RELIABLE CHANGE INDICES OF VISUAL AND SENSORY PERFORMANCE MEASURES

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ABSTRACT

TARYN ELIZABETH GILREIN: Reliable change indices of visual and sensory
performance measures.
(Under the direction of Jason P. Mihalik)

The purpose was to determine the test-retest reliability and establish reliable

change indices for measures of visual and sensory performance in healthy college

students. Participants were administered several clinical and research tests of static and

dynamic visual acuity, gaze stability, and visual-motor sensory performance 14 days

apart. The test-retest ranged from 0.08 to 0.81 across all measures, and some

demonstrated significant practice effects. Clinicians should recognize employing reliable

change indices is but one method to manage concussed patients, and should consider

employing other tools to assess those tests demonstrating the lowest reliability. A

secondary purpose was to explore if visual deficits exist in college athletes who have

been cleared to return to play following concussion. We were unable to sufficiently

power these exploratory analyses. Therefore, subsequent studies should evaluate the

sensitivity, specificity, and predictive values of visual performance testing in the context

of concussion diagnosis and management.

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CHAPTER I

INTRODUCTION

Concussions have recently become a spotlight health concern in today's society.

The number of reported concussions continues to rise with approximately 1.6 to 3.8

million reported each year[2] and many other suspected head injuries that go unreported.[3]

Concussion, or mild traumatic brain injury, has been defined as a complex

pathophysiologic process affecting the brain and its functioning capacities following an

injury to the head.[4] Concussions typically results from either a direct blow to the head or

a traumatic force to the body that transmits an impulsive force to the head.[5] The trauma to

the head leads to an energy crisis in the brain that results in decreased oxygen delivery

and functioning.[6] As a result, concussions can result in multiple debilitating symptoms

including cognitive, balance, and visual deficits. These deficits typically resolve in 7-10

days, but may last several months in a subset of the population.[4] Currently, concussion

evaluation typically includes reliable and sensitive[7-9] measures of symptoms,

neurocognition, and postural control, but often does not address aspects, such as dynamic

or static vision or gaze stability, which may be associated with concussion.

Ideally, the results of the current post-concussion assessments are compared to the

individual's baseline measures. Not all sports teams have the benefit of baseline testing

every athlete or have the medical staff to assess concussed patients. In the absence of pre-

injury scores for an athlete, the post-injury measures can be compared to normative data

that has been compiled from various populations.[7-9] The reliable change indices for

cognitive, memory, and balance measures should be utilized when comparing subjects to a 'norm' for return to play decisions in addition to the individual baseline comparison.[10] The computerized neuropsychological tests provide more sensitive and objective measures when compared to the subjective pencil and paper battery tests. The computerized battery also demonstrated a longer duration of symptoms in patients post-concussion when compared to paper and pencil assessments.[11]

An important performance measure that is not considered in current post-concussion return to participation is visual performance. Vision is critical to athletes of all expertise levels and every sport.[12,13] The visual demands and subsequent skills needed for hitting a baseball, catching a football, and spotting a 4-inch balance beam are vastly different. In order to objectively determine the demands necessary of the specific athlete, a task analysis is performed considering the environment, opponents, targets and other external factors involved in the particular sport. Athletes are required to take visual perception and interpret the information to create a motor response dependent on the stimuli. If an athlete is not receiving visual feedback fast enough to assess the situation and act on the information, performance will suffer.[14] Both static and dynamic visual acuity measures should be taken and analyzed to expose deficits that could potentially affect an athlete's functional ability during dynamic sport. Visual performance measures should be incorporated into the baseline testing of athletes to compare and observe progress or deficit throughout the season, regardless of injury.[15] These measures should include assessments that address visual skills such as depth perception, reaction time, and near-far quickness.[12] If there are deficits in the visual system due to concussion, an

objective measure of a subject's vision should be recorded and evaluated, similar to a subject's cognitive processing and postural stability.

Concussion evaluation paradigms typically use a pre-injury (baseline) to post-injury comparison to identify deficits caused by concussion. In some cases, baseline measures are not available, so it is important to have a 'normal' value with which to compare an athlete's results. The change from an individual's pre-injury to post-injury score can be compared to a reliable change index (RCI). Comparison to an RCI creates a more sensitive conclusion as to if the athlete has returned to a normal measure prior to resuming participation after injury, specifically concussion. Visual deficits have been demonstrated following concussion,[16] but there is a lack of data supporting the validity and reliability of visual assessments that might aid in concussion evaluation and management. To accurately assess the visual system in order to manage patients with visual deficits, a clinical measure must be reliable, sensitive, and clinically applicable. The primary purpose of this study was to determine the test-retest reliability and reliable change indices for measures of visual performance in college athletes. A secondary and exploratory purpose was to determine if visual deficits exist in college athletes who report being asymptomatic following concussion.

Research Questions

1. What is the reliability of visual and sensory performance measures (Nike SPARQ Sensory Station, NeuroCom Gaze Stability Test, NeuroCom Dynamic Visual Acuity Test, and King-Devick Test) in healthy college students?

2. What are the reliable change indices for visual and sensory performance measures (Nike SPARQ Sensory Station, NeuroCom Gaze Stability Test, NeuroCom Dynamic Visual Acuity Test, and King-Devick Test) in healthy college students?

3. *Exploratory:* Is there a significant difference in visual and sensory performance between concussed patients compared to match healthy controls?

Research Hypotheses

1. There will be moderate reliability across serial visual and sensory performance assessments (Nike SPARQ Sensory Station, NeuroCom Gaze Stability Test, NeuroCom Dynamic Visual Acuity Test, and King-Devick Test) in healthy college students.

2. Reliable change indices will be computed and yield clinically reasonable confidence intervals.

3. *Exploratory:* Concussed individuals will perform worse on visual and sensory performance measures compared to match healthy controls.

Variables

Independent variables

1. Time

   a. Testing Session One

   b. Testing Session Two

2. Group

   a. Healthy College Students

   b. Concussed Patients (exploring potential)

Dependent variables

1. Nike SPARQ Sensory Station

   a. Visual Clarity (Static visual acuity)

   b. Contrast Sensitivity

   c. Depth Perception

   d. Near-Far Quickness

   e. Target Capture (Dynamic visual acuity)

   f. Perception Span

   g. Eye-Hand Coordination

   h. Go/No-Go

   i. Reaction Time

   j. Response Time

   k. Motor Movement Time

2. Gaze Stability Test (NeuroCom)

   a. Maximum head speed (degrees/second) achieved while correctly identifying orientation of visual stimulus; measured in yaw, pitch, and roll directions

3. Dynamic Visual Acuity (NeuroCom)

   a. Dynamic visual acuity loss (dynamic visual acuity minus static visual acuity); measured in the Logarithm of the Minimum Angle of Resolution (logMAR)

4. King-Devick Test

   a. Completion time

   b. Number of errors committed

Operational Definitions

1. Healthy participants: athletic individual participating in physical activity three to four times per week.

2. Concussed participant: varsity or club athlete ages 18-25 who underwent a direct blow to the head, neck, or elsewhere on the body with an impulsive force transmitted to the head that resulted in concussive symptoms and were diagnosed by the respective doctor with a concussion.

3. Matched control: uninjured individual matched to the concussed patients based on age, gender, sport, and position on team. (Exploratory Research Question 3)

Delimitations

1. Data limited to college athletes at the University of North Carolina at Chapel Hill.

2. There will only be two data collection time intervals.

3. The SPARQ Sensory Station, Neurocom GST and DVAT, and the King-Devick Test are the only visual measures that were used.

Limitations

1. Attrition rate leading to small sample size.

2. Low concussion rate leading to small sample size.

3. Forced to cease testing if symptoms return during assessments.

Assumptions

1. Nike SPARQ and NeuroCom SOT will accurately record data.

2. All participants will provide full effort during testing.

3. All participants will return for second testing session.

4. All participants will be truthful and honest about concussion symptoms and history.

5. The ability of the examiner will not interfere with testing results.

6. Effects of mental and physical fatigue will not significantly alter participant's visual performance.

7. A convenient sample of athletes chosen based on proximity and availability will accurately represent the population.

8. Data will be properly interpreted by examiner.

9. Team physicians and athletic trainers are properly evaluating and diagnosing concussions.

CHAPTER II

REVIEW OF LITERATURE

Introduction

Concussions are a serious health concern in today's society and have led to a heightened sense of awareness in all factions of sports and athletics. It has been estimated that well over 1 million people in the United States sustain a concussion annually, leading to a critical movement for prevention, education, and research surrounding concussion.[2,17] The main focus of current sports-related concussion research is the identification of cognitive and vestibular deficits post-injury. Due to the complexity of the injury, a comprehensive paradigm of assessments examining cognitive function, postural-stability, and neurological symptoms should be used to assess an individual who has sustained a suspected concussion.[4] The more assessments utilized by a clinician for evaluation of a potential concussed individual, the more sensitive the tests become to identifying deficits due to a concussion.[18] A multifaceted approach is recommended, because a combination of measures increases the sensitivity to greater than 90 percent, compared to the sensitivities of one single assessment, which range from 43 to 80 percent.[19,20]

While the current evidence based assessments are sensitive and reliable, there is a possibility that these assessments are missing certain deficits post-concussion. This potential flaw in the standard assessment may result in an individual's premature return to activity, leaving them at risk for further injury and the potential for a prolonged

recovery. This leads us to ask the question: what deficits are we missing in our current assessment of a concussed individual in the absence of symptoms? One potential deficit we may be missing is visual disturbances. The visual system accounts for 80 percent of an individual's sensory input and 50 percent of the brain's pathways are devoted to vision.[21] Visual deficits and symptoms related to vision have been identified in concussed individuals upon sideline evaluation post-concussion but visual testing is still not always recognized as part of the recommended evaluation.[16] Visual performance measures should be considered in evaluation of a concussion, because vision is important to all individuals, but particularly athletes.

Concussion Epidemiology

Annually, there are approximately 44 million children and young adults participating in organized sports, and approximately 170 million adults participating in some type of physical activity in the United States.[22,23] The large number of children and adults participating in physical activity and sports further confirms the need for educational programs that promote awareness of high risk situations and demonstrate preventative measures. With the implementation of educational programs in the past few years, there has been a significant decrease in the number of catastrophic injuries from head injuries.[24]

Each year, there are an estimated 1.6 to 3.8 million people who report sustaining a sports concussion,[17,25,26] making it the most common traumatic brain injury in athletic young adults.[27] The number is only an approximation because many of these head injuries may go unreported.[3,28] The culture of the sport, attitude of the athlete, and pressure from the team or coaches has been found to affect the validity of an individual's

subjective statements and athletes are now admitting to lying about symptoms in order to continue playing.[3,29]

There is a higher incidence of concussion in adolescents that is speculated to be the result of younger, more susceptible brains. Traumatic brain injury in children and adolescents can lead to persistent cognitive dysfunction, even when no initial effects are observed.[6] Increased susceptibility to concussion in children and adolescents, as compared to adults, has been attributed to decreased myelination, a greater head-to-body ratio, and thinner cranial bones, all which provide less protection to the developing cortex.[30-32] Females are also thought to be at a higher risk for sustaining a concussion, both at the high school and collegiate level.[33] Barnes et al. suggested that female soccer players are more susceptible due to the biomechanical factors such as smaller head to ball ratios and weaker musculature.[34] It is speculated that the higher frequency of concussion in male sports compared to female sports may be attributed to the different styles of play including lacrosse, basketball, and softball.[33] Concussions after getting hit by a pitch are more likely in baseball than in softball.[33] Other studies have suggested that females are more likely to report symptoms after a potential concussion when compared to males who may try to play through the pain.[3]

There is no single agreed upon definition of concussion. In 1996, the Congress of Neurological Surgeons in America agreed on the following definition: a concussion is "...a clinical syndrome characterized by immediate and transient post-traumatic impairment of neural functions, such as alteration of consciousness, disturbance of vision or equilibrium due to brain stem involvement."[35] It is important to point out the inclusion

of vision comprised in the definition of concussion, as it is part of some clinician's post-injury evaluation, but is not always highlighted.

