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Dr. Anne Olson, Director of Graduate Studies

ALTERATIONS IN VISUAL PROCESSING AND ITS IMPACT ON UPRIGHT
POSTURAL STABILITY IN ATHLETES FOLLOWING SPORT-RELATED
CONCUSSION

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in the College of Health Sciences
at the University of Kentucky

By

Andrea E. Cripps
Lexington, Kentucky

Director: Dr. Scott C. Livingston, Assistant Professor of Physical Therapy
Lexington, Kentucky

2013

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ABSTRACT OF DISSERTATION

ALTERATIONS IN VISUAL PROCESSING AND ITS IMPACT ON UPRIGHT POSTURAL STABILITY IN ATHLETES FOLLOWING SPORT-RELATED CONCUSSION

Athletes are at risk of sustaining a concussion in all sports and at all competitive levels which may lead to balance impairments. Balance results from the integration of visual, vestibular, and somatosensory information. The underlying pathophysiology for balance impairments is not well understood and visuo-motor processing impairments and how these impairments contribute to balance in concussed athletes has not been reported. Objectives: (1) to investigate the influence of visual perturbation on upright postural stability and balance in athletes who have recently suffered a sports-related concussion, (2) to establish the test-retest reliability of a simple visuo-motor processing task. Design: A longitudinal, cohort design. Setting: University research laboratory. Subjects: Fourteen interscholastic, club, and intercollegiate athletes (8 males, 6 females, age 17.21 ± 2.97 years, height 176.43 ± 12.73 cm, mass 75.55 ± 22.76 kg) participated. Seven subjects with acute concussions (<48 hours since time of injury) were matched to seven control subjects. Intervention(s): All subjects completed a simple visuo-motor processing task (SVMP), Sensory Organization Test (SOT), and modified Clinical Test of Sensory Interaction in Balance (mCTSIB). Each subject's balance was tested under two visual testing conditions: (1) standard testing methods with normal visual fields, and (2) visual distraction through optical flow motion using a computer-generated optical flow pattern. Testing was done 24-48 hours and ten days following injury. The order of the testing was counterbalanced (standard protocol or visual distraction) and day of testing. Main Outcome Measures: Reaction time, accuracy, number of errors on SVMP; composite equilibrium score, sensory system preference on SOT; and mean center of gravity sway velocity on mCTSIB. Results: Significant impairments were noted on day 1 of testing

compared to day 10 for SVMP reaction time (day 1=496.18±52.82ms, day 10=439.01±20.62ms, F=4.72, p=0.01), and SOT composite equilibrium score standard (day 1=73.14±5.73, day 10=83.57±2.15, F=7.60, p<0.001). Conclusion: Physiological changes occur immediately following concussions that affect the visual system, more specifically, visuo-motor processing. The SVMP task provides unique information about visuo-motor processing following a concussion that is not currently being assessed. Visuo-motor processing is correlated with upright balance and should be evaluated following a sports-related concussion.

KEYWORDS: Concussion, Balance, Visuo-Motor Processing, Visual Processing

Andrea E. Cripps
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May 29, 2013
Date

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Chapter 1 Introduction

Background

Concussions occur a rate of approximately 1.6-3.8 million annually.¹ High-school football concussion rates are 250,000 per season,² while other reports suggest that concussions represent 22.2% of all high-school sport related injuries;³ of those, 66.6% occurred in competition and 33.4% occurred during practice. Additionally, the incidence of concussions has been reported as 2.5 concussions per 10,000 athletic exposures.⁴ These numbers, however, may be misleading because approximately 50% of all concussions go undiagnosed or unreported.¹ Challenges associated with concussion diagnosis and management relate to the variety of signs and symptoms experienced by the athlete, the degree to which the symptoms affect cognitive function, as well as the lack of standardized assessment guidelines. The International Concussion in Sport Group has defined the injury as, “a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces”.⁵ This definition has common features that tend to occur with a concussion, which include: (1) a concussion may be caused by direct blow to the head, face, neck, or elsewhere on the body with an impulsive force transmitted to the head; (2) typically results in onset of short-lived impairments or neurological function that resolves spontaneously; (3) may result in neuropathological changes but the acute clinical symptoms largely reflect a functional disturbance rather than a structural injury; (4) results in graded set of clinical symptoms that may or may not involve loss of consciousness; and (5) resolution of clinical and cognitive symptoms typically follow a sequential course.⁵ With the multitude of clinical sign and symptoms

