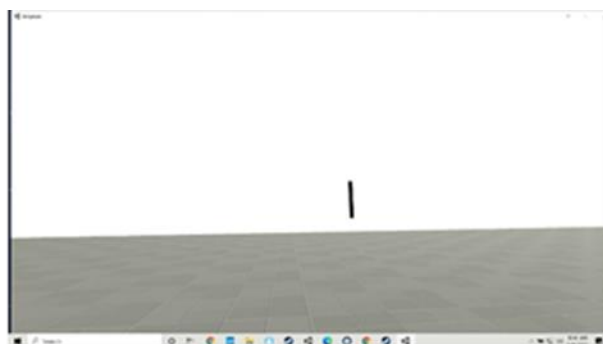
## 5.2 Accounting for VR Sickness Potential

There is the potential for the subject to experience VR sickness with the VR stimuli. This is especially true of subjects that have not experienced a VR environment. Since the VOMS challenges ocular-motor and vestibular function, VR environments can create a sense of disorientation which has been identified as visually induced motion sickness (VIMS).<sup>55</sup> The presence of SRC symptoms can exacerbate VIMS.<sup>56</sup> In this situation, it would be difficult to determine if the symptoms being reported are related to the SRC or from VR sickness. It has been demonstrated that through repeated exposure to the VR environment, the subject will eventually adapt<sup>57</sup> but the VR stimuli is rather short (around 5-7 minutes) and would not provide enough time for adaptation.<sup>58</sup> This would include symptoms related tovection (visually induced apparent motion), VIMS, or simulator sickness in which the common symptoms are also symptoms that are similar to what the VOMS is designed to elicit (headache, dizziness, and nausea).<sup>59</sup> Prior studies have shown that the potential for symptoms related to the VR stimuli can be reduced with the use of a field of view (FOV) restrictor within the VR stimuli.<sup>60,61</sup> Another prior systematic review and meta-analysis indicated that a VR stimulus that had a highly detailed gaming environment and/or involved a 360-degree panoramic video had the highest reported symptoms related to VR sickness whereas those stimuli that had a focused scenic environment or minimal, simple content had the lowest reported VR sickness symptoms according to the total scores from the Simulator Sickness Questionnaire (SSQ) that were averaged across all of the studies involved in the systematic review.<sup>61</sup>

To minimize the potential for VR sickness, vection, or VIMS, the VOMS VR stimuli was developed with a simple, monochromatic environment. The background is comprised of simple hues of gray and the targets are black dots for the first six tests and a black bar for the VMS (See Figures 6 and 7).



**Figure 6:** This is the screen shot of the Vestibular Ocular Reflex (VOR) test within the VOMS stimuli. It is used for the horizontal and vertical VOR in which the subject rotates their head side to side (horizontal) or up and down (vertical) while focusing on the dot at a rate of 180 beats per minute.



**Figure 7:** This screen shot shows the setting for the Visual Motion Sensitivity test within the VOMS. The subject focuses on the black bar while rotating their head and trunk side to side at the rate of 50 beats per minute.

Additionally, the subjects are screened before administration of the VR stimuli. They are asked if they have ever used a VR system. If they have, they are then asked what their reactions were while using the VR HMD and if they have prior issues with motion sickness. Their answer was recorded in the database. Such subjects who report sensitivity to the VR environment or suffer from motion sickness were given the chance to complete the assessment with the VR stimuli. Our previous and current data suggest that most of the subjects who have indicated that they are sensitive to motion sickness have been able to complete the VR-VOMS without having to exit the testing due to increased symptoms because of the stimuli. (See Motion Sickness Tables 1 and 2 in the Results Section)

### 5.3 Random administration

Randomization with controlled trials is a common practice as it is accepted as the best method for evaluation of the efficacy in comparing two methods of test administration. Through this process, mitigation of varying forms of bias (accidental or selection) is addressed.<sup>62</sup> There are several methods of

randomizing. Simple randomization minimized bias through the elimination of predictability. Block randomization involves two treatment groups which can be repeatedly organized in a randomized block design which does not eliminate selection bias. Restricted randomization for an unbalanced allocation is used in the case where there is a high dropout rate or the sample size requires the addition of more subject.<sup>62</sup> For this study, a simple randomization tool using a pair of dice is used to select either the manual mode (MAN) or virtual reality mode (VR) will be used for baseline assessment. The same protocol will be used in the event the assessment is for a post-injury test. This would be the appropriate method of randomization for this part of the project in that allow for group allocation while maintaining randomness with respect to the mode of the VOMS stimuli. As mentioned above, this method minimizes bias by eliminating predictability.<sup>62</sup>

## 5.4 Methods

### **Collegiate Sample Group: 2023-24 Academic Year**

530 Division I athletes (Female=244, Male=286; avg. age=20.7±4.9 years) completed the VOMS baseline (BAS) concussion assessment as part of the yearly pre-participation physical assessment. 35 Division I athletes (Female=18, Male=17; avg. age=19.9±1.4 years) completed the VOMS within 72 hours of being diagnosed with a concussion by the university team physician per university concussion management protocol. Baseline testing inclusion criteria again, consisted of healthy subjects without recent (within the prior 6 months) diagnosed SRC or learning disabilities, uncorrected vision impairment, learning disabilities, or attention deficit hyperactivity disorder.

This group was further divided between the different methods that consisted of MAN baseline, VR baseline, MAN Post-Injury, and VR Post-Injury and the subject's response to a question of a prior history of motion sickness (Hx of Mo Sick). The individual demographics of the sub-divided groups consisted of the following; MAN baseline that confirmed prior Hx of Mo Sick ("Yes") (n=97, female=77, male=20, avg age=19.7±1.3); MAN baseline without Hx of Mo Sickness ("No") (n=263, female=111,

male=152, avg age=20.6±2); VR baseline “Yes” (n=25, female=16, male=9, avg age=20.5±2.5); VR baseline “No” (n=201, female=90, male=111, avg age=21.1±7.5); MAN post-injury “Yes” (n=6, female=5, male=1, avg age=19.3±1); MAN post-injury “No” (n=18, female=6, male=12, avg age=20.4±1.6); VR post-injury “Yes” (n=3, female=3, male=0, avg age=18.8±0.4); VR post-injury “No” (n=8, female=4, male=4, avg age=19.7±1).