The most recent National Athletic Training Association Consensus Statement released included the following definition: "Concussion is defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces."[5] The statement goes on to describe common features that are typically, but not always seen in those individuals who sustain a concussion. The most common mechanism includes either a direct blow to the head, or indirect blow to anywhere on the body transmitting "impulsive" forces to the head that lead to the rapid onset of temporary neurologic function impairment.[5] Recently, it has been determined that a concussion is a functional injury rather than a structural injury and typically there is no abnormalities found on standard neuroimaging that identify a concussion.[5]

The etiology of concussion is largely dependent on the sport;[36] the majority of these injuries occurring in contact sports such as football, boxing, hockey, in addition to soccer and basketball.[32,36-38] Concussions occur during a direct blow or indirect impact to the head, face, or neck and lead to a rapid acceleration and subsequent deceleration of the brain.[5] The biomechanical forces lead to linear and rotational accelerations in the brain causing injury to delicate white matter and brain tissue, ultimately leading to the biochemical response that results in the presence of the acute symptoms of a concussion.[6,39]

The rotational and linear acceleration and deceleration of the head are the most common mechanisms of injury and result in shearing, compressive, and tensile forces to the axons, tissue, vessels and other structures in the brain.[40] The injury to the brain causes

the presentation of temporary clinical signs and symptoms that should be evaluated by a healthcare professional to determine the status and further management of the individual.[6,40] Physical signs that present after a concussion include loss of consciousness, amnesia, behavioral changes including irritability, cognitive impairment, slowed reaction time, sleep disturbance, headaches, blurred or double vision, feeling in a 'fog', or increased emotional sensitivity.[5,41]

After the physical trauma of a concussion, a metabolic cascade ensues at the cellular level in the pathways of the brain.[6] There is a release of potassium as well as an influx of calcium in the neurons that ultimately reduces the cell's ability to generate oxygen.[6] Essentially, the high energy demand of brain cells, restricted blood flow, and oxygen debt cause mental confusion, failed memory, and dizziness in an individual.[6] These changes do not result in any abnormality on standard structural neuroimaging studies including MRIs or CTs.[5] While this process leads to neuropathological changes, the acute symptoms observed post-concussion are indicative of a functional impairment rather than a structural deficiency.[42,43]

Current assessments/management of concussion

There are several consensus statement and position statements outlining the evaluation and management of sport-related concussion.[4,5] According to the most recent recommendations, when an athlete sustains a blow to the head, either from an object, an opponent, the ground, or experiences a severe 'whiplash' activity, a healthcare professional should be suspicious of a concussion.[5] The athlete should be removed from activity for the remainder of the day if he or she is experiencing concussion symptoms, or appears 'out of it.' In the past, if an individual's symptoms had resolved in less than 15

minutes, he or she could potentially return to participation at that time. Instead of relying on a subjective decision, clinicians should take the functioning of the brain into account. The sideline assessment has become more in depth, allowing for improvement upon the 15-minute symptom "check-up". A concise evaluation using tools such as the Standardized Assessment of Concussion (SAC) in addition to an evaluation of symptoms and motor response should be performed during the primary survey of an athlete with a suspected concussion. If the athlete is diagnosed with a concussion, they are removed from the event and should be taken through further physical evaluation and close monitoring of symptoms.[28,44]

If an individual has experienced more than one concussion, the result of any subsequent head impact may be worse and can lead to long lasting repercussions.[45,46] Poorly managed concussions may lead to a host of complications such as post-concussion syndrome, second impact syndrome, post-traumatic stress disorder and potential lasting memory, visual, vestibular, or cognitive impairments.[31,47] Prompt and thorough evaluation and management of concussion may aid in preventing long-term consequences, but the deterioration process cannot be terminated if mental and physical stresses persist.[5]

Baseline Measures

Recent studies recommend pre-injury baseline testing for each athlete on neurocognitive measures, symptoms, and postural control abilities post-injury.[5] Baseline tests are suggested to account for differences in individual scores and measures on specific tasks compared to post-injury to determine an appropriate return to play.[4,5] A

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complex baseline testing battery is beneficial for the detection of deficits in objective measures of neurocognition and postural control despite symptom resolution.[48]

Baseline testing should take place prior to the beginning of season, in a quiet setting allowing the individual to focus and take the test seriously for accurate results.[49] These measures may be influenced by predisposing factors such as developmental disorders, attention deficit hyperactivity disorder (ADHD), migraine history, or previous concussions.[41,50] The time of day an individual completes the evaluation, the individual's mood, external stress level, and fatigue may all have a detrimental effect on the testing and outcome measures, therefore affecting the return to participation decision for that individual.[49,50]

Baseline testing for all measures discussed would provide a comprehensive representation of college athletes, but it is not practical in all scenarios. The equipment and resources needed are costly and testing can be time-consuming.[51] If administering baseline measures is not an option in a certain setting, clinicians may look into using normative data for comparison of differences.[48,52] Organizations that have limited resources and do not have access to balance-diagnostic equipment or computerized neurocognitive testing programs typically use the standardized, self-reported symptom checklist as a practical method for monitoring concussion symptoms[53] in addition to simpler, more cost-effective measures such as other paper-pencil batteries, BESS testing, and King-Devick Testing.

Symptoms

The comprehensive symptom checklist is one of the most commonly used portions of the post-concussion evaluations and requires a subjective interpretation of the

symptoms experienced at a given time.[54,55] Most checklists include a numerical scale allowing the individual to rate the presence and intensity of symptoms commonly exhibited in concussed individuals such as headache, dizziness, drowsiness, vision problems, balance difficulty, trouble falling asleep, drowsiness, sadness, difficulty concentrating, difficulty remembering, feeling "in a fog"[54,55] and irritability.[4,5,56,57] Symptom checklists have been further studied by many researchers and have been found to carry well-distinguished validity and reliability.[51,58,59] While symptom checklists provide a clinically relevant and useful tool for identifying symptoms that are typically present post-concussion, it should be combined with other recommended tests for a complete assessment of an individual.[51]

Piland et al. examined the validity of subjective symptom reports and found evidence of factorial and construct validity for the Head Injury Scale, a checklist that includes nine of the most common symptoms reported in concussed individuals and is typically used in the SAC and SCAT2 forms.[51] The commonly associated symptoms with concussions can be separated into three constructs: somatic, neuropsychological, and cognitive symptoms.[51,60] While the symptoms may interrelate and overlap, the theoretical distribution of symptoms is as such:

> Somatic symptoms include headache, nausea, vomiting, balance, sensitivity numbness; those considered in the cognitive construct include "slowed down", "in a fog", difficulty concentrating, difficulty remembering; and those thought to be neuropsychological in nature include fatigue, difficulty falling asleep, sleeping more than usual, nervousness, drowsiness, and sadness.[51,60]

Each individual concussion is unique and there is no way of predicting which symptoms an individual will exhibit after a concussion or how long the symptoms will last. Certain symptoms and risk factors are more likely to contribute to prolonged recovery, such as history of previous concussions[45] or sustaining a concussion at a young age.[31] Deficits may be masked in the absence of symptoms during the return to play progression and might not present until the individual returns to a high level of activity. Athletes returning to an environment with excessive visual stimuli such as a soccer field or a basketball court might experience the return of symptoms when dynamic visual acuity is necessary. If visual performance tests were performed prior to return to participation post-concussion, deficits in dynamic visual acuity might be identified to avoid premature return to play.

Neurocognitive Evaluation

Concussions are typically associated with neurological and mental status impairments that affect cognitive, academic, and behavioral functioning.[61] Neurocognitive testing can help identify deficits in an athlete's sustained attention, executive functioning, processing speed, reaction time, and recall of new information.[62] Neurocognitive tests provide a more concrete and objective measure of deficits present after concussion when compared to a subjective symptom report from the individual.[9,63]

The Standardized Assessment of Concussion (SAC) is a screening instrument in the form of a paper-pencil test that was developed in order for clinicians to establish an idea of the athlete's current mental status within minutes of an athlete sustaining a concussion.[9] While the test can be quick and efficient, it does not test brainstem or cerebellar function.[21,64] The traditional neurocognitive assessment includes a paper and

pencil battery that has been proven valid and reliable and has been shown to be sensitive to concussion symptoms.[65] Computerized tests may be more beneficial, than the traditional paper and pencil tests, because computer tests provide a large variety of various forms, minimizing the learning effect of athletes who take assessment multiple times.[62,65] The traditional neurocognitive evaluation is also dependent on the ability of the tester to correctly time processing speed and reaction time of the concussed individual, potentially leading to inaccurate response times and false conclusions regarding neurocognitive functioning.[62,65]

Computerized neurocognitive testing is a fairly novel assessment that addresses the flaws in the paper-pencil battery of neurocognitive testing. The computerized tests carry a well-established reliability and validity and similar to traditional testing, they also have been shown to be sensitive and reliable for the effects of concussion.[29,66,67] Several computerized testing programs have been developed in recent years including Automated Neuropsychological Assessment Metrics (ANAM)(National Rehabilitation Hospital Assistive Technology and Neuroscience Center, Washington, DC), ImPACT Concussion Management Software (ImPACT Applications, Pittsburgh, PA), and HeadMinder Concussion Resolution Index (CRI)(Headminder Inc, New York, NY).[4] Computerized neurocognitive testing typically assesses verbal memory, visual memory, processing speed, executive function, psychomotor speed, reaction time, complex attention and cognitive flexibility.[7]

Postural Control

Postural stability is the ability of a person to control the position and action of their body against the demands placed upon it. There are measures of postural stability

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that can be used to assess for vestibular deficits in concussed individuals.[68] Fatigue, vestibular disturbances, and removal of visual stimuli are all factors that affect the body's ability to control postural sway.[69-71] The Balance Error Scoring System (BESS) is used currently as a sideline measure of an athlete's balance after a suspected concussion.[68] The inexpensive assessment gives a clinician an objective measure of postural stability after a suspected head injury.[68,72] Visual and vestibular function are affected after an individual sustains a concussion[5,41] and therefore difficulties with an individual's ability to control postural sway may indicate disturbances in the brain's pathways for vision. Results of these sideline tests should then be compared to the athlete's baseline BESS scores that should have been established in the athlete's resting state during preseason screening.

Multifaceted Approach

A concussion is a complex injury, affecting many different systems of the body as previously discussed. The convolution of the injury leads to the need for a multifaceted approach to evaluation of an athlete with a suspected concussion. The Standardized Concussion Assessment Tool is a quick subjective assessment that includes a symptom checklist along with a brief evaluation of attention, concentration, and memory.[5,73] In addition to cognitive processing, balance and coordination have been widely researched for the identification of deficits and other vestibular problems[8,74] and can be assessed with the BESS test. Slower reaction time, slower processing speed and reduced memory performance are among the deficits seen in concussed individuals during post-injury testing.[75] While encompassing many systems and identifying present deficits in those concussed individuals, the evaluation of a concussed athlete is not complete. One deficit that might be overlooked in the assessment of these individuals is vision.

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Return to Play Decision

Once all of the athlete's symptoms have resolved and he or she has returned to baseline on all neurocognitive and balance tests, the next step is a gradual progression that includes five levels of physical exertion, each increasingly more demanding.[5,76] No concussed individual should begin the physical activity progression without being evaluated and cleared by a physician or alternate health care professional specifically trained in concussion evaluation.[5]

The gradual progression protocol is the generally accepted return to play protocol used by clinicians in accordance with the most recent NATA Consensus Statement.[5] The clinician should take into account the specific individual's symptoms and response to the injury, the severity of the concussion, and the number of previous concussions the individual has experienced. The individual is allowed to return to limited activity when they are completely asymptomatic at rest, demonstrates performance comparable to baseline values, or normative values on all accepted assessments of neurocognitive function and postural stability and remains asymptomatic with physical exertion.[4,5] An individual may not exhibit visual deficits during post-concussive testing as most current assessments do not require dynamic head motion, which may contribute to the return of symptoms when individuals resume activity. Visual performance during dynamic movement is essential for athletes and if deficits are not identified before the individual's return to sport, performance may be affected and it may be an indicator that the athlete returned prematurely from concussion.