(**Figure 1.1**) that may occur following a concussive injury, health care providers may have difficulty identifying the extent of a concussion and when recovery is complete.

Current approaches to the diagnosis and assessment of sport-related concussions are largely based upon symptom reporting by the athlete, neuropsychological testing, and balance testing.⁶⁻¹² Standard neuroimaging techniques (e.g. magnetic resonance imaging and computed tomography) are typically unable to detect the physiological changes that occur in the brain following a concussion.¹³ The lack of standardized assessment protocols requires that health care providers must rely on clinical experience and subjective measures to make the diagnosis of concussion and to determine return to play eligibility. However, as subjective measures, such as self-reported symptoms, are dependent on what the athlete reports, results of these measures may be disingenuous.¹⁴ Self-reported symptom inventories have been used to describe changes in reported symptoms initially following the concussion¹⁵ and demonstrate that post-concussive symptoms typically return to normal limits within the first three days following injury.¹⁶ Self-reported symptom inventories, however, can be misleading; it has been suggested that over one-third of undiagnosed concussions may result from that athlete not being aware of the signs and symptoms.¹⁴ Symptom inventories are recommended to be used in conjunction with object measures such as neuropsychological and balance assessment. As self-reported symptom inventories are subjective in nature and may not be truly representative of the injury, health care providers need to establish objective measures to determine the concussion diagnosis. Neuropsychological measures have gained popularity in the past 15 years but are limited in clinical application because a trained neuropsychologist is often required to interpret the results.^{17,18} Neuropsychological

measures are often used to assess attention, visual processing, working memory, concentration, memory recall, verbal memory, and learning in the concussed athlete.^{7,19,20} However, the clinical use and reliability of neuropsychological evaluations has been shown to be poor^{18,21} among concussed athletes and requires further investigation for its usefulness in acute post-concussion assessments battery. Deficits in balance and postural control are another objective finding that health care providers should use in the evaluation of the concussed athlete.

Researchers have shown that many athletes experience balance impairments during the acute post-concussion period.^{6,22-25} Impairments in balance following concussion typically resolve (i.e. recover back to baseline levels or comparable to healthy controls) between 3 and 10 days following injury.^{7,26-28} Balance impairments following a concussive injury occur when information processing is delayed between the visual, vestibular, and somatosensory systems.²⁴ Additionally, healthy individuals (including athletes) tend to rely on information from one sensory system at a time;²⁹ consequently, if an athlete relies too heavily on one sensory system as a compensatory mechanism for impairments in one (or more) other sensory systems. Multiple sensory systems are responsible for different aspects of balance but work together to produce coordinated postural stability. The visual system utilizes information about the external environment to determine where the body is in space.²³ Visual system impairments or alteration of visual information leads to a greater demand on the vestibular and somatosensory systems, and potentially produces balance deficits. Visual system disruption following concussion could be the cause of symptoms such as blurred or double vision (diplopia) and possibly headache.³⁰ The vestibular system helps to determine movement of the head

in order to determine where the body is in space, and is also involved in keeping the eyes fixed on a target.³¹ Following a concussion an individual may experience ‘imbalance’ as a result of vestibular damage. Peripheral vestibular components (e.g. the labyrinth of the inner ear or the vestibular nerve), or central components (e.g. brainstem or vestibule-cerebellum)³¹ may be damaged as a result of a concussion which may lead to symptoms of dizziness, vertigo, and balance impairments.³² Damage to the somatosensory cortex following concussion, however unlikely, may result in an inability to discriminate the properties of proprioception and touch.³³ Differentiating between balance deficits caused by visual, vestibular, or somatosensory impairments is important for health care providers as it permits more defined treatments parameters as well as allowing for retraining of the affected system to return balance to prior injury status.^{6,7,23,30} Health care providers have a variety of balance assessments to use following concussion which help to identify which sensory system is affected.