### **Adolescent Sample Group: 2023-24 Academic Year**

36 Adolescent athletes (Female=11, Male=17; avg. age=15.5±1.4 years) completed the VOMS at various time points post-injury. Assessment outside the ideal 72-hour time was due to the availability of a medical professional for SRC evaluation and access to the lab for testing. The average time for lab VOMS assessment post-injury was 14.8±13.8 days. Baseline data for these subjects was not assessed using the same criteria used in the Neuromechanics Lab so there was no basis for a baseline to post-injury comparison. Only post-injury data was analyzed for this group.

The subjects for both groups were verbally screened for the inclusion criteria and for any lower extremity disability that would prevent them from standing which is required for the VMS test within the VOMS. The subjects were verbally screened for motion sickness or prior VR experiences. Motion sickness in subjects being assessed for SRC is a component that should be addressed. Studies have shown that those with motion sickness reported increased symptomology scores with the VOMS at baseline<sup>39</sup> as well as increased vestibular dysfunction<sup>63</sup> with the current MAN method. Research in VR’s propensity for motion sickness has been historically screened with the Motion Sickness Susceptibility Questionnaire-Short Form (MSSQ-S) with many age groups on patient populations with vestibular issues as well as those with concussions.<sup>64</sup> Due to the time it takes for the subjects to complete the full battery of concussion assessment in the laboratory, it was determined that it was best to use a yes or no response to the following question: “Do you have prior history of motion sickness?”

## Data Collection

The determination of which method of the VOMS (VR or MAN) would be used was conducted by a roll of a pair of dice. An even number on the dice indicates the VR method will be used on that subject. An odd number indicates the MAN method will be used. The data consisted of the subject responding to the rating (via a 11-point Likert scale) of symptoms to include headache, dizziness, nausea, and fogginess. Those are recorded before and after each test of the VOMS whether it is administered through the MAN method or the VR method. NPC for the MAN method will be physically measured by the administrator and recorded for each of the three trials which were averaged. NPC was measured within the VR-VOMS stimuli. Through the VR stimuli the convergence distance is measured through the eye tracking component in the HMD. They are then manually transferred from the VR NPC measurements data table into the external VOMS database and averaged. The VR HMD unit measures NPC from the ocular mid-point rather than the end of the nose in the MAN method. To account for this the length of the subject's nose is physically measured in centimeters (cm) and recorded by the administrator in the database. This data is part of the direct comparison of the MAN method to the VR method such that it can be seen if the distance of convergence is similar between the two methods in both the baseline and post-injury conditions.

## Data Analysis:

Symptom data within each subtest (baseline, SP, H\_Sacc, V\_Sacc, NPC, H\_VOR, V\_VOR, and VMS) was analyzed for skewness and kurtosis. Since skewness is a measure of symmetry in a sample and kurtosis measures the weight of the tails in distribution, the analysis indicates the VOMS data is non-symmetrical. A high kurtosis indicates heavy tails in the distribution which indicate many outliers. Individual subtests were averaged and measured for dispersion (standard deviation). Additionally, averages and standard deviations were calculated for baseline total symptom provocation change score (TSPCS), baseline NPC average, post-injury change score and NPC average, symptom-free (SF) TSPC and

NPC average. This analysis was completed for the groups identified in the Statistical Analysis section below. Keeping with protocol used in Ch. 4, Alpha level was set at 0.05 a priori and Cohen's d effect sizes were calculated to aid in determining clinical utility.

### **Statistical Analysis**

Again, the VOMS variables are not normally distributed. Nonparametric tests were again completed using Statistical Package for the Social Sciences (SPSS, IBM Inc. Armonk, NY, 2020, v 28.0.0.0). Mann-Whitney U tests were used to make the following comparisons of the PRO and the VR conditions of the VOMS:

#### For the Collegiate Group:

*Baseline MAN vs Baseline VR (see Appendix, Table 6)*

*Baseline MAN vs Post-Injury MAN (see Appendix, Table 7)*

*Baseline VR vs Post-Injury VR (see Appendix, Table 8)*

*Post-Injury MAN vs Post-Injury VR (see Appendix, Table 9)*

*Baseline No Hx of Motion Sickness MAN vs Hx of Motion Sickness MAN (see Appendix, Table 10)*

*Baseline No Hx of Motion Sickness VR vs Hx of Motion Sickness VR (see Appendix, Table 11)*

*Post-Injury No Hx of Motion Sickness MAN vs Hx of Motion Sickness MAN (see Appendix, Table 12)*

*Post-Injury No Hx of Motion Sickness VR vs Hx of Motion Sickness VR (see Appendix, Table 13)*

#### For the Adolescent Group:

*Post-Injury MAN vs Post-Injury VR (see Appendix, Table 14)*

## 5.5 Results

Based on our prior research, the MAN method has shown increased symptom scores among each sub-test within the VOMS and TSPCS. Additionally variable NPC measurements are apparent.<sup>15,38,39</sup> This research has also indicated that the VR method has also shown increased symptom scores and NPC measurements. Keeping with the same clinical cutoff scores used in section 4.6 (TSPCS  $\geq 2$ )<sup>47</sup> and NPC  $\geq$

5cm)<sup>48</sup>), comparisons were made within the conditions set forth with the Collegiate Group and the Adolescent Group.

### 5.5.1 Collegiate Group

The results at baseline indicate the MAN had a greater change score and pre-test symptoms compared to VR ( $p < .001$ ). However, the MAN had a lower NPC measurement ( $p < .001$ ) when compared to VR (see Table 6). There were no significant differences between VR and MAN with all sub-test symptom scores except for H-VOR ( $p = 0.01$ ). See Appendix Table 6 for all descriptive and statistical data.

There was a significant increase with symptom change score, pre-test, and all subtests including NPC measurement upon comparing MAN baseline to MAN post-injury ( $p < .001$ ). See Appendix Table 7 for all descriptive and statistical data for MAN baseline to MAN SRC post-injury comparisons.

The VR baseline comparison to the VR post-injury also demonstrated significantly increased symptom scores with pre-test, change score, and all sub-tests symptoms ( $p < .001$ ). NPC measurement increased as well from baseline ( $3.2 \pm 1.29$ cm) to post-injury ( $5.73 \pm 5.71$ cm) ( $p = .22$ ). See Appendix Table 8 for all descriptive and statistical data for VR baseline to VR SRC post-injury comparisons.