Importance of Sports Vision for Athletes

Regardless of athletic classification, vision is the dominant sense in most individuals and is critical for optimal performance in high intensity athletics as well as in everyday life.[77-79] Sensorimotor and semantic visual functioning are two important factors necessary for the analysis of multiple visual stimuli during sport and the ensuing motor response.[80] The combination of the sensorimotor function with the semantic visual function allows an individual to identify and interpret a situation.[80] Elite athletes demonstrate an advanced ability to combine these senses when compared with non-athletes in situations with multiple stimuli.[80]

It has been said that hitting a baseball is "the single most difficult skill in all of sports."[81] The ability to see a round object moving at such a high velocity accompanied with spin and trajectory and then analyze how and when to hit the ball in such a short amount of time with a separate round object moving in the opposite direction proves to be a skill for those with elite senses and efficient responses.[80-83] Constant convergence of both eyes is required to assess the speed of the ball, predict the movement pattern and path, and intercept the ball or object.[14] These athletes must adjust quickly to the approaching object and initiate efficient and appropriate motor responses based on the sensory stimuli.[14]

When compared to non-athletes, athletes display heightened visual skills including visual acuity, reaction speed, and contrast sensitivity.[13,82,84] Kirschen et al. developed a diagram to demonstrate the many layers of visual functions that build upon each other, such that of a pyramid.[79] This "Sports Vision Pyramid" describes monocular vision as the stable foundation of the pyramid necessary for all other functioning.

Monocular vision, or that of the single eye, utilizes the functions of visual acuity and contrast sensitivity and may be affected by astigmatism or a change in the amount of light available.[79] The next level of the pyramid is concerned with how both eyes work together, or binocular vision, and stereopsis, or the visual perception of depth. The eyes are designed to work together to produce visual images yet when under visual conditions causing motor problems such as fixation disparity or sensory problems such as amblyopia, the loss of one eye's ability to see details, the information processed and produced through binocularity may be incorrect.[79] If both monocular and binocular processes are working efficiently and correctly, the visual mechanics will be optimized. There is an important interaction between the brain and the rest of the body when a visual stimulus is interpreted and a motor response ensues.[79] Athletes perform at the optimal intensity if all three levels of the pyramid are functioning properly.[79]

The visual system provides information about target distance and the presence of obstacles in the visual field, both frontal and periphery, in a static situation. In addition, the visual stimuli provides additional information to maintain balance during standing, walking, running, and in adjusting pathways when obstacles appear, the target moves, or the pathway changes.[85]

Visual Deficits after Concussion

Memory, anticipation, pathways for fast eye movements, and accuracy of the eye muscles are controlled by the cerebral cortex and are not always flagged during cognitive testing.[21] Common symptoms post-concussion that are related to the visual system include blurred vision, double vision, difficulty focusing vision, balance problems, and difficulty in busy visual environments.[21,64] Blurred vision can be a result of either an

efferent or afferent pathway dysfunction from the eyes to the brain.[86,87] Other visual issues including double vision, vertigo and photophobia may be a sign of brainstem or cerebellar pathway dysfunction from the widespread energy crisis occurring during the biochemical response to a concussion.[86] According to Heitger et al., impaired eye movements are an indicator of suboptimal brain function and "may help demonstrate incomplete recovery of brain function."[86]

Visual symptoms do not always present for obvious diagnosis of concussion as some may be masked or confused with neurologic deficits.[16] The frontal lobe of the brain is a primary site of injury in many mechanisms of concussion and can lead to temporary disturbances in the frontal eye fields, impaired visual attention and delayed visual saccades.[88] Disturbances to the midbrain may produce impairments in the visual system including double vision, abnormal pupil activity, or difficulty controlling eyelid functions.[16] Impairments with convergence and nystagmus may be indicative of injury to cranial nerves or the brain stem.[16]

Quality vision is critical for optimal performance for athletes at any level. Just as baseline measures are taken for neurocognitive, balance, and symptom scores, baseline visual performance measures should be taken for both static and dynamic visual acuity.[78] The vestibulo-ocular reflex is a critical reflex of the eye in response to movement that provides information and proprioception that stabilizes vision and the line of sight.[89] These visual signals interact and combine with vestibular information to stabilize gaze during most normal head motions.[89] If there is a deficit in either system, the individual may experience balance problems or vertigo and is prone to further injuries and falls.

Visual performance tests exist to measure and compare injured patients, but are not widely used at this time. The additional time commitment for the tests, questionable reliability and validity, lack of normative values, and lack of sensitivity for concussion identification may be among reasons why visual performance tests are not always used.[90] One purpose of this study is to justify the necessity for a visual performance assessment post-concussion in order to identify potential deficits prior to the individual's full return to participation.

Visual Assessments

Over 50% of the brain's pathways are examined via visual assessments, yet visual performance measures are not always considered part of the comprehensive concussion evaluation.[86] Visual assessments include assessments of static visual acuity, dynamic visual acuity, gaze stability and several other functional measures. Static visual acuity is the ability to see clearly when remaining still and watching a nonmoving object. It is typically assessed using chart systems such as Snellen eye chart. The optimal acuity measurement for a non-athlete is 20/20.[91] There are no differences in static visual acuity between athletes and non-athletes.[13,82,83]

Dynamic visual acuity (DVA) is the ability to resolve detail when there is relative movement between the target and the observer.[13] DVA can be measured by a computerized system that assesses the ability of the patient's vestibulo-ocular reflex to maintain accurate and optimal visual acuity while moving their head with a fixed head velocity requirement.[90] Maintaining focus and sight while moving the head is a crucial function, which is essential for athletes to accurately perceive and identify a moving target during dynamic situations.[91] Patients with vestibular or visual deficits exhibit lower

scores on a DVAT, reflecting a decrease in functioning and requiring some type of compensation from the visual and vestibular systems.[92,93] Compensations such as vestibular adaptation and central programming have been observed in some subjects with vision loss or decreased visual acuity.[92] The vestibular system is adaptive in nature, contributing to the recovery of vestibular response after vestibular loss or injury.[93] The computerized NeuroCom DVAT has high sensitivity and specificity for diagnosing vestibular dysfunction.[92] The high sensitivity and specificity further support the reliability of the dynamic visual acuity test and the ability of the test to distinguish between healthy participants and subjects with vestibular or visual deficits.[92]

The Gaze Stability Test was created to assess how quickly a participant can move their head while maintaining focus on a computer-generated target of fixed size.[94] The GST quantifies the ability of a person to recognize a target projected on a personal computer monitor during active head movement. Outcomes are calculated using the means of the three fastest head velocities with accurate identification and orientation of the target.[90] The information produced demonstrates the functional capacity of vestibulo-ocular reflex and the maximum active head velocity at which a person can stabilize their gaze.[90]

Dynamic visual acuity is often not assessed clinically due to limitations in instrumentation for measurements of DVA. Measures of DVA appear to have similar within session reliability and lower between session reliability when compared to measures of the Gaze Stability Test.[1,90,94,95] The DVAT has been associated with less muscle fatigue than GST. While both use a fixed wait time for the optotype to appear on the screen in front of the individual, the DVAT has a fixed moderate head velocity as

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compared to the GST which requires the subject to maintain higher head velocities during the trials. The DVAT also has caused the return of symptoms in some affected subjects leading to nausea, blurred vision, dizziness, and headache due to the nature of the test and accompanying head movements.[90,94,95]

The inVision System from NeuroCom can be used for the assessment of dynamic visual acuity and gaze stability. The reliability and sensitivity of these tests vary in the literature but when combined, the sensitivity to visual and vestibular disturbances increased to 79% and the specificity was 88%.[92,94] The GST has good test-retest reliability and may be more useful as a measure of treatment outcome or identification of deficits and disabilities when compared to DVAT.[94] Both tests have been found to minimal symptoms in healthy participants.

The Nike SPARQ Sensory Station was created as a functional measure of visual clarity, near far quickness, target capture, reaction time, and eye hand coordination. The SPARQ allows for an interactive testing environment that is able to identify deficits in visual measures and reaction times.[91] A single study has examined the reliability of the SPARQ in a group of younger adults. There were no practice effects for the following measures: visual clarity, contrast sensitivity, depth perception, target capture, perception span, and reaction time. There were practice effects for near-far quickness, eye-hand coordination, and go/no go. The motor response characteristics of these measures are a possible explanation for the practice effect associated with near-far quickness, eye-hand coordination, and go/no go.[91] While Erickson et al. provided a preliminary estimation of reliability for the SPARQ, their sample was not required to be physically active and ranged in ages from 18-30. In order to implement the SPARQ as a concussion evaluation

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measure in college athletes, the reliability of the measure in healthy physically-active college-aged individuals must be established.

King-Devick Test

The King-Devick (K-D) test is a sideline visual screening tool that assesses an individual's ability to read aloud single digit numbers on a screen or a card quickly and efficiently. The test is based on measurement of the speed of rapid number naming (reading single-digit numbers from 3 test cards in addition to any errors the individual makes. The King-Devick test captures impairments of eye movements, attention, language, and visual-motor functioning and it can be used to identify individuals with dyslexia, learning disabilities, suboptimal brain or vision function, and it may be useful in detecting visual impairments following concussion.[96] In addition, it may be used as a rapid sideline assessment for faulty or slow eye movements and other characteristics following a potential brain injury.[96] The King-Devick test has been used to accurately diagnose concussions in some boxers and mixed-martial arts fighters.[97] Similar results were found in a collegiate athletic population.[96] The lower scores recorded for individuals who sustained a concussion suggest that the King-Devick test may be sensitive to visual tracking deficits that occur post-concussion.

Why Test Vision?

It is important to examine vision following a head injury to identify deficits that may go unnoticed in the absence of reported subjective symptoms. Blurred vision, dizziness, sensitivity to light, and inefficient convergence are all symptoms commonly experienced in concussed individuals and all could be indicative of suboptimal functioning in some part of the brain.[86] While there are reliable change indices for

measures of symptoms,[91] postural sway,[91] and neurocognitive functioning,[91] there is

limited evidence establishing the reliability of visual performance measures in an athletic

collegiate population.

There is a gap in the literature regarding psychometric properties of visual

assessments that may be used in the evaluation and management of concussion. Reliable

change indices demonstrate the change in an individual's score we should expect to see

between a first and second testing session. Reliable change indices for visual measures

will allow for a comparison in the change of concussed individual's scores between a first

and second testing session and the change we would expect to see if that individual was

healthy. If the change in the patient's scores is within the RCI for those measures, then

we would expect that the individual is healthy. If the change is the patient's scores is

larger than the RCI for those measures, then we would expect that there is some type of

deficit.

Visual assessments should be involved in concussion evaluation. Athletes should

not return to full participation until visual performance measures have returned to

baseline. The addition of visual assessments to the composite evaluation may identify

deficits that are masked in the absence of symptoms and create a more conservative

return to play paradigm, ultimately leading to better prognosis for concussion.

CHAPTER III

METHODS

Participants

We studied a convenience sample of 44 active, healthy college students (29 male and 15 female; age = 19.90 ± 0.96 yrs; height = 172.03 ± 11.13 cm). Participants were excluded from this study if they had known neurocognitive deficits or disorders, known psychological conditions, color blindness, history of dizziness, imbalance or abnormal vestibular function, or musculoskeletal abnormalities to the head, neck, shoulder, or back that would disrupt normal range of motion. All participants read and signed consent forms approved by our institution's ethics review board. Participants also completed a pre-participation form providing us with demographic, sleep habit, history of vision problems, and concussion history.

Our third research question sought to explore the effect of concussion on vision. Unfortunately, we were only able to capture 5 injuries, an insufficient number to yield any meaningful data to address this research question. These 5 cases are instead used to support some aspects of the discussion related to our other two research questions.

Instrumentation

Dynamic Visual Acuity Test

The Dynamic Visual Acuity Test (DVAT) was performed using the InVision system (NeuroCom International Clackamas, OR). An IBM-PC compatible computer and

a 15-in flat panel high contrast liquid-crystal display monitor were used to display an optotype (the letter "E"). The DVAT began with assessment of the participant's static visual acuity by having them identify the orientation of the optotype "E" on a computer screen located 8 feet in front of them, as illustrated in Figure 3.1. Responses were recorded using a handheld remote with buttons that indicated whether the "E" was positioned to the right, left, upwards, or downwards. The size of the "E" was reduced if the participant correctly identified 3 out of 5 "E"s of a given size. Static visual acuity was defined based on the smallest "E" correctly identified, and measured in logMAR.