Balance assessment strategies are typically classified into two main categories, low technology or high technology, both of which have benefits and limitations. Low technology assessment tools such as the Balance Error Scoring System (BESS),^{27,28,34} are economical, easy to administer, and convenient but learning effects and evaluator bias may play a factor in the test outcome.³⁵ High technology assessment tools for balance are commonly referred to as computerized dynamic posturography (CDP) measures²⁴ and include assessments such as the Sensory Organization Test (SOT).^{6,23,24} CDP assessment demonstrates a learning effect but still yields reliable and valid results;^{36,37} however, the cost, time, and space needed for the equipment is impractical for the majority of clinicians to routinely use in balance assessment post-concussion.

The SOT has been used extensively to identify post-concussion balance deficits in athletes^{7,23,24,26-28,38} and is a clinical test of balance designed to systematically disrupt the sensory selection process by altering the information available to the somatosensory, vestibular and/or visual systems.^{29,39} Under normal (non-concussed) conditions an individual is able to maintain standing balance by using incoming information from the visual, vestibular and somatosensory systems.²⁴ Following a concussion, balance impairments occur if the integration of the sensory information is impaired or if an individual relies too heavily on one system as a compensation for deficits in one or more of the other sensory systems.²⁴ The SOT was developed to isolate which sensory system is most involved in regulating balance and to determine how the interactions between these systems affects postural control.⁴⁰ The SOT is a valid test of balance impairments among athletes with mild TBI.^{26,41,42} The testing protocol objectively identifies abnormalities related to the individual's use of the somatosensory, visual and vestibular systems contributing to balance by systematically eliminating visual input and/or support surface (somatosensory) information and creates conflicting sensory situations; SOT conditions 5 & 6 isolate the vestibular system as well as stressing the adaptive responses of the central nervous system. A depiction of the six testing conditions of the SOT is presented in **Figure 1.2** and a description of their functional relevance is summarized in **Table 1.1**.

The SOT test is an accurate method for determining dynamic balance deficits following concussion.^{6,23,27,28} However, the standard SOT protocol uses high technology force-plates that are not readily available for sideline assessments. The Balance Error Scoring System (BESS)⁴³ is a commonly used economical sideline balance assessment

which allows clinicians to make sideline decisions regarding the athlete's balance. The BESS is test consisting of six different conditions which consist of two testing surfaces (firm and foam) and three different stance conditions (double limb, single limb, and tandem stance) all with the eyes closed. The subject is told to remain as motionless as possible for each 20 second condition. The number of errors are counted by the test administrator and totaled at the end of testing session. Error consist of moving hands off iliac crest, opening eyes, step or fall, hip flexion/abduction greater than 30°, lifting the forefoot or heel off the testing surface, and remaining out of testing position for greater than 5 seconds. The BESS has demonstrated moderate to good reliability³⁵ and has been shown to be correlated with measures of CDP. Having a laboratory measure that is similar to the BESS would allow researchers to provide results that translate easily from the laboratory to the clinical setting. The modified Clinical Test of Sensory Interaction and Balance (mCTSIB)^{31,44} is a laboratory measure which replicates the BESS.