Upon comparing MAN post-injury to VR post-injury, there were no significant differences with TSPCS, NPC, and all sub-tests. NPC measurement averages were higher for MAN ( $8.19 \pm 8.2$ cm) than VR ( $5.73 \pm 5.71$ cm). See Appendix Table 9 for all descriptive and statistical data for VR baseline to VR SRC post-injury comparisons.

### 5.5.2 Adolescent Group

Post-injury results for this group also demonstrated no significant difference between MAN and VR with TSPCS, all sub-tests, and NPC measurements. See Table 14 for all descriptive and statistical data for VR baseline to VR SRC post-injury comparisons.

### 5.5.3 Self-reported History of Motion Sickness Data Results

Comparison data for the collegiate group was divided dependent on the response of the subject from the question they answered regarding a prior history of motion sickness (Hx of Mo Sick). This data set was broken into two groups that consisted of those who answered “Yes” to the Hx of Mo Sick question and those who answered “No.”

The MAN baseline group who reported a Hx of Mo Sick (Yes) comparison to those who did not have a Hx of Mo Sick (No) had a significant difference with TSPCS ( $p=.001$ ) V-VOR ( $p=.009$ ), and VMS ( $p=.032$ ). The remaining sub-tests were not significantly different with p-values above the 0.05 mark. See Appendix Table 10 for all descriptive and statistical data for MAN baseline Hx of Mo Sick=No to MAN baseline Hx of Mo Sick=Yes SRC comparisons.

The VR baseline group for those that reported “Yes” compared to the subjects in this group that reported “No” there was not a significant difference between the two groups with TSPCS ( $p=.81$ ) and NPC distance ( $p=.26$ ). See Appendix Table 11 for all descriptive and statistical data for VR baseline Hx of Mo Sick=No to VR baseline Hx of Mo Sick=Yes SRC comparisons.

MAN post-injury statistical analysis showed no significant differences between the “Yes” group and the “No” group for Hx of Mo Sick with TCPSC ( $p=.763$ ), NPC distances ( $p=.062$ ), and all sub-tests. See Appendix Table 12 for all descriptive and statistical data for MAN post-injury Hx of Mo Sick=No to MAN baseline Hx of Mo Sick=Yes SRC comparisons.

With the VR post-injury data, there a was no significant difference between the “Yes” group and the “No” group with respect to TSPCS ( $p=.682$ ) and NPC distances ( $p=.102$ ) as well as all sub-tests for Hx of Mo Sick. See Appendix Table 13 for all descriptive and statistical data for VR post-injury Hx of Mo Sick=No to VR post-injury Hx of Mo Sick=Yes SRC comparisons.

For the Adolescent Data set, there was only one subject who indicated a Hx of Mo Sick out of the sample that consisted of ages of 11-17 (sample total=46). That one individual completed the VOMS via the manual method. There was one subject who did not indicate Hx of Mo Sick that had to switch from the VR to MAN due to brightness sensitivity to the VR stimuli. This subject presented with a pre-test symptom score of 13. Another subject had to stop at H-VOR with the MAN method due to dizziness. This subject had a TSPCS of 13 up to that point. All the subjects who were administered the VOMS in VR (n=10) were able to complete the test (see Appendix Table 14 for baseline to post-injury SRC comparisons).

In addition to the statistical analysis of those who indicated a history of motion sickness versus those who did not, TSPCS and NPC distance averages were calculated for each method at baseline and post-injury (see Motion Sickness Table 1). The percentages of those who completed the VOMS who indicated a history of motion sickness at baseline and post-injury are found in Motion Sickness Table 2.

**Motion Sickness Table 1: The type of VOMS stimuli is listed here separated out by the indication of a prior history of motion sickness. The total symptom provocation change score (TSPCS) averages are listed as well as the near point convergence (NPC) measurement averages per stimuli condition. (2023-24 Collegiate Data)**

Variable	Condition	Motion Sickness	TSPCS (AVG)	NPC (AVG)cm
MAN	Baseline	Y	1.66	3.07
MAN	Baseline	N	0.39	2.87
VR	Baseline	Y	0.6	2.9
VR	Baseline	N	0.13	3.18
MAN	Post-Injury	Y	13.2	13.3
MAN	Post-Injury	N	13.5	6.4
VR	Post-Injury	Y	10.3	8.9
VR	Post-Injury	N	7.9	4.5

**Motion Sickness Table 2: The total population, baseline manual (MAN), baseline virtual reality (VR), post-injury (PI) MAN, and PI VR are displayed along with the percentage of those subjects that confirmed they had a prior history of motion sickness and the percentage of those who completed the stimuli even though they had a prior history of motion sickness. (2023-24 Collegiate Data)**

Population of Stimuli	% with Motion Sickness	% Completion of stimuli
Total: n=530	23% (122/530)	100
Baseline MAN: n=301	32% (97/301)	100
Baseline VR: n=229	11% (25/229)	100
PI MAN: n=24	25% (6/24)	100
PI VR: n=11	27% (3/11)	100

## 5.6 Discussion

The purpose of this third experiment was to compare the current clinical manual method of administering the VOMS to a VR delivery of the same VOMS protocol through randomized trials. The hypothesis is that there would be no difference in TSPCS and NPC distance measurement between the two methods. Reviewing the collegiate data, the hypothesis is correct as there was no significant difference between the symptom scores at baseline between MAN and VR. This consistent with the prior studies using both MAN and PRO comparisons.<sup>52</sup> The two methods also are not different with post-injury data. As stated earlier, the VOMS is designed to illicit symptoms via the seven subtests.<sup>40</sup> It appears that both methods do just that, however, a comparison of the MAN to the VR method has shown to have increased symptom scores at baseline and TPSCS. This could be attributed to the variability of how the administrator holds the targets or the distance that they are away from the subject during the test. As the method of collecting NPC measurement varied between the two methods (VR was measured at ocular mid-point, MAN was measured from the tip of the nose), it was interesting to see that there was a significant difference between MAN and VR at baseline ( $p < .001$ ). This may be due to the number of subjects that did not experience any loss of convergence with the MAN or the number of subjects that had a measurement from ocular mid-point that went beyond the tip of their nose. As expected, there was a significant difference between MAN baseline to post-injury as prior

research suggests ocular convergence can be affected with SRC.<sup>65</sup> What was unexpected was there was no significant difference between VR baseline to post-injury ( $p=.22$ ) and the MAN post-injury compared to the VR post-injury ( $p=.109$ ). There were some issues with the VR NPC test not initializing with some subjects and NPC was performed manually with that portion of the test. Another issue with the VR NPC tests was the subject not understanding the instructions as to when they should pull the trigger on the joystick when they saw the one target become two or the target became blurry.