The participant's dynamic visual acuity (DVA) was measured in three different axes: the "yaw" (vertical axis rotation), "pitch" (medial-lateral rotation), and "roll" (antero-posterior axis rotation). The participant wore a head harness (InterSense Inertia Cube, Engineering Systems Technology, Kaiserslautern, Germany) with a sensor that integrated the 3 axes the head was moving about to determine rotational velocity (deg/sec) of the head. Participants were required to generate rotational head movements at least 20 degrees from midline in each direction while still being able to correctly analyze an optotype *"E"* of varying sizes. Each test allowed for a practice trial. The size of the smallest optotype identified correctly while rotating the head faster than the minimum velocity was recorded for results of the DVAT. The DVAT scores were converted to visual loss by subtracting dynamic visual acuity from baseline static visual acuity for each eye, averaging the two means, and reporting the outcome in logMAR.[90]

Gaze Stability Test

The InVision system (NeuroCom International,Clackamas, OR) used for the DVAT was also used for the Gaze Stability Test. The GST uses the same static visual

acuity measured with the DVAT. The GST measures head movement velocities that the participant achieves while maintaining their static visual acuity. Participants were required to maintain gaze on the center of a computer screen, demonstrated in Figure 3.1, and correctly identify the orientation of the optotype *"E"* while generating repetitive head movements at varying velocities. Participants used the same headband with a 3-axis integrating gyro to determine velocity for each trial. The participants were instructed to perform a smooth sinusoidal head shake movement until the display screen was visible. Two feedback bars gave the participant information on the velocity and amplitude of the head and disappeared when the participant's head velocity exceeded the required minimum threshold for a trial. The optotype was displayed on the monitor until the participant's head velocity fell below the requirement for that trial or the participant reached a maximum time. If three out of five "E"s were identified correctly, the minimum head velocity that the participant must attain was increased. This was repeated until the participant was unable to correctly identify three out of five "E"s, at which point the velocity was reduced. If the participant was unable to achieve the minimum required head velocity within 8 seconds from the start of head movement or unable to maintain velocity for the required duration, or if the participant achieved and maintained the required velocity but incorrectly identified the orientation, the trial was recorded as a failure.[90] The GST generated maximum head movement velocity (deg/sec) at which the participant was able to maintain visual acuity in each of the three axes of movement (yaw, pitch, and roll).

Nike SPARQ Sensory Station

The Nike SPARQ Sensory Station is operated by a single computer controlling 2 high-resolution liquid crystal display monitors as shown in Figure 3.3. A handheld Apple iPod touch (Apple Corporation, Cupertino, CA) was connected via wireless input to the computer and was used to send the participant's response to the computer software for processing. Prerecorded instructions were automatically played at the start of each assessment and repeated if the participant was unclear on the procedure. Participants completed testing on the Nike SPARQ Sensory Station standing upright under ambient lighting. Participants were aligned at 16 feet away from the monitor for Visual Clarity, Contrast Sensitivity, Depth Perception, Near-Far Quickness, and Target Capture and moved to within arm's length distance from the monitor for Perception Span, Eye-Hand Coordination, Go/No-Go, and Reaction Time assessments. More detailed descriptions of each of the individual tests are included in Table 3.2.

King-Devick Test

This quick sideline assessment requires an individual to read aloud a series of single digit numbers from left to right on three test cards. Standardized instructions are used; the test requires less than 2 min to administer. The King-Devick test includes one demonstration card and three test cards. Participants are asked to read the numbers on each card from left to right as quickly as possible but without making any errors. The sum of the three test card time scores constitutes the summary score for the entire test. Numbers of errors made in reading the test cards are also recorded. The King-Devick test can either be administered with paper cards or on portable computerized devices, illustrated in Figure 3.3.

Procedure

        Participants were tested under best-corrected vision condition. Participants completed a questionnaire to ensure that all inclusion and exclusion criteria were met, and to gather information about sleep patterns and cognitive load on the day of testing (Appendix 1). All participants completed the Dynamic Visual Acuity Test (DVAT), Gaze Stability Test, and the complete Nike SPARQ Sensory Station battery. Additionally, 40 of the 44 participants also completed the King-Devick Test. The order in which the test batteries were administered was counterbalanced to control for order effect (Table 3.1). The data collection session was concluded after the participant completed all three test batteries. Participants reported to the research center for a total of two visits each with at least 14 days, but no more than 19 days, between visits (mean time between testing session: 14.6 ± 1.6 days). The second data collection session consisted of repeating the four protocols in the same test order as the initial data collection session. Each testing session lasted approximately one hour.

Data Reduction

        We computed a number of outcome measures pertaining to our research study. The two King-Devick Test measures included total completion time and number of committed errors. The SPARQ Sensory Station measures included Visual Clarity (measured in logMAR), Contrast Sensitivity (contrast ratio), Depth Perception (mean of left and right threshold reached; measured in arc seconds), Near-Far Quickness (frequency of trials completed within 30 seconds), Target Capture (threshold response time in milliseconds), Perception Span (frequency of correct responses), Eye-Hand

Coordination (time in milliseconds), Go/No-Go (number of correct responses minus number of incorrect responses), and Reaction Time (consisting of Reaction Time, Response Time, and Motor Movement Time; all in milliseconds). We calculated DVA loss in logMAR by subtracting the dynamic visual acuity for each eye from the participant's static visual acuity, and then computed the average between the two sides. We computed this in yaw, pitch, and roll directions. Similarly, the Gaze Stability Test measured rotational velocity (in degrees/second) in the left and right directions; these were averaged for each direction (yaw, pitch, and roll).

Data Analysis

General descriptive statistics were computed for each clinical outcome measure on the Gaze Stability Test, the Dynamic Visual Acuity Test, the King-Devick Test, and the Nike SPARQ Sensory System in our sample of healthy participants. Additionally, interclass correlation coefficients were computed using Pearson correlations to assess the test-retest reliability of our measures. Since this technique is unable to identify systematic differences, we also employed paired-samples t-tests comparing both test sessions for each outcome measure. We employed this approach since the Pearson correlation coefficient is a required step in determining the Reliable Change Index (RCI) for our measures.

The RCI outcomes were computed using an identical and systematic approach employed for each outcome measure. First, the correlation (r) between the two test sessions was determined. Descriptive statistics included standard deviations (SD) for each outcome measure derived for each test session. This information was used to

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compute the standard error of the measurements (SEM) for each test session using the

following formula:

$$SEM = SD\sqrt{1-r}$$

Next, we computed the standard error of the difference (SE$_{diff}$):

$$SE_{diff} = \sqrt{SEM_1 + SEM_2}$$

Lastly, the SE$_{diff}$ was multiplied by the *z* scores associated with 80% (z = 1.282), 90% (z

= 1.684), and 95% (z = 1.96) confidence intervals to compute the RCI values for each of

the measures as follows:[98,99]

RCI = SE$_{diff}$ x *z* score for associated confidence level

Data were analyzed using SPSS 19 (SPSS Inc.; Chicago, IL). An a priori α level of

significance was set at 0.05 for all analyses.

Table 3.1. Counterbalanced test order for all assessments.

Testing Order Option	First Assessment	Second Assessment	Third Assessment	Fourth Assessment
1	Dynamic Visual Acuity Test	Gaze Stability Test	Nike SPARQ Assessment	King-Devick Test*
2	Gaze Stability Test	Dynamic Visual Acuity Test	Nike SPARQ Assessment	King-Devick Test*
3	Nike SPARQ Assessment	King-Devick Test*	Gaze Stability Test	Dynamic Visual Acuity Test
4	Nike SPARQ Assessment	King-Devick Test*	Dynamic Visual Acuity Test	Gaze Stability Test

*King-Devick Test was always performed after Nike SPARQ Assessment for logistical purposes

Table 3.2. Data analysis summary table.

Research Question	Description	Data Source	Comparison	Method
1	Are athletes' visual test performances reliable on Nike SPARQ, King-Devick Test, Neurocom gaze stability test and Neurocom dynamic visual acuity test?	IV: **Time** Test Session 1 Test Session 2 (14 days) DV: SPARQ measures (10) DVT (3) GST (3) King-Devick (2)	Visual performance on SPARQ, GST, DVAT from testing session 1 to testing session 2	Paired-samples t-test Pearson correlations $ICC_{3,1}$ values
2	What are the reliable change indices between testing session 1 and testing session 2 on the measures?	IV: **Time** Test Session 1 Test Session 2 (14 days) DV: SPARQ measures (10) DVT (3) GST (3) King-Devick (2)	Visual performance on SPARQ, GST, DVAT from testing session 1 to testing session 2	S_{diff} RCI 80%, 90%, 95%
3 (Exploratory)	Is there a significant difference in scores on visual performance measures between individuals with a concussion and matched controls across time?	IV: **Group** Healthy vs. Concussed **Time** Asmptomatic/Full Participation DV: SPARQ measures (10) DVT (3) GST (3) King-Devick (2)	Difference of scores between groups on SPARQ domains and between the two testing sessions.	2x2 mixed model repeated measures ANOVAs, with Tukey post hoc when the omnibus test for interaction effects were significant

Table 3.3. Nike SPARQ Sensory Station module descriptions.

Measure	Protocol Description	Outcome Measure Computation
Visual Clarity †	A Landolt ring of 20/50 equivalent stimulus appears on the screen -Athlete is instructed to swipe in the direction of the gap / If correct, the ring decreases in size until the athlete does not correctly identify stimulus / Stimulus then increases in size until gap direction is identified correctly Assessment continues until several reversal points are complete / Performed with vision occluded in left eye, then right eye, and then binocularly	System identifies the threshold acuity between 20/8 and 20/99 using a staircase reversal algorithm / LogMar values for oculus Uterque (both eyes) were used
Contrast Sensitivity †	4 black circles present in a diamond configuration on a light gray background / 1 circle contains a pattern of concentric rings that vary in brightness from the center to the edge / Athlete swipes their finger on screen in the direction of the circle with the contrasted pattern / Assessed at 6 and 18 cycles per degree	System identifies the cycles per degree threshold / Contrast sensitivity at 18 cycles per degree was used
Depth Perception †	Athletes wear a pair of liquid crystal goggles that cause 1 of the 4 rings to appear to float 3-dimensionally in front of the screen / Instructed to swipe in the direction of the floating ring	System identifies the arc second threshold between 237 and 12 using a staircase reversal algorithm
Near-Far Quickness †	Athlete holds the iPod 16 inches from the eyes, with the top edge positioned just below the bottom of the display / A black Landolt ring of 20/80-equivalent presents on the far screen / Athlete swipes in the direction of the gap in the ring presented on the far display / If correct, a Landolt ring appears on the iPod screen / Continually switch focus between far and near for 30 seconds	Calculated by summing the # of times each subject correctly responds by swiping towards the gap in the Landolt ring within the 30 second trial
Target Capture ‡	Athlete is instructed to fixate on a central black dot / A Landolt ring (0.1 log unit > visual clarity threshold) appears briefly in 1 of the 4 corners of the screen / Athlete swipes in the perceived direction of the gap in the ring	System identifies the millisecond threshold between 0 at 500 using a staircase reversal algorithm
Perception Scan ΩΣ	Focused on a black dot in the center of a grid pattern composed of up to 30 blank circles / A pattern of turquoise dots flashes within the grid of circles simultaneously for 100 milliseconds / Athlete is instructed to touch the screen to recreate the pattern of dots / If 75% correct, the grid increases in size and # of dots. / The first two levels consist of 6 blank circles in the grid pattern with 2 and 3 turquoise dots, the next 5 levels consist of 18 blank circles with 3 to 7 turquoise dots, and the last 4 levels consist of 30 blank circles with 7 to 10 turquoise dots / If not 75% correct, the level is be repeated - If failed twice, the assessment is terminated	Calculated by summing the number of correct responses minus the number of missed responses and extra guesses
Eye-Hand Coordination ΩΣ	Athletes hold arms parallel to the ground at shoulder height in front of an 8x6 grid of equally spaced blank circles / A turquoise dot appears within one blank circle of the grid / Athlete is instructed to touch the dot as quickly as possible using either hand / As soon as they touched the dot, another turquoise dot appears. 96 dots total	Calculated as the total time to touch all 96 dots
Go/No-Go ΩΣ	Same as the eye hand coordination, except that the dot stimulus could be either turquoise or red / Turquoise dot: touch dot at quickly as possible / Red dot: do not to touch. / 96 total dots (64 turquoise, 32 red) / Each dot is presented for 450 milliseconds, with no time gap between dot presentations	Calculated by summing the # of turquoise dots touched minus any red dots touched
Reaction Time Ω	Two annular patterns appear on the screen - place fingertips of dominant hand on the annulus on that side of the screen / Center body in front of the opposite annulus and focus attention on the center of that annulus / After a randomized delay of 2, 3, or 4 seconds, the test annulus turns turquoise / Move hand to touch the annulus as quickly as possible	Calculated as the elapsed time between onset of the test annulus and release of the control annulus

† Athlete stands 16 feet away from the 22-inch display and respond to stimuli using iPod touch
‡ Athletes stood 16 feet away from the 42-inch display and respond to stimuli using iPod touch
Ω Athletes were positioned within arm's length of the 42-inch touch-sensitive display, with the center of the screen adjusted to their height using a ruler mounted on the right side of the Sensory Station.
Σ Dots were pseudorandomized to maintain equivalent spatial distribution within each presentation and to eliminate "clustering" of dots and easily recognizable patterns.