The mCTSIB, which was modified from the Clinical Test of Sensory Interaction on Balance (CTSIB), simulates conditions frequently encountered in daily life activities. The CTSIB was originally described by Shumway-Cook in 1986 and is described as an assessment of the influence of sensory interactions on upright balance.³¹ The tests uses a series of 30 second trials in which a patient's postural sway is measured using two support-surface conditions and three visual conditions; the support-surface conditions include firm and foam surfaces and the visual conditions include eyes open, eyes closed, and visual-conflict conditions. Visual-conflict conditions involve the subject wearing a half- dome that is lined with a series of black vertical lines. The purpose of the visual-conflict condition was to provide conflicting information to the vestibular system.⁴⁵ The

CTSIB was later modified to remove the condition in which the paper dome was placed on the subjects head, leaving the 4 current testing conditions (combination of eyes open/eyes closed, firm/foam surfaces). The conditions that were removed were not correlated with other posturography measures of sway-reference visual surround, and the values obtained during these visual-conflict conditions were not significantly different from values obtained with the eyes closed.^{46,47}

The mCTSIB is effective for determining balance deficits in an elderly population⁴⁸⁻⁵⁰ and the pediatric version of the test has been used in determining balance deficits among children with concussions,^{51,52} however it has not been studied in an acutely concussed athletic population. The mCTSIB could be beneficial to identify balance problems among concussed athletes and, thereby, provide the clinician with the information required to support further post-concussion assessment. The mCTSIB is a laboratory measure that represents clinical (or sideline) measures such as the BESS.⁵³ For health care providers, a balance assessment tool that can be replicated on the field or in the clinic would be the most beneficial and practical approach in the absence of a CDP system. Therefore, the mCTSIB may be more clinically relevant than the SOT for identifying concussion-related balance impairments because the mCTSIB more closely relates to common sideline measures (such as the BESS) and can be performed without the use of expensive force plate technology. While the SOT and mCTSIB tests have been shown to be a valid and reliable tool in the evaluation of postural deficits in a variety of populations^{7,15,24,54} testing protocols have been established using only two primary visual conditions: eyes open (normal visual input) or eyes closed (no visual input). Standard balance testing protocols do not include visual perturbation conditions which may identify

subtle balance impairments in concussed athletes. By adding visual perturbation stimuli to the standard balance protocol, the level of difficulty rises. The increase in difficulty will challenge the athlete in a more dynamic manner, which will help to identify athletes who are suffering from balance impairments even if standard balance assessments showed no impairments. The SOT and mCTSIB are typically conducted in control laboratory environments that do not account for environmental distractors such as noise, or visual distractors. Previous researchers have established a correlation between testing environment and balance impairments (e.g. balance is impaired in healthy subjects when tested on the sidelines but not in a control locker room environment) when environmental conditions during balance testing have been taken into account.²⁵ Enhancing our understanding of the nature of balance impairments while in the presence of visual perturbation will allow health care providers to make a more informed decision about the type and extent of post-concussion balance deficits and use this information to track clinical recovery. The underlying physiologic mechanism for post-concussive balance impairments while in the presence of a visual perturbation is not well understood and has not been systematically investigated among concussed athletes. If the addition of a visual perturbation stimulus during balance testing reveals impairments related to the individual's ability to effectively process visual information, a likely explanation may be the physiologic changes that occur throughout the brain following a concussion.

A concussion results in widespread functional changes that occur at many levels in the brain⁵⁵ and which may cause failure of the sensory systems to properly interact with each other. When the visual, vestibular and somatosensory systems do not interact with each other, balance impairments result.^{7,43} The widespread physiologic disruption that occur in

the brain following a concussive injury relate to both the neurometabolic cascade of concussion⁵⁵ and diffuse axonal injury (DAI).⁵⁶ The neurometabolic cascade of concussion and DAI are believed to be a result of the rapid forces that are transmitted through the brain at the time of injury. These forces cause both shearing and stretching injuries at the cellular level of the brain and cause “an abrupt neuronal depolarization, release of excitatory neurotransmitters, ionic shifts, changes in glucose metabolism, altered cerebral blood flow, and impaired axonal function.”⁵⁵ Diffuse axonal injury, specifically, is a result of mechanical stretching of axons which results in disruption and depolarization of the cellular membrane and widespread damage to axons in the brainstem, parasagittal white matter of the cerebral cortex, and corpus callosum.⁵⁵ These changes in cellular physiology are responsible for cognitive deficits such as disorders in memory and information processing as well as slowed