Recent research suggests that athletes with a prior history of sensitivity to physical motion may be more symptomatic and have prolonged vestibular dysfunction.<sup>63</sup> Our subjects with a self-reported history of motion sickness and without were able to complete the VOMS in both MAN and VR. Although there was some difference with the MAN baseline data for those with a Hx of Mo Sick, the data suggests that prior experiences with motion sickness may not be a factor in the SRC VOMS assessment. However, it should be part of the pre-test screen as some sub-tests like the H-VOR, V-VOR, and VMS sub-test challenge the vestibular system.<sup>64</sup> The majority of the reported motion sickness triggers were car or boat related. These triggers of motion sickness can be related to the mismatch of sensory input to expectations of the sensory input which disrupt the vestibular and oculo-motor systems.<sup>57,66</sup> Thus, it is reasonable that these subjects may have issues with certain sub-tests of the VOMS.

The adolescent data appears to be consistent with the symptom scores among the two methods of administration even though the testing may not have been done within the ideal 72-hour window post-injury.<sup>4,67</sup> Delayed reporting and assessment can prolong the SRC injury management process.<sup>68</sup> The post-injury VOMS assessment for this group varied anywhere from 1 day to 14 days which was largely dependent on how soon the subject was diagnosed and referred to the concussion assessment lab. Motion sickness was also reviewed with this group and the data suggests that it was not a factor in SRC assessment. One study conducted by Elbin, et al<sup>64</sup> looked at high school athletes (avg age= $15.13 \pm 1.21$  years) with a history of motion sickness when testing performance with vestibular and oculo-motor

scores. This study used the current clinical manual method of the VOMS. The result of this study suggests that those students with a history of motion sickness present with higher baseline symptom scores specific to those sub-tests that challenge vestibular and oculo-motor function.<sup>64</sup> Since baseline data was not available for this group, only post-injury data was analyzed with only one subject reporting any prior motion sickness experience. That subject completed the VOMS via the MAN method.

## 5.7 Limitations

There were limitations in this project. Research examining motion sickness has constantly used some form of a questionnaire to assess this among their subjects. There are several types of questionnaires including the Motion Sickness Severity Scale (MSSS), the Patient Global Impression of Severity (PGI-S), and the Motion Sickness Assessment Questionnaire (MSAQ).<sup>69</sup> This project merely asked a simple question regarding prior history of motion sickness. With our concussion assessment whether at baseline or post-injury, there is already a series of forms they are asked to complete. A solution could be a modified version of one of these motion sickness assessments to be included with the intake forms. Doing a post baseline or injury assessment may be in order as well to fully address this potential with the subjects. An additional limitation was equipment failure with the VR system in that at times the NPC test would not initialize, or the VMS target would not show up on the screen. Bugs in the Unity program should be addressed to minimize this problem so that it does not occur.

## Chapter 6

### 6.1 Summary

A pilot study examined the current clinical protocol of VOMS administration to a novel prototype and determined that there is a variability among raters. The MAN method had greater

symptom severity scores compared to the novel prototype. A standardized means of VOMS administration gives consistent results among varying raters.

Experiment one involved examining the baseline symptom scores of the VOMS using current MAN method, the PRO method, and a VR method. The MAN method again produced higher symptom scores than the standardized PRO and VR methods. This established that through standardization, consistent symptom scores are recorded among raters. This also established the potential of the VOMS being administered through a VR system.

Experiment two looked specifically at the PRO and the VR methods. The focus now looked at the symptoms scores and NPC measurements from baseline to post-injury. This experiment would look at how the subjects would respond to these methods comparing baseline data and post-injury data. The results indicate through a comparison at baseline to baseline and baseline to post-injury overall, VR stimuli can be used for VOMS assessment.

Experiment three circled back to a direct comparison of the current MAN method to the VR method via subject randomization. Through this comparison, questions regarding the safety of using VR with a concussed individual are addressed as this again examines the symptom scores and NPC measurements from baseline to post-injury between the two methods. An additional component that examines a prior history of motion sickness was included to determine if that would affect the symptom reporting during the VOMS in VR. It was concluded that our subjects were able to compete with the VOMS with both methods with very few exceptions. This experiment also looked at an adolescent post-injury population. The data analysis for this group suggests that these subjects can also complete the VOMS with both methods, with or without a history of motion sickness.

Through the pilot study and these three subsequent experiments the common thread indicates that the VOMS can be administered safely with a VR system. This provides consistency among clinicians and potentially can be automated for timely assessment and management of SRC.

There are additional findings from this study that warrant further investigation. The collegiate and adolescent data indicate there are gender differences with symptom reporting. This has been explored with our prior research examining the VOMS delivery with a novel prototype versus the manual method.<sup>52</sup> The average age of subjects who sustained a SRC within each group is a finding that raises concerns as to how age may be a factor for risk of SRC and the severity of symptoms. The adolescent group appeared to have higher symptom reporting scores with the post-injury assessment compared to the collegiate group. Lastly, with the adolescent group, the variability in time it took for the subject to be assessed through the VOMS with either method was alarming in that varied from as little as one day to as long as 14 days. A recent study looked at the access to care after a SRC with athletes ranging from 14-19 in age. Their findings indicate those athletes with access to a certified athletic trainer (ATC) had a lower amount of time it took from presentation to general healthcare than those who did not.<sup>70</sup>

Proper SRC assessment relies on having a trained medical professional present to identify signs and symptoms and to apply the appropriate screening tools. This is more prevalent at the collegiate and professional levels of sports. This is not the case with high school sports. Only about 66% of secondary schools have access to Athletic Training Services.<sup>71</sup> From that statistic about half were from full-time employed athletic trainers (AT's) while the rest were employed part-time. Thus, many student-athletes at the secondary level are being assessed by coaches, administrators, or parents. The goal of this project is to give not only the AT's a tool for assessment and management but to aid those who may not have the proper medical training with a means of assessment and pertinent data collection that can be made available to medical professionals in a timely, efficient manner. Continued evolution of this project

would involve the development of a phone app coupled with an inexpensive head-mounted VR appliance that automates this process. The VR-VOMS app would run the assessment independently, collect the data, track the eyes during the tests, and collect symptomology and NPC data. At the completion of the assessment, the data is uploaded to a secure cloud service in which a qualified healthcare professional would be notified. They then can look at the data and make a proper diagnosis such that the SRC can be assessed in a timely manner and managed appropriately.