Figure 3.1. NeuroCom test setup
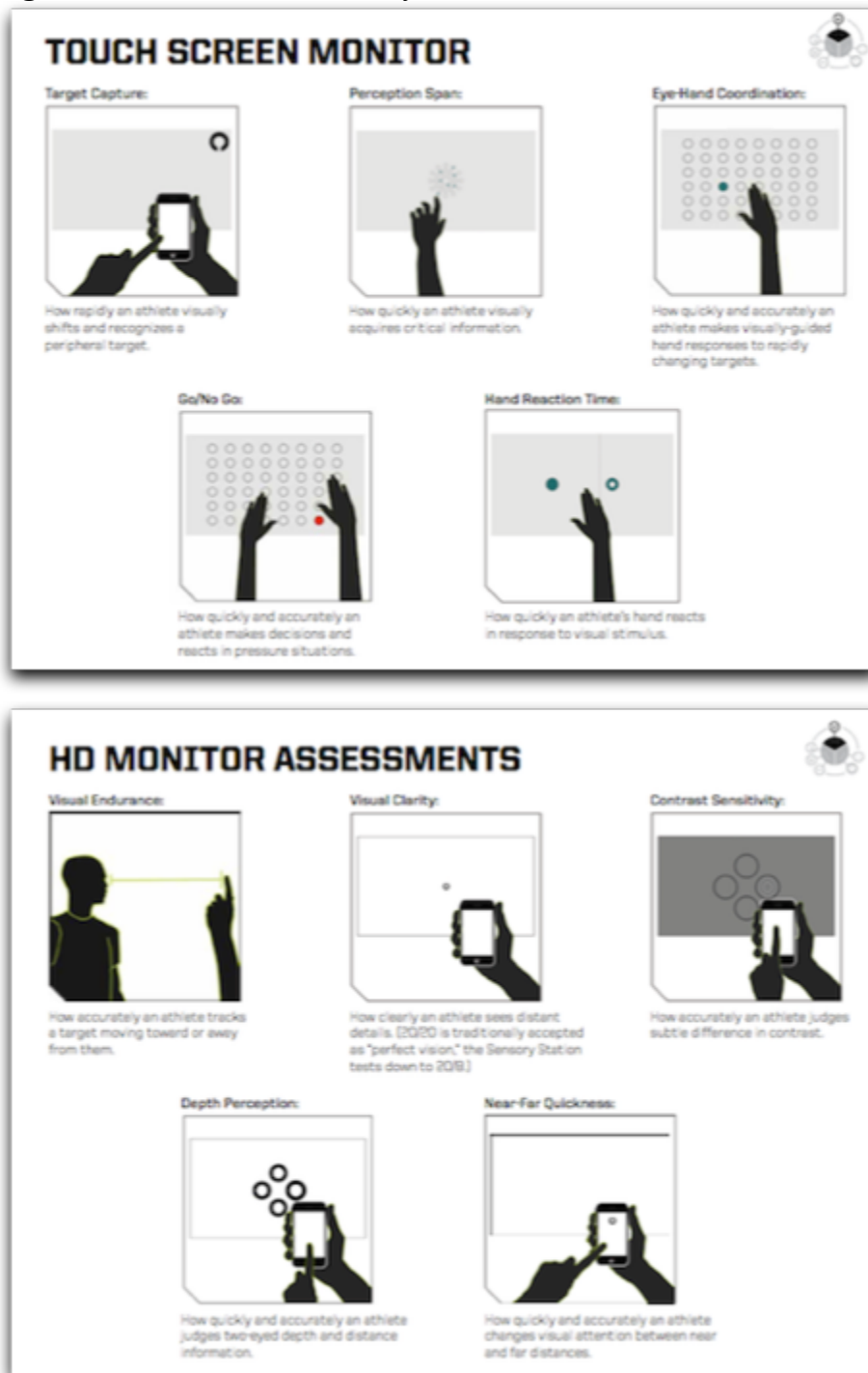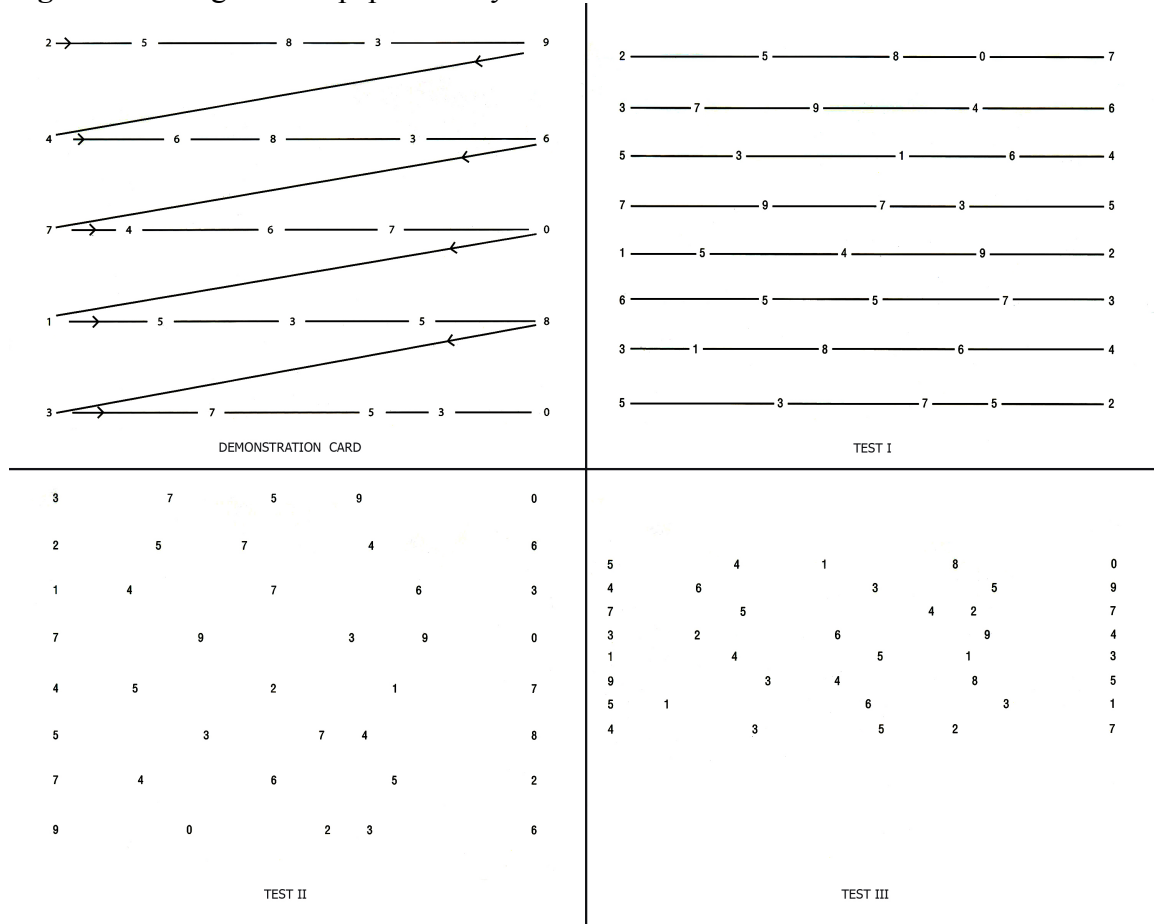
Figure 3.2. Nike SPARQ Sensory Station test constructs

Figure 3.3. King-Devick paper battery

DEMONSTRATION CARD

TEST I

TEST II

TEST III

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CHAPTER IV

MANUSCRIPT

Introduction

Concussions are a public health concern in today's society, with as many as 3.8 million reported each year in the United States from sports and recreational activity alone.[2] Many other suspected head injuries may go unreported.[3] The frequency of head injuries has seen a steady increase over the past 5-10 years,[32,100] likely due to an escalation in education efforts and improvements in concussion assessment tools and treatments. Concussion, a form of mild traumatic brain injury, has been defined as a complex pathophysiologic process affecting the brain and its functioning following an injury to the head.[4] Concussions result in debilitating symptoms including cognitive, balance, and visual deficits that can last anywhere from 24 hours to several months after the initial injury.[4] While subjective assessments can expose acute symptoms such as mental status deterioration, dizziness, headache, nausea, confusion, tinnitus, and blurry vision,[4] objective assessments are typically employed to expose cognitive, balance, and vision disturbances.

The commonly used symptom, neurocognitive and balance assessments are well established, reliable and sensitive for specific deficits,[7-9] but do not address aspects such as dynamic or static vision or gaze stability, which may be associated with concussion. Recent literature suggests incorporating visual evaluations may lead to a more complete assessment of an individual.[15] This is not surprising given the critical role general vision

plays for all athletes,[12,13] and the sport-specific visual skills required to perform tasks such as hitting a baseball, catching a football, or spotting a 4-inch balance beam. To accomplish these tasks, athletes interpret visual information and pattern motor responses dependent on the stimuli. There is proportional relationship between an athlete's perceptual ability and motor response.[14] Successful athletes generally interpret visual information better and, therefore, have sharper visual acuity, accuracy and spatio-temporal awareness.[14] If an athlete is not receiving visual feedback fast enough to assess the situation and act on the information, performance will decline.[14] Impaired visual performance may inhibit the ability to anticipate potentially injurious mechanisms during participation and, thus, increase injury risk.[101,102] To account for the changing nature of athletic performance, static visual acuity is an insufficient measure of visual and sensory performance. We posit that dynamic visual acuity measures may be more appropriate to expose deficits that could potentially affect an athlete's functional visual ability during sport participation. Given the potential interrelationship between performance and injury prevention, we believe that visual performance measures may have a doubly important role in the concussion management paradigm that has too long been limited to symptoms, cognition, and balance testing.[15] Such measures should include functional visual skills such as depth perception, dynamic visual acuity, contrast sensitivity, and vergence-accomodation[12] If there are deficits in the visual system due to concussion, employing objective measures of an athlete's vision as part of the baseline-testing program will yield helpful clinical information for the athlete's post-injury care. Unfortunately, very little is known about the potential clinical utility of vision and sensory performance measures in this context.

Therefore, the purpose of this study was to determine the test-retest reliability and reliable change indices for measures of visual and sensory performance in healthy college participants. Reliable change methodology has been described in detail,[103-106] and revised over the years to encompass both the reliability and the practice effects of an instrument.[103] The RCI incorporates the reliability and variance of a measure to produce a value that represents a clinically meaningful change, which can be defined as change that occurred beyond the scope of measurement error or variability. Reliable change methodologies have been used for various concussion assessment measures including cognition and balance.[19,99,107,108]

Methods

Participants

We studied a convenience sample of 44 active, healthy college students (29 male and 15 female; age = 19.90 ± 0.96 years). Participants were excluded from this study if they had known neurocognitive deficits or disorders, known psychological conditions, color blindness, history of dizziness, imbalance or abnormal vestibular function, or musculoskeletal abnormalities to the head, neck, shoulder, or back that would disrupt normal range of motion. All participants read and signed consent forms approved by our institution's ethics review board.