## Appendix

**Table 1:** Mean, standard deviation, and range of the Vestibular/Ocular Screening Exam baseline, change score, and subtest change score symptoms along with near point convergence measurement by each device with associated false positives.

Variable	Device	Mean (SD)	Range	False Positives (%)
Baseline symptoms <sup>*, †, §</sup>	Manual	0.446 (1.165)	0 to 6	
	Prototype	0.163 (0.644)	0 to 6	
	VR	0.161 (0.933)	0 to 10	
Change score symptoms <sup>*, †</sup>	Manual	0.396 (1.081)	0 to 7	4.5%
	Prototype	0.128 (0.427)	0 to 3	0.3%
	VR	0.170 (0.903)	0 to 8	3.3%
Smooth pursuit symptoms <sup>*, †</sup>	Manual	0.455 (1.17)	0 to 6	8.1%
	Prototype	0.151 (0.622)	0 to 6	1.6%
	VR	0.165 (0.885)	0 to 10	1.9%
Horizontal saccades symptoms <sup>*, †</sup>	Manual	0.482 (1.18)	0 to 6	9%
	Prototype	0.162 (0.645)	0 to 6	1.6%
	VR	0.165 (0.885)	0 to 10	1.9%

Vertical saccades symptoms <sup>*,†</sup>	Manual	0.473 (1.17)	0 to 6	8.1%
	Prototype	0.173 (0.663)	0 to 6	1.9%
	VR	0.151 (0.852)	0 to 10	1.4%
Near point convergence symptoms <sup>†</sup>	Manual	0.437 (1.164)	0 to 6	8.1%
	Prototype	0.156 (0.634)	0 to 6	1.6%
	VR	0.222 (0.985)	0 to 10	3.3%
Horizontal vestibular ocular reflex symptoms <sup>*,†</sup>	Manual	0.581 (1.22)	0 to 6	8.1%
	Prototype	0.184 (0.671)	0 to 6	1.6%
	VR	0.212 (0.953)	0 to 10	2.8%
Vertical vestibular ocular reflex symptoms <sup>*,†</sup>	Manual	0.500 (1.207)	0 to 6	8.1%
	Prototype	0.173 (0.671)	0 to 6	1.9%
	VR	0.208 (0.941)	0 to 10	2.4%
Visual motion sensitivity symptoms <sup>*, †</sup>	Manual	0.563 (1.348)	0 to 6	7.2%
	Prototype	0.227 (0.759)	0 to 8	1.9%
	VR	0.231 (0.963)	0 to 10	3.3%
Near point convergence (cm) <sup>†,§</sup>	Manual	2.91 (3.35)	0 to 15	20.7%
	Prototype	2.21 (1.81)	0 to 9	7.9%
	VR	2.99 (0.684)	0 to 4	0%

Notes: \*=significant difference between Manual and Prototype; † = significant difference between Manual and Virtual Reality; § = significant difference between Prototype and Virtual Reality. Note = VR = virtual reality, cm = centimeters, the near point convergence false positives are derived from a cutoff of 5cm or less to determine the false positive percentage. For all symptom provocation, these false positives are derived using a greater than 2 symptoms.

Table 2: Vestibular Ocular/Motor Screening test mean and standard deviation prototype (PRO)baseline (n=365) vs virtual reality (VR) baseline (n=511)

<b>Variable</b>	<b>Condition</b>	<b>Mean (SD)</b>	<b>p-value</b>	<b>Cohen's d</b>
Change score symptoms	Baseline-PRO	0.13 (0.43)	.022	0.92
	Baseline-VR	0.59 (2.43)		
Pre-test symptoms	Baseline- PRO	0.15 (0.61)	.004	0.2
	Baseline-VR	0.25 (0.94)		
Smooth pursuit symptoms	Baseline - PRO	0.15 (0.62)	<.001	0.1
	Baseline-VR	0.02 (0.4)		
Horizontal saccades symptoms	Baseline - PRO	0.16 (0.64)	<.001	0.3
	Baseline-VR	0.01 (0.38)		
Vertical saccades symptoms	Baseline - PRO	0.17 (0.66)	.013	0.28
	Baseline-VR	0.03 (0.38)		
Near-point convergence symptoms	Baseline - PRO	0.16 (0.63)	.660	0.14
	Baseline-VR	0.09 (0.49)		
Horizontal vestibular ocular reflex symptoms	Baseline - PRO	0.18 (0.67)	.141	0.22
	Baseline-VR	0.07 (0.54)		
Vertical vestibular ocular reflex symptoms	Baseline - PRO	0.17 (0.67)	.457	0.16
	Baseline-VR	0.09 (0.58)		
Visual motion sensitivity symptoms	Baseline - PRO	0.22 (0.76)	.294	0.14
	Baseline-VR	0.15 (0.8)		

Near-point convergence (cm)	Baseline - PRO	2.20 (1.8)	<.001	1.2
	Baseline-VR	2.82 (0.51)		

Table 3: Vestibular Ocular/Motor Screening test mean and standard deviation prototype baseline (n=365) vs prototype post injury (n=29)

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Baseline	0.13 (0.43)	<.001	20.1
	Post Injury	10.2 (11.3)		
Pre-test symptoms	Baseline	0.15 (0.61)	<.001	15.5
	Post Injury	7.9 (7.2)		
Smooth pursuit symptoms	Baseline	0.15 (0.62)	.092	0.24
	Post Injury	0.27 (0.7)		
Horizontal saccades symptoms	Baseline	0.16 (0.64)	<.001	1.68
	Post Injury	1 (1.5)		
Vertical saccades symptoms	Baseline	0.17 (0.66)	<.001	2.2
	Post Injury	1.27 (1.6)		
Near-point convergence symptoms	Baseline	0.16 (0.63)	<.001	1.88
	Post Injury	1.1 (1.78)		
Horizontal vestibular ocular reflex symptoms	Baseline	0.18 (0.67)	<.001	3.44
	Post Injury	1.9 (2.4)		
Vertical vestibular ocular reflex symptoms	Baseline	0.17 (0.67)	<.001	4.14
	Post Injury	2.24 (2.8)		