Instrumentation

Dynamic Visual Acuity Test

The Dynamic Visual Acuity Test (DVAT) was performed using the InVision system (NeuroCom International; Clackamas, OR). An IBM-PC compatible computer

and a 15-in flat panel high contrast liquid-crystal display monitor were used to display an optotype (the letter "E"). The DVAT began with assessment of the participant's static visual acuity by having them identify the orientation of the optotype "E" on a computer screen located 8 feet in front of them seen in Figure 3.1. Responses were recorded on the computer by the clinician after the subject indicated whether the "E" was positioned to the right, left, upwards, or downwards. The size of the "E" was reduced if the participant correctly identified 3 out of 5 "E"s of a given size. Static visual acuity was defined based on the smallest "E" correctly identified, and measured in logMAR units.

The participant's dynamic visual acuity (DVA) was measured in three different axes: the "yaw" (vertical axis rotation), "pitch" (medial-lateral rotation), and "roll" (antero-posterior axis rotation). The participant wore a head harness (InterSense Inertia Cube, Engineering Systems Technology, Kaiserslautern, Germany) with a sensor that integrated the 3 axes the head was moving about to determine rotational velocity (deg/sec) of the head. Participants were required to generate rotational head movements at least 20 degrees from midline in each direction while still being able to correctly analyze an optotype *"E"* of varying sizes. Each test allowed for a practice trial. The size of the smallest optotype identified correctly while rotating the head faster than the minimum velocity was recorded for results of the DVAT. The DVAT scores were converted to visual loss by subtracting dynamic visual acuity from baseline static visual acuity for each eye, averaging the two means, and reporting the outcome in logMAR units.[90]

Gaze Stability Test

The InVision system (NeuroCom International; Clackamas, OR) used for the DVAT was also used for the Gaze Stability Test. The GST uses the same static visual acuity measured with the DVAT. The GST measures head movement velocities that the participant achieves while maintaining their static visual acuity. Participants were required to maintain gaze on the center of a computer screen and correctly identify the orientation of the optotype *"E"* while generating repetitive head movements at varying velocities. Participants used the same headband, seen in Figure 3.1, with a 3-axis integrating gyro to determine velocity for each trial. The participants were instructed to perform a smooth sinusoidal head shake movement until the display screen was visible. Two feedback bars gave the participant information on the velocity and amplitude of the head and disappeared when the participant's head velocity exceeded the required minimum threshold for a trial. The optotype was displayed on the monitor until the participant's head velocity fell below the requirement for that trial or the participant reached a maximum time. If three out of five "E"s were identified correctly, the minimum head velocity that the participant must attain was increased. This was repeated until the participant was unable to correctly identify three out of five "E"s, at which point the velocity was reduced. If the participant was unable to achieve the minimum required head velocity within 8 seconds from the start of head movement or unable to maintain velocity for the required duration, or if the participant achieved and maintained the required velocity but incorrectly identified the orientation, the trial was recorded as a failure.[90] The GST generated maximum head movement velocity (deg/sec) at which the

participant was able to maintain visual acuity in each of the three axes of movement (yaw, pitch, and roll).

Nike SPARQ Sensory Station

The Nike SPARQ Sensory Station is operated by a single computer controlling 2 high-resolution liquid crystal display monitors illustrated in Figure 3.3. A handheld Apple iPod touch (Apple Corporation, Cupertino, CA) was connected via wireless input to the computer and was used to send the participant's response to the computer software for processing. Prerecorded instructions were automatically played at the start of each assessment and repeated if the participant was unclear on the procedure. Participants completed testing on the Nike SPARQ Sensory Station standing upright under ambient lighting. Participants were aligned at 16 feet away from the monitor for Visual Clarity, Contrast Sensitivity, Depth Perception, Near-Far Quickness, and Target Capture and moved to within arm's length distance from the monitor for Perception Span, Eye-Hand Coordination, Go/No-Go, and Reaction Time assessments. More detailed descriptions of each of the individual tests are included in Table 3.2.

King-Devick Test

This quick sideline assessment requires an individual to read aloud a series of single digit numbers from left to right on three test cards. Standardized instructions are used; the test requires less than 2 min to administer. The King-Devick test includes one demonstration card and three test cards. Participants are asked to read the numbers on each card from left to right as quickly as possible but without making any errors. The sum of the three test card time scores constitutes the summary score for the entire test. Numbers of errors made in reading the test cards are also recorded. The King-Devick test

can either be administered with paper cards, as seen in Figure 3.3, or on portable computerized devices.

Procedure

Participants were tested with best-corrected vision. Participants completed a questionnaire to ensure that all inclusion and exclusion criteria were met, and to gather information about sleep patterns and cognitive load on the day of testing (Appendix 1). All participants completed the Dynamic Visual Acuity Test (DVAT), Gaze Stability Test, and the complete Nike SPARQ Sensory Station battery. Additionally, 40 of the 44 participants also completed the King-Devick Test. The order in which the test batteries were administered was counterbalanced to control for order effects (Table 3.1). The data collection session was concluded after the participant completed all four test batteries. Participants reported to the research center for a total of two visits each with at least 14 days, but no more than 19 days, between visits (mean time between testing session: 14.6 ± 1.6 days). The second data collection session consisted of repeating the four protocols in the same test order as the initial data collection session. Each testing session lasted approximately one hour.

Data Reduction

We used the following outcome measures for the King-Devick Test: total completion time (seconds) and number of committed errors. The SPARQ Sensory Station outcome measures included Visual Clarity (measured in logMAR units), Contrast Sensitivity (average between 6 and 18 cycles/degree thresholds), Depth Perception (mean of the forward-, left- and right-facing condition threshold reached; measured in arcseconds), Near-Far Quickness (number of correctly identified targets completed within

30 seconds), Target Capture (minimum duration of stimulus in milliseconds), Perception

Span (total number of correct responses minus errors), Eye-Hand Coordination (total

completion time in milliseconds), Go/No-Go (number of correct responses minus number

of incorrect responses), and Reaction Time (which also includes Motor Movement Time;

in milliseconds). We subtracted the dynamic visual acuity for each eye from the

participant's static visual acuity, and then computed the average between the two sides to

calculate the Dynamic Visual Acuity loss in logMAR units. We computed this in yaw,

pitch, and roll directions. Similarly, the Gaze Stability Test measured rotational velocity

(in degrees/second) in the left and right directions; these were averaged for each direction

(yaw, pitch, and roll).

Data Analysis

General descriptive statistics were computed for each clinical outcome measure

on the Gaze Stability Test, the Dynamic Visual Acuity Test, the King-Devick Test, and

the Nike SPARQ Sensory System in our sample of healthy participants. Additionally,

intraclass correlation coefficients ($ICC_{2,1}$) were computed to assess the test-retest

reliability of our measures. The RCI outcomes were computed using an identical and

systematic approach employed for each outcome measure. First, the correlation (r)

between the two test sessions was determined. Descriptive statistics included standard

deviations (SD) for each outcome measure derived for each test session. This information

was used to compute the standard error of the measurements (SEM) for each test session

using the following formula:

$$SEM = SD\sqrt{1-r}$$

Next, we computed the standard error of the difference (SE_{diff}):

$$SE_{diff} = \sqrt{SEM_1 + SEM_2}$$

Lastly, the SE_{diff} was multiplied by the z scores associated with 80% ($z = 1.282$), 90% ($z = 1.684$), and 95% ($z = 1.96$) confidence intervals to compute the RCI values for each of the measures as follows:[98,99]

RCI = SE_{diff} x z score for associated confidence level

We also employed paired-samples t-tests comparing both test sessions for each outcome measure to identify significant practice effects, as these findings are factored into RCI interpretation. Data were analyzed using SPSS 19 (SPSS Inc.; Chicago, IL). An a priori α level of significance was set at 0.05 for all analyses.

Results

All participants completed the Dynamic Visual Acuity Test, Gaze Stability Test, and the complete Nike SPARQ Sensory Station battery. Additionally, 40 of the 44 participants also completed the King-Devick Test. Only 43 subjects were included for Visual Clarity, Contrast Sensitivity, Near-Far Quickness and Target Capture for the SPARQ, because one participant's Visual Clarity measurement during their second testing session was an outlier, consequently affecting the other measures that use Visual Clarity. Only 42 participants were analyzed for Reaction Time on the SPARQ, because 2 participants were not properly saved due to technical issues.

All data are presented in Tables 4.1 and 4.2. We observed a learning effect (improvement) on the following SPARQ Sensory Station measures: Visual Clarity ($t_{41} = 2.30$; $P = 0.027$); Near-Far Quickness ($t_{41} = -4.13$; $P < 0.001$); Eye-Hand Coordination ($t_{42} = 4.73$; $P < 0.001$); Go/No-Go ($t_{42} = -4.34$; $P < 0.001$) and Reaction Time ($t_{40} = 2.24$;

$P = 0.031$). No other significant learning effects were observed on the remaining SPARQ

Sensory Station measures, or those observed for the King-Devick Test, DVAT, or GST

($P > 0.05$ for all). The following tests demonstrated statistically significant test-retest

correlations: Visual Clarity ($r_{41} = 0.50$; $P = 0.001$), Depth Perception ($r_{42} = 0.39$; $P =$

0.009), Near-Far Quickness ($r_{41} = 0.42$; $P = 0.005$), Perception Span ($r_{42} = 0.60$; P

<0.001), Eye-Hand Coordination ($r_{42} = 0.46$; $P = 0.002$), Reaction Time ($r_{40} = 0.53$; P

<0.001), and Motor Movement Time ($r_{40} = 0.47$; $P = 0.002$).

Discussion

This study highlights the reliability of visual and sensory performance

assessments that have the potential use of evaluating concussion. We examined the test-

retest reliability in the GST, DVA, King-Devick and Nike SPARQ System to determine

if any measures could be used to assess visual performance in athletes and identify

potential deficits in individuals after returning from a head injury or other visual

disturbances. The majority of correlations that we calculated demonstrated that the GST

and DVA test on the NeuroCom system possess low reliability across two testing

sessions, which corresponds to results previously presented in the literature.[19,90] Ward et

al. examined test-retest reliability in the NeuroCom DVA and GST within a single

session and across a 7-10 day interval. Intrasession reliability for the GST (pitch = 0.69;

yaw = 0.75) and DVA (pitch=0.60; yaw = 0.56) were good to excellent. The intersession

reliability across two serial testing sessions separated by 7-10 days for the GST (pitch =

0.54; yaw = 0.59) and DVA (pitch = 0.10; yaw = 0.49) were fair to good.[90] One possible

explanation for the differences in findings is the disparity in ages and physical activity

level of our participants. Ward et al. looked at a sample of subjects in two very different

age groups; mean age of the younger adults was 25.2 years and mean age of the older adults was 76.3 years. These subjects performed the GST and DVA test twice on the first testing session and followed up with a repeat performance on a second testing session 7-10 days later.[90] This may account for the high stability and test-retest reliability on the same day as the subjects were familiarized with the testing and did not have as much time as our subjects did between testing sessions. Participants in our study were healthy and active but more importantly the first group of 20 participants were tested at the end of the semester while the second group of 24 subjects were testing toward the middle of the school semester. This may have resulted in extra stress weighing on the subjects, potentially affecting their level of focus or motivation to perform the tests. The NeuroCom tests require a great deal of focus and concentration. If participants lost focus or were not putting forth their best effort during the assessments, the results may be different from one session to the next. An alternate explanation for the change in results on visual and sensory performance measures could be how participants achieved their "best corrected vision." For example, it is possible that old prescriptions, or damaged or dirty corrective lenses, may have led to a test-retest difference in vision. Another consideration with the NeuroCom testing is the potential for return of symptoms in an injured population. Out of the 44 healthy participants tested, 5 subjects complained of dizziness or a headache following the testing session. In our small sample group of concussed individuals for the exploratory project, there were no complaints or return of symptoms. We tested the concussed individuals when they had reported being symptom-free for 24 hours, which may be why we did not see any testing-induced symptoms in these individuals. Among our healthy sample, there were 2 participants who reported a

previous attention disorder diagnosis, and were currently taking medications (Adderall) over the course of the testing session. One of these participants complained of dizziness, and became irritable and frustrated due to NeuroCom DVA and GST testing procedures. Since many vision tests inherently require attention demands, future studies should explore how attention disorders and learning disabilities—and the medications used to manage them—may influence visual performance assessments, and may point to a different set of RCI values that may better apply to these unique clinical populations.