Visual motion sensitivity symptoms	Baseline	0.22 (2.8)	<.001	4.36
	Post Injury	2.4 (2.8)		
Near-point convergence (cm)	Baseline	2.2 (1.8)	<.001	6.2
	Post Injury	5.3 (6.1)		

Table 4: Vestibular Ocular/Motor Screening test mean and standard deviation VR Baseline (n=511) vs VR Post Injury (n=40)

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Baseline	0.59 (2.4)	<.001	1.06
	Post Injury	10.5 (12.9)		
Pre-test symptoms	Baseline	0.25 (0.94)	<.001	1.45
	Post Injury	7.6 (7.1)		
Smooth pursuit symptoms	Baseline	0.02 (0.36)	<.001	0.21
	Post Injury	0.34 (0.84)		
Horizontal saccades symptoms	Baseline	0.01 (0.38)	<.001	.067
	Post Injury	0.7 (1.2)		
Vertical saccades symptoms	Baseline	0.03 (0.38)	<.001	0.83
	Post Injury	1.3 (2.14)		
Near-point convergence symptoms	Baseline	0.09 (0.49)	<.001	0.9
	Post Injury	1.38 (1.97)		
Horizontal vestibular ocular reflex symptoms	Baseline	0.07 (0.54)	<.001	0.89
	Post Injury	1.8 (2.7)		

Vertical vestibular ocular reflex symptoms	Baseline	0.09 (0.58)	<.001	0.89
	Post Injury	1.9 (2.8)		
Visual motion sensitivity symptoms	Baseline	0.15 (0.8)	<.001	1.07
	Post Injury	2.07 (2.4)		
Near-point convergence (cm)	Baseline	2.84 (0.51)	.657	0.078
	Post Injury	2.8 (0.51)		

Table 5: Vestibular Ocular/Motor Screening test mean and standard deviation prototype (PRO) Post Injury (n=29) vs VR Post Injury (n=40)

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Post Injury-PRO	10.2 (11.3)	.515	0.6
	Post Injury-VR	10.5 (12.9)		
Pre-test symptoms	Post Injury-PRO	7.9 (7.2)	.894	0.6
	Post Injury-VR	7.6 (7.1)		
Smooth pursuit symptoms	Post Injury-PRO	0.27 (0.7)	.411	0.14
	Post Injury-VR	0.34 (0.84)		
Horizontal saccades symptoms	Post Injury-PRO	1.27 (1.6)	.401	1.14
	Post Injury-VR	0.7 (1.2)		
Vertical saccades symptoms	Post Injury-PRO	0.17 (0.66)	.642	2.26
	Post Injury-VR	1.3 (2.14)		
Near-point convergence symptoms	Post Injury-PRO	1.1 (1.78)	.569	0.56
	Post Injury-VR	1.38 (1.97)		

Horizontal vestibular ocular reflex symptoms	Post Injury-PRO	1.9 (2.4)	.616	0.2
	Post Injury-VR	1.8 (2.7)		
Vertical vestibular ocular reflex symptoms	Post Injury-PRO	2.24 (2.8)	.936	0.68
	Post Injury-VR	1.9 (2.8)		
Visual motion sensitivity symptoms	Post Injury-PRO	2.4 (2.8)	.837	0.66
	Post Injury-VR	2.07 (2.4)		
Near-point convergence (cm)	Post Injury-PRO	5.3 (6.1)	.746	5.0
	Post Injury-VR	2.8 (0.51)		

Table 6: Vestibular Ocular/Motor Screening test mean and standard deviation Manual (MAN)baseline (n=301) vs virtual reality (VR) baseline (n=229), 2023-24 Collegiate Data

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Baseline-MAN	0.54(1.9)	<.001	0.28
	Baseline-VR	0.02(1.8)		
Pre-test symptoms	Baseline-MAN	0.22(0.75)	<.001	0.37
	Baseline-VR	0.02(0.09)		
Smooth pursuit symptoms	Baseline-MAN	0.20(0.72)	.402	0.17
	Baseline-VR	0.32(0.62)		
Horizontal saccades symptoms	Baseline-MAN	0.20(0.66)	.332	0.19
	Baseline-VR	0.32(0.62)		
Vertical saccades symptoms	Baseline-MAN	0.24(0.73)	.102	0.07
	Baseline-VR	0.29(0.63)		

Near-point convergence symptoms	Baseline-MAN	0.19(0.66)	.885	0.27
	Baseline-VR	0.37(0.64)		
Horizontal vestibular ocular reflex symptoms	Baseline-MAN	0.35(0.87)	.01	0.01
	Baseline-VR	0.34(0.65)		
Vertical vestibular ocular reflex symptoms	Baseline-MAN	0.27(0.80)	.09	0.09
	Baseline-VR	0.34(0.65)		
Visual motion sensitivity symptoms	Baseline-MAN	0.32(0.86)	.057	0.11
	Baseline-VR	0.41(0.72)		
Near-point convergence (cm)	Baseline-MAN	2.88(3.23)	<.001	0.13
	Baseline-VR	3.20(1.29)		

Table 7: Vestibular Ocular/Motor Screening test mean and standard deviation manual baseline (n=301) vs manual post injury (n=24), 2023-24 Collegiate data

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Baseline	0.54(1.9)	<.001	1.35
	Post Injury	13.17(13.05)		
Pre-test symptoms	Baseline	0.22(0.75)	<.001	1.57
	Post Injury	9.87(8.65)		
Smooth pursuit symptoms	Baseline	0.20(0.72)	<.001	1.62
	Post Injury	10.45(8.9)		

Horizontal saccades symptoms	Baseline	0.20(0.66)	<.001	1.65
	Post Injury	11.08(9.3)		
Vertical saccades symptoms	Baseline	0.24(0.73)	<.001	1.66
	Post Injury	11.5(9.56)		
Near-point convergence symptoms	Baseline	0.19(0.66)	<.001	1.60
	Post Injury	11.45(9.9)		
Horizontal vestibular ocular reflex symptoms	Baseline	0.35(0.87)	<.001	1.81
	Post Injury	12.33(10.11)		
Vertical vestibular ocular reflex symptoms	Baseline	0.27(0.80)	<.001	1.67
	Post Injury	12.45(10.3)		
Visual motion sensitivity symptoms	Baseline	0.32(0.86)	<.001	1.7
	Post Injury	12.8(10.4)		
Near-point convergence (cm)	Baseline	2.88(3.23)	<.001	0.85
	Post Injury	8.19(8.20)		

Table 8: Vestibular Ocular/Motor Screening test mean and standard deviation VR Baseline (n=229) vs VR Post Injury (n=11), 2023-24 Collegiate data

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Baseline	0.02(1.8)	<.001	1.8
	Post Injury	8.54(6.3)		
Pre-test symptoms	Baseline	0.02(0.09)	<.001	1.94
	Post Injury	8.54(6.2)		

Smooth pursuit symptoms	Baseline	0.32(0.62)	<.001	1.8
	Post Injury	8.45(6.4)		
Horizontal saccades symptoms	Baseline	0.32(0.62)	<.001	1.9
	Post Injury	9.1(6.4)		
Vertical saccades symptoms	Baseline	0.24(0.73)	<.001	2.02
	Post Injury	9.45(6.4)		
Near-point convergence symptoms	Baseline	0.37(0.64)	<.001	2.03
	Post Injury	9.63(6.4)		
Horizontal vestibular ocular reflex symptoms	Baseline	0.34(0.65)	<.001	2.18
	Post Injury	10.3(6.4)		
Vertical vestibular ocular reflex symptoms	Baseline	0.34(0.65)	<.001	2.17
	Post Injury	10.2(6.4)		
Visual motion sensitivity symptoms	Baseline	0.41(0.72)	<.001	2.12
	Post Injury	10.54(6.7)		
Near-point convergence (cm)	Baseline	3.20(1.29)	.220	0.61
	Post Injury	5.73(5.71)		

Table 9: Vestibular Ocular/Motor Screening test mean and standard deviation Manual (MAN) Post Injury (n=24) vs VR Post Injury (n=11), 2023-24 Collegiate data

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Post Injury-MAN	13.17(13.05)	.605	0.45
	Post Injury-VR	8.54(6.3)		

Pre-test symptoms	Post-Injury MAN	9.87(8.65)	.802	0.18
	Post Injury-VR	8.54(6.2)		
Smooth pursuit symptoms	Post-Injury MAN	10.45(8.9)	.616	0.26
	Post Injury-VR	8.45(6.4)		
Horizontal saccades symptoms	Post-Injury MAN	11.08(9.3)	.580	0.34
	Post Injury-VR	9.1(6.4)		
Vertical saccades symptoms	Post-Injury MAN	11.5(9.56)	.568	0.25
	Post Injury-VR	9.45(6.4)		
Near-point convergence symptoms	Post-Injury MAN	11.45(9.9)	.694	0.22
	Post Injury-VR	9.63(6.4)		
Horizontal vestibular ocular reflex symptoms	Post-Injury MAN	12.33(10.11)	.643	0.24
	Post Injury-VR	10.3(6.4)		
Vertical vestibular ocular reflex symptoms	Post-Injury MAN	12.45(10.3)	.631	0.26
	Post Injury-VR	10.2(6.4)		
Visual motion sensitivity symptoms	Post-Injury MAN	12.8(10.4)	.593	0.26
	Post Injury-VR	10.54(6.7)		
Near-point convergence (cm)	Post-Injury MAN	8.19(8.20)	.109	0.37
	Post Injury-VR	5.73(5.71)		

Table 10: Vestibular Ocular/Motor Screening test mean and standard deviation Manual (MAN) baseline Motion Sickness (MS) = No (N)(n=263) vs MAN baseline, MS=Yes (Y)(n=38) 2023-24 Collegiate data with a self-reported history of motion sickness.

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Baseline-MS=N	0.4(1.5)	.001	0.42
	Baseline-MS=Y	1.6(3.7)		
Pre-test symptoms	Baseline-MS=N	0.23(0.8)	.39	0.17
	Baseline-MS=Y	0.12(0.4)		
Smooth pursuit symptoms	Baseline-MS=N	0.21(0.75)	.09	0.13
	Baseline-MS=Y	0.13(0.42)		
Horizontal saccades symptoms	Baseline-MS=N	0.21(0.7)	.10	0.19
	Baseline-MS=Y	0.1(0.4)		
Vertical saccades symptoms	Baseline-MS=N	0.24(0.74)	.09	0.07
	Baseline-MS=Y	0.19(0.59)		
Near-point convergence symptoms	Baseline-MS=N	0.19(0.7)	.32	0
	Baseline-MS=Y	0.19(0.53)		
Horizontal vestibular ocular reflex symptoms	Baseline-MS=N	0.31(.82)	.10	0.33
	Baseline-MS=Y	0.63(1.1)		
Vertical vestibular ocular reflex symptoms	Baseline-MS=N	0.23(0.75)	.009	0.05
	Baseline-MS=Y	0.6(10.6)		
Visual motion sensitivity symptoms	Baseline-MS=N	0.3(0.82)	.032	0.19
	Baseline-MS=Y	0.5(1.2)		

Near-point convergence (cm)	Baseline-MS=N	2.9(3.2)	.12	0.06
	Baseline-MS=Y	3.1(3.3)		

Table 11: Vestibular Ocular/Motor Screening test mean and standard deviation VR baseline Motion Sickness (MS) = No (N)(n=200) vs VR baseline, MS=Yes (Y)(n=28) 2023-24 Collegiate data with a self-reported history of motion sickness.