Out of the 10 Nike SPARQ tests that make up the full assessment, 5 of them demonstrated a high, statistically significant correlation. The results from session 2 were strongly related to the results from session 1 on the Visual Clarity, Near-Far Quickness, Perception Span, Eye-Hand Coordination, and Go/No-Go testing constructs. These tests are also those that require a quicker motor response, potentially leading to a learning effect between the two testing sessions, similar to that seen in previously presented research by Erikson.[91] The SPARQ assessment of static visual acuity (Visual Clarity) demonstrated a strong reliability; whereas, the NeuroCom assessment of static visual acuity did not. Interestingly, the NeuroCom SVA demonstrated good concurrent validity with the Visual Clarity test on the SPARQ for time session 1 ($r = 0.61$) and for time session 2 ($r = 0.45$). These were the only significant correlations we observed between the test batteries; the NeuroCom DVA and the Target Capture (Nike SPARQ measure of dynamic visual acuity) were not significantly correlated. Participants on the NeuroCom are required to maintain visual acuity while moving their head in three different planes for the DVA test. Dyamic visual acuity is measured on the Nike SPARQ in the Target Capture assessment which requires more eye tracking and the participants are not

required to move their entire head as much as they are on the NeuroCom. The subjects

stood approximately 12 feet away from the HD monitor when performing the SPARQ

test and sat at about 8 feet away from the computer monitor during the NeuroCom test.

Looking at the change between sessions for static visual acuity, the average mean static

visual acuity measured on the SPARQ Visual Clarity test increased from 20/13 (-0.18

logMAR units) on the first testing session to 20/12 (-0.21 logMAR units) on the second

testing session. This improvement may be attributed to participants familiarizing

themselves with the testing and not an actual improvement in the subject's visual acuity.

Those tests that show a low correlation include Contrast Sensitivity, Depth

Perception, and Reaction Time. Both Contrast Sensitivity and Depth Perception require

the subject to identify correct optotypes with varying background patterns, shading and

different dimensions. The low correlation may be due to the lighting in the testing

environment or the use of the 3D glasses which is discussed later in the section. Erikson

performed a reliability test on the Nike SPARQ with 1 week between testing sessions and

also found no significant difference on these same three constructs.[91] If clinicians have

the opportunity to use the Nike SPARQ Sensory Station for evaluation or rehabilitation

purposes in an injured population, they should consider employing other tools to assess

individuals' contrast sensitivity, depth perception, and reaction time. These oculomotor

tasks may be assessed by more sideline-accessible and clinically relevant tests. Low

performers in Target Capture and Depth Perception have been reported to subsequently

experience higher head accelerations suggesting that while the strength in those two

measures may not be clinical, they do provide a potential metric that may be used for

injury prevention purposes.[101]

We then looked at the reliability and stability of the King-Devick Test, the quick sideline assessment that has been used to accurately diagnose concussions in a collegiate population, boxers, and mixed martial art athletes.[97,96] The lower scores recorded for individuals who sustained a concussion in the previous mentioned studies suggest that the King-Devick test may be sensitive to visual tracking deficits that occur post-concussion. In our study, the King-Devick test proved to be the quickest assessment, required the least amount of equipment, and demonstrated good reliability.

Our results provide the preliminary data to consider the inclusion of non-traditional visual performance measures in the evaluation—and possible rehabilitation—of concussed athletes. Future studies should explore the clinical utility of visual performance testing in injured athletes, as subtle visual deficits may identify still-injured athletes when other traditional measures (e.g. neurocognition, balance testing, symptoms) may have fully resolved. Subsequent studies should evaluate the sensitivity, specificity, and predictive values of visual performance testing in the context of concussion diagnosis and management. Clinicians should measure multiple domains of function (neurocognition, balance testing, symptoms, etc.), as this will likely increase their ability to identify impaired athletes and provide the best medical care. Injured individuals may be identified when compared to the RCIs found in this study; however, clinicians should recognize it is possible that patients who do not exceed clinical RCI may still be experiencing problems related to their injury. A common approach to chart recovery is to compare an athlete's score on post-concussion measures to their own baseline score. A anecdotally employed practice is to clear an athlete of a domain-specific impairment if they meet 95% of their own pre-injury score (e.g. neurocognitive function, symptom

score, and balance performance). Using RCIs may prove to be a more conservative approach in identifying athletes who may continue to present with deficits. For example, suppose a women's soccer athlete completes the Eye-Hand Coordination test during a pre-injury baseline test session in 50 seconds, and sees a decline in performance (52.5 seconds) when she completes the test post-injury. While she meets the 95% of her pre-injury baseline measure, a 2.5-second departure exceeds the 80%, 90%, and 95% reliable change index for this measure. In this example, her clinical care provider would be able to identify a persistent deficit by employing a RCI approach to clinical interpretation of her post-injury data.

Previous studies have applied reliable change methodology to concussion assessment measures, but there had not been extensive research incorporating visual and sensory performance assessments. The computerized NeuroCom DVAT has been seen to carry high sensitivity and specificity for diagnosing vestibular dysfunction,[92] further supporting the potential of the test to reliably distinguish between healthy participants and subjects with vestibular or visual deficits.[92] The vestibular system is adaptive in nature, contributing to the recovery of vestibular response after vestibular loss or injury, which may be a potential reason for the learning affect from session 1 to session 2.[93]

With regard to the use of visual and sensory performance assessment procedures in sports medicine, it is important to stress that the reliable change indices are meant to support and supplement clinical judgment along with the paradigm of other assessments post-concussion. If a clinician choses to incorporate visual performance assessments post-injury, the RCIs computed in this study may be helpful to compare to changes in a healthy individual. The RCIs may allow clinicians to estimate the probable range of

measurement error surrounding test-retest difference scores. If a clinician is still questioning an individual who does not present with deficits outside of the RCI, the ancillary tests may provide more information on the subject's motor, visual, and somatosensory functioning.

The results in the healthy participants demonstrate the reliable change index that we would expect to see between two testing sessions on the same test. While we were able to establish RCIs in our study, an important next step will be to validate these RCIs (sensitivity, specificity, and predictive values) in a larger study of injured participants and uninjured controls. Our healthy participants were tested approximately 14 days apart as an initial investigation of test-retest reliability and development of RCIs. It is unknown at this time whether we would see the same degree of reliability and precision of our RCIs were we to employ a longer test-retest interval. Future studies should also explore the implications of longer test-retest periods to mimic those likely to occur in a traditional baseline—post-injury concussion management paradigm. If a post-concussive individual's scores fall outside the range of the RCI relative to their own baseline, the clinician can be confident that the reason for the deficit is due to some reason other than chance of testing variance depending on the confidence interval chosen (80%, 90%, and 95%). Mean improvements were then added to the RCIs for the specific variable as an indicator of reliable improvement in the presence of a significant practice effect for that measure. The three different confidence intervals may be applied based on clinician preference and the complexity of the individual case. The 80% RCI is the most clinically conservative value as more values outside of the normal change range are identified as deficits. Though the 80% RCI is not as clinically liberal as the 95% RCI, the clinician is

accepting a higher probability that the change was due to error or variance in test performance. The 95% RCI is typically the most statistically accepted value, but identifies fewer deficits outside the range. The RCIs we computed are designed to identify the reliable clinical deficit change among patients measured on the domains. Since several of our tests resulted in observed practice/learning effects, the magnitude of these differences should be added to the respective RCI values presented to identify clinical improvement in patients evaluated for whom we may not have pre-injury data with which to compare post-injury scores.

Our study measured the reliability of visual performance measures, and used this information to develop clinical RCIs. In conducting our study, however, we observed the potential role these platforms—though evaluative in nature—may play in rehabilitating concussed athletes who are complaining specifically of visual and visual-motor dysfunction. Under currently accepted concussion management guidelines, athletes are required to complete a gradual progression into physical and mental stress once they are symptom-free. During this process, designed to gradually enhance physical exertion as a means to functionally re-integrate them back into their sport, we feel that many of the visual performance measures may be used as a visual training and rehabilitative tool. Along these lines, reintegration into activity should begin by first verifying and correcting any visual deficits including, but not limited to, restoring static visual acuity, addressing any monocular and binocular convergence and accommodative issues, and enhancing dynamic visual acuity. Addressing these visual deficits may also play a considerable role in mitigating symptoms athletes often experience during acute recovery when they are returned to the classroom prematurely. Future studies should continue to

explore the role of ophthalmological and neuro-optometric interventions as part of the concussion management care plan.

Limitations

This study is not without some limitations. Our research was limited by the relatively small sample size as well as the assessments on only the NeuroCom DVA, GST, Nike SPARQ, and the King-Devick Tests. Future studies should examine the performance in concussed individuals and either compare to an individual's baseline measures or compare the change between testing session to the RCIs of the healthy subjects. We attempted to control for the variability in the participants' daily schedules by scheduling the participants' testing sessions at the same time of day 2 weeks apart, and advised them to maintain a similar exercise and sleep schedule, water and caffeine consumption, and any medications they were taking over both testing sessions. Our finding of low reliability for the Depth Perception test on the Nike SPARQ System may best be explained by technical limitations with our instrumentation that affected the synchronization between our test platform and 3D glasses the participants wear during the test. While none of our participants complained about glare on the screen, researchers should recognize this may adversely affect test performance on some of our measures.[12,91] We kept our testing conditions consistent from one test session to the next by using black-out blinds over windows, maintaining consistent level of overhead lighting, and draping the test area to separate participants from the rest of the clinical research center.

Conclusions

It is important for clinicians to consider test reliability and validity when using test instruments of any kind to make return to activity decisions. Based on our experiences with these two platforms—NeuroCom DVA/GST and Nike SPARQ Sensory Station—we feel the RCIs we reported fall within tolerable ranges in the participants we evaluated. Unfortunately, both of these instruments are costly and likely not to be found widely used in most clinical settings. In our study, the King-Devick Test performed reliably well and was a cost-effective and easy to administer instrument to evaluate basic saccadic function in both healthy and injured individuals. Future work in this should continue developing cost-effective portable platforms that evaluate visual performance (e.g. dynamic visual acuity, gaze stability, and visual-motor function) beyond that of the saccadic movements addressed by the King-Devick.

Table 4.1. Healthy sample descriptive statistics used to compute predictive values

Test Variable	Time 1			Time 2			r	ICC	t-test p-value	S_{diff}
	Mean	SD	SEM	Mean	SD	SEM				
NeuroCom										
Static visual acuity, logMar units	-0.229	0.053	0.043	-0.240	0.047	0.037	0.36	0.36	0.196	0.057
DVA (yaw), logMar units	0.112	0.092	0.014	0.010	0.080	0.012	0.09	0.09	0.506	0.018
DVA (pitch), logMar units	0.147	0.072	0.011	0.132	0.082	0.0123	0.08	0.08	0.353	0.016
DVA (roll), logMar units	0.179	0.107	0.016	0.157	0.102	0.015	0.19	0.19	0.282	0.022
GST (yaw), deg/sec	144.0	28.9	4.4	143.1	28.9	4.357	0.19	0.19	0.871	6.160
GST (pitch), deg/sec	130.0	31.2	4.7	131.0	29.1	4.386	0.18	0.18	0.862	6.441
GST (roll), deg/sec	117.6	31.5	4.8	113.3	33.2	5.007	0.37	0.37	0.442	6.902
Nike SPARQ Sensory Station										
Static visual acuity[a], logMar units	-0.176	0.1	0.016	-0.21	0.089	0.014	0.50	0.49	0.027*	0.021
Contrast Sensitivity, cycles/deg	0.2	0.2	0.02	1.9	0.2	0.03	0.09	0.09	0.339	0.040
Depth Perception, seconds	63.0	61.9	9.3	64.8	66.0	10.0	0.39	0.39	0.869	13.6
Near-Far Quickness, # correct	26	5.6	0.9	29.6	5.0	0.8	0.42	0.42	<0.001*	1.2
Target Capture[a], milliseconds	315.3	136.5	21.1	304.1	140.4	21.4	0.08	0.08	0.688	30.0
Perception Span, #/64	38.2	10.5	1.6	40.4	12.7	1.9	0.60	0.59	0.163	2.5
Eye-Hand Coordination, seconds	55.5	4.6	0.7	52.5	3.6	0.6	0.46	0.45	<0.001*	876.5
Go/No-Go, # correct response	20.6	10.7	1.6	29.2	11.1	1.7	0.28	0.28	<0.001*	2.3
Reaction Time, milliseconds	373.1	34.5	5.4	361.2	28.0	4.3	0.53	0.52	0.031*	6.9
Motor Time, milliseconds	139.8	42.7	6.3	128.4	45.8	7.1	0.47	0.47	0.223	9.5
King-Devick Test										
Time, seconds	44.9	7.1	1.1	43.8	7.0	1.1	0.81	0.81	0.127	1.6
Error	0.6	0.8	0.1	0.7	1.2	0.2	0.30	0.30	0.593	0.2