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Baseline-MS=N	0.13(1.8)	.81	0.04
	Baseline-MS=Y	0.56(1.7)		
Pre-test symptoms	Baseline-MS=N	0.001(0.1)	.71	0.04
	Baseline-MS=Y	0.12(0.4)		
Smooth pursuit symptoms	Baseline-MS=N	0.15(0.64)	.96	0.09
	Baseline-MS=Y	0.2(0.5)		
Horizontal saccades symptoms	Baseline-MS=N	0.15(0.64)	.96	0.09
	Baseline-MS=Y	0.2(0.5)		
Vertical saccades symptoms	Baseline-MS=N	0.16(0.65)	.95	0.02
	Baseline-MS=Y	0.2(0.5)		
Near-point convergence symptoms	Baseline-MS=N	0.17(0.65)	.7	0.21
	Baseline-MS=Y	0.3(0.61)		
Horizontal vestibular ocular reflex symptoms	Baseline-MS=N	0.16(0.66)	.87	0.23
	Baseline-MS=Y	0.32(0.7)		
Vertical vestibular ocular reflex symptoms	Baseline-MS=N	0.15(0.63)	.87	0.3
	Baseline-MS=Y	0.36(0.81)		

Visual motion sensitivity symptoms	Baseline-MS=N	0.2(0.73)	.99	0.3
	Baseline-MS=Y	0.4(0.71)		
Near-point convergence (cm)	Baseline-MS=N	3.1(1.4)	.26	0.04
	Baseline-MS=Y	3.1(3.3)		

Table 12: Vestibular Ocular/Motor Screening test mean and standard deviation Manual (MAN) Post Injury Motion Sickness (MS) = No (N)(n=18) vs MAN Post Injury, MS=Yes (Y)(n=6) 2023-24 Collegiate data with a self-reported history of motion sickness.

<b>Variable</b>	<b>Condition</b>	<b>Mean (SD)</b>	<b>p-value</b>	<b>Cohen's d</b>
Change score symptoms	Post Injury-MS=N	13.2(12)	.763	0.03
	Post Injury-MS=Y	13.2(1)		
Pre-test symptoms	Post Injury-MS=N	10.22(9.1)	.736	0.16
	Post Injury-MS=Y	8.83(7.8)		
Smooth pursuit symptoms	Post Injury-MS=N	10.88(9.4)	.737	0.19
	Post Injury-MS=Y	9.2(7.9)		
Horizontal saccades symptoms	Post Injury-MS=N	11.6(9.8)	.789	0.23
	Post Injury-MS=Y	9.5(8.4)		
Vertical saccades symptoms	Post Injury-MS=N	11.9(10)	.867	0.19
	Post Injury-MS=Y	10.1(8.8)		
Near-point convergence symptoms	Post Injury-MS=N	11.6(9.9)	1.00	0.08
	Post Injury-MS=Y	10.8(10.6)		

Horizontal vestibular ocular reflex symptoms	Post Injury-MS=N	12.5(10.2)	.947	0.08
	Post Injury-MS=Y	11.7(10.6)		
Vertical vestibular ocular reflex symptoms	Post Injury-MS=N	12.7(10.5)	.947	0.09
	Post Injury-MS=Y	11.7(10.6)		
Visual motion sensitivity symptoms	Post Injury-MS=N	13.1(10.5)	.920	0.21
	Post Injury-MS=Y	10.8(11)		
Near-point convergence (cm)	Post Injury-MS=N	6.4(6.5)	.062	0.77
	Post Injury-MS=Y	13.3(10.9)		

Table 13: Vestibular Ocular/Motor Screening test mean and standard deviation VR Post Injury Motion Sickness (MS) = No (N)(n=8) vs VR Post Injury, MS=Yes (Y)(n=3) 2023-24 Collegiate data with a self-reported history of motion sickness.

Variable	Condition	Mean (SD)	p-value	Cohen's d
Change score symptoms	Post Injury-MS=N	7.9(7.3)	.682	0.44
	Post Injury-MS=Y	10.3(2.3)		
Pre-test symptoms	Post Injury-MS=N	8.1(7.3)	.757	0.30
	Post Injury-MS=Y	9.7(1.1)		
Smooth pursuit symptoms	Post Injury-MS=N	8.4(7.4)	.758	0.05
	Post Injury-MS=Y	8.7(3.5)		
Horizontal saccades symptoms	Post Injury-MS=N	8.5(7.5)	.605	0.41
	Post Injury-MS=Y	10.7(1.1)		
Vertical saccades symptoms	Post Injury-MS=N	8.9(7.4)	.605	0.39
	Post Injury-MS=Y	11(1.7)		

Near-point convergence symptoms	Post Injury-MS=N	9.4(7.5)	.837	0.16
	Post Injury-MS=Y	10.3(2.5)		
Horizontal vestibular ocular reflex symptoms	Post Injury-MS=N	9.9(7.5)	.759	0.25
	Post Injury-MS=Y	11.3(1.5)		
Vertical vestibular ocular reflex symptoms	Post Injury-MS=N	9.7(7.5)	.609	0.29
	Post Injury-MS=Y	11.3(1.5)		
Visual motion sensitivity symptoms	Post Injury-MS=N	9.7(7.7)	.536	0.52
	Post Injury-MS=Y	12.7(2.3)		
Near-point convergence (cm)	Post Injury-MS=N	4.5(4)	.102	0.61
	Post Injury-MS=Y	8.9(9.3)		

Table 14: Vestibular Ocular/Motor Screening test mean and standard deviation Manual (MAN) Post Injury (n=35) vs VR Post Injury (n=10), 2023-24 11-17 age data

<b>Variable</b>	<b>Condition</b>	<b>Mean (SD)</b>	<b>p-value</b>	<b>Cohen's d</b>
Change score symptoms	Post Injury-MAN	8.08(12.04)	.55	0.24
	Post Injury-VR	11.4(15.3)		
Pre-test symptoms	Post Injury-MAN	4.78(6.29)	.67	0.05
	Post Injury-VR	5.1(6.5)		
Smooth pursuit symptoms	Post Injury-MAN	4.86 (6.33)	.46	0.19
	Post Injury-VR	6.3(8.4)		
Horizontal saccades symptoms	Post Injury-MAN	5.42 (6.85)	.61	0.12
	Post Injury-VR	6.3(8.2)		

Vertical saccades symptoms	Post Injury-MAN	5.72 (7.07)	.70	0.09
	Post Injury-VR	6.4(8.5)		
Near-point convergence symptoms	Post Injury-MAN	5.7 (7.02)	.70	0.1
	Post Injury-VR	6.5(8.2)		
Horizontal vestibular ocular reflex symptoms	Post Injury-MAN	5.9 (7.4)	.67	0.12
	Post Injury-VR	6.9(9)		
Vertical vestibular ocular reflex symptoms	Post Injury-MAN	5.92 (7.3)	.82	0.08
	Post Injury-VR	6.6(8.6)		
Visual motion sensitivity symptoms	Post Injury-MAN	2.4 (2.8)	.99	0.69
	Post Injury-VR	7(9.01)		
Near-point convergence (cm)	Post Injury-MAN	6.5 (7.8)	.52	0.13
	Post Injury-VR	5.5(7.9)		

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