Abbreviations: DVA=Dynamic Visual Acuity; GST=Gaze Stability Tets; r=Pearson Correlation between Time 1 and Time 2; SD = standard deviation; SEM = standard error of the measurement; S_{diff} = standard error of the difference

*Denotes a significant difference between test time 1 and test time 2

[a] These values are measured as Visual Clarity (static visual acuity) and Target Capture (dynamic visual acuity) on the Nike SPARQ Sensory Station

Table 4.2. Predictive values for concussion testing battery outcomes measures

Testing Variable	80%CI Predictive Cut	90%CI Predictive Cut	95%CI Predictive Cut	Practice Effect*
NeuroCom				
Static visual acuity, logMar units	0.073	0.0931	0.111	—
DVA (yaw), logMar units	0.023	0.030	0.036	—
DVA (pitch), logMar units	0.021	0.027	0.032	—
DVA (roll), logMar units	0.029	0.034	0.044	—
GST (yaw), deg/sec	7.9	10.1	12.1	—
GST (pitch), deg/sec	8.3	10.6	12.6	—
GST (roll), deg/sec	8.9	11.4	13.5	—
Nike SPARQ Sensory Station				
Static visual acuity, logMar units	0.027	0.035	0.041	0.034
Contrast Sensitivity, cycles/deg	0.1	0.1	0.1	—
Depth Perception, seconds	17.5	22.4	26.7	—
Near-Far Quickness, # correct	1.5	1.9	2.3	3.6
Target Capture, milliseconds	38.5	49.4	58.9	—
Perception Span, #/64	3.2	4.1	4.9	—
Eye-Hand Coordination, seconds	1.12	1.44	1.72	3.08
Go/No-Go, # correct response	3.0	3.8	4.6	8.6
Reaction Time, milliseconds	8.8	11.3	13.5	12.0
Motor Time, milliseconds	12.1	15.6	18.5	—
King-Devick Test				
Time, sec	2.0	2.6	3.1	—
Errors	0.3	0.4	0.5	—

*These practice effects are all in the direction of improvement

APPENDIX 1. PARTICIPANT DEMOGRAPHIC FORM

To Be Completed by Research Assistant

ID-

Participant Questionnaire

Please answer all of the questions below to the best of your ability. If you have any questions, please ask your research assistant.

Gender: Male   Female

What is your date of birth? _____/_____/_____
                          (month)   (date)   (year)

What year are you? Please check the correct response.

  1st year (Freshman)   2nd year (Sophomore)   3rd year (Junior)   4th year (Senior)

  5th year   Graduate Student   Other

How many days a week do you typically workout (cardio or resistive exercises)? _____ days/week

How long do you typically workout for on those days? _____ minutes/day

How long have you been working out? _____ months or _____ years

Have you suffered a head injury, vestibular dysfunction or any injury that has affected your physical activity within the past 6 months? Please check the correct response.

        Yes   No

If yes, please explain:

How many times have you been diagnosed with a concussion?
- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3 or more

Indicate whether you have experienced the following:
    □ Yes   □ No   Received speech therapy
    □ Yes   □ No   Attended special education classes
    □ Yes   □ No   Repeated one or more years of school
    □ Yes   □ No   Diagnosed attention deficit hyperactivity disorder (ADHD)
    □ Yes   □ No   Diagnosed learning disability
    □ Yes   □ No   Treatment for headaches by physician
    □ Yes   □ No   Treatment for migraine headaches by physician
    □ Yes   □ No   Treatment for epilepsy/seizures
    □ Yes   □ No   History of brain surgery
    □ Yes   □ No   History of meningitis
    □ Yes   □ No   Treatment for substance/alcohol abuse
    □ Yes   □ No   Treatment for psychiatric condition (depression, anxiety, etc.)

Please list any medications you are currently taking:

How many hours sleep did you get last night?

How many hours have you spent in class or studying today?

How many minutes have you worked out today?

Approximately how many ounces of water have you had today (1 cup= 8 ounces)?

Approximately how many ounces of caffeine have you had today?

APPENDIX 2. ADDENDUM TO SPARQ DESCRIPTIONS

Visual Clarity. Static visual acuity was measured by having the participant stand 16 feet away from the 22-inch display. During this test, black Landolt rings (-ring that has a gap, looking similar to the letter C), with gaps at the top, bottom, left, and right, were presented in random order on a white background at preset acuity demands. Participants were instructed to swipe the screen of the iPod touch in the direction of the gap in the Landolt ring as soon as they identified the gap. Participants saw an example before the test begun and completed three practice trials. If the gap direction was not easily discriminated, the participants were instructed to guess. The test started with a large (20/50 equivalent) stimulus and decreased in size until the participant did not correctly identify the stimulus. If the participant could no longer correctly identify the direction of the gap, the stimulus increased in size until it was identified correctly. This procedure continued until several reversal points were complete. The procedure was then repeated isolating the right and left eye. In order to obtain monocular visual clarity, the investigator held a vision occluder over the non-tested eye.

Contrast Sensitivity. Four black circles were presented on a light gray background in a diamond configuration. One circle at random contained a pattern of concentric rings that varied sinusoidally in brightness from the center to the edge. Participants were instructed to swipe the screen of the iPod touch in the direction of the circle with the pattern. Animation examples were shown, followed by 3 practice trials. If the patterned circle was not easily discriminated, the participant was encouraged to guess, per the instructions. Contrast sensitivity was measured binocularly at 2 spatial frequencies, 6 and 18 cycles per degree (cpd), using a staircase reversal algorithm similar to that described previously.

Final threshold contrast sensitivity was measured between 10 and 1.0 percent contrast at

6 cpd, and between 32 and 25 percent contrast at 18 cpd.

Depth Perception. Depth perception was a measurement of stereopsis in a participant. For

this test, the participant wore a pair of liquid crystal goggles (NVIDIA 3D Vision, Santa

Clara, California), connected via wireless link to the computer, while viewing the 22-inch

display at 16 feet. The liquid crystal shutter system created simulated depth in 1 of 4

black rings presented on a white background, such that the ring should appear to float in

front of the screen. The sizes and arrangement of the rings were identical to those of the

circles used in Contrast Sensitivity. The width of the lines defining each ring was 12mm.

Participants were instructed to swipe the screen of the iPod touch in the direction of the

floating ring and were encouraged to respond as quickly as possible. Animation examples

were shown, followed by 3 practice trials. If the floating ring was not easily

discriminated, the participant was encouraged to guess, per the instructions. Threshold

stereopsis was measured between 237 and 12 arc seconds using a staircase reversal

algorithm similar to that described previously. In addition, response time for the first 2

stimulus presentations at the participant's threshold was recorded, and an average

response time for the testing was calculated.

Near Far Quickness. Participants stood 16 feet away from the 22-inch display holding the

iPod touch 16 inches from the eyes, with the top edge of the iPod touch positioned just

below the bottom of the display. Positioning and instructions were presented with an

animation example, and if needed, the researcher helped the participant with the

positioning adjustments. Alternating between screens, a black Landolt rings of 20/80-

equivalent was presented in a box on the far screen and then on the handheld iPod screen.

The participant was instructed to swipe the screen of the iPod touch in the perceived direction of the gap in the ring presented on each display. The assessment began with three practice trials. The first Landolt ring was always presented on the far screen, followed by a Landolt ring appearing on the handheld screen once the correct direction was chosen. Participants then continually alternated focus between far and near for 30 seconds, trying to correctly identify as many rings as possible.

Target Capture. Participants stood 16 feet away from the 42-inch display and were instructed to fixate on a central white dot until a yellow-green Landolt ring appears briefly in one of the four corners of the screen. As before, participants indicated the perceived direction of the gap by swiping the screen of the iPod touch. Participants watched an animation example before the test began and completed three practice trials. Participants were instructed to guess if the orientation of the gap was not easily discriminated.

Perception Span. The participant was positioned within arm's length of the 42-inch touch-sensitive display, with the center of the screen at about eye level. Automated instructions directed the participant to focus on a shrinking white dot in the center of a grid pattern composed of up to 30 circles. When the dot disappeared, a pattern of yellow-green dots (same color parameters as above) flashed simultaneously for 100 milliseconds within the grid. The participant then touched the screen to recreate the pattern of dots. If the participant answered more than 75 percent correct, considered passing, the grid pattern increased in size with an increasing number of dots. The first 2 levels had 6 circles in the grid pattern with 2 and 3 dots, the next 5 levels had 18 circles with 3 to 7 dots, and the last 4 levels had 30 circles with 7 to 10 dots. Each circle was 19 mm in

diameter, and the largest grid pattern was 18 cm in diameter. The grids and dot patterns were preset to maintain standardization. The dot patterns at each level were pseudorandomized to maintain equivalent spatial distribution of the dots for each presentation and to eliminate ''clustering'' of dots and easily recognizable patterns or shapes. Animation examples were shown, followed by 2 practice trials. The overall score for this assessment was based on the cumulative number of correct responses; missed responses and extra guesses were subtracted from the cumulative score. If the participant did not achieve a passing score on a level, that level was repeated. If the participant again failed to pass that level, the assessment was terminated. If the participant achieved a passing score on the second attempt, only the higher score was used for the overall score and testing continued. The maximum score possible was 64.

Eye-hand coordination. For this assessment, participants held their arms parallel to the ground at shoulder height within easy reach of a grid of circles presented on the 42-inch touch-sensitive display. The grid consisted of eight columns (68.6 cm) and six rows (44.5 cm) of equally spaced circles. During the assessment, a yellow-green dot appeared within 1 circle of the grid. Participants were instructed to touch the dot as quickly as possible using either hand. As soon as they touched the dot, another dot was presented. A sequence of 96 dots were pseudo-randomized to maintain equivalent spatial distribution within each presentation and to eliminate ''clustering'' of dots and easily recognizable patterns. Participants watched an animation example before the test began and completed one practice trial.

Go/No-Go. The participant was in the same position as during the Eye-Hand Coordination assessment. However, the dot stimulus could be either yellow-green (same

color parameters as above) or red. Although these colors could be confused by some color-deficient individuals, the difference in apparent brightness of the dots is sufficient to allow easy discrimination. If the dot was yellow-green, the participant was directed to touch it as before. But if the dot was red, the participant was instructed not to touch it. Both the red and yellow-green dots appeared at random locations for only 450 milliseconds, with no time gap between dot presentations. If a yellow-green dot was not touched within this time, no point was awarded for that presentation; if a red dot was touched, a point was subtracted from the overall score. Again, participants were encouraged to touch as many yellow-green dots as possible. Automated instructions and animation examples were shown, but there was no practice trial for this assessment. Ninety-six total dots (64 yellow-green, 32 red) were presented in a pseudorandomized sequence to maintain

equivalent spatial distribution within each presentation and to eliminate "clustering" of dots and easily recognizable patterns. The overall score was the cumulative number of yellow-green dots touch minus any red dots touched.

Reaction Time. For the final assessment, participants remained at arm's length from the 42-inch touch-sensitive display. Two annular patterns appeared on the screen, consisting of two concentric circles. Automated instructions directed the participant to place the fingertips of the dominant hand on the inner circle of the annulus on that side of the screen, with no portion of the hand extending across the boundary line marked on the screen. If the hand was aligned correctly, the control annulus would change color to yellow-green. The athlete was instructed to center the body in front of the opposite annulus and focus attention on the center of that annulus. After a randomized delay of

two, three, or four seconds, the test annulus turned yellow-green, and the participant

moved the hand to touch its inner circle as quickly as possible. Participants watched an

animation example before the test began and completed two practice trials.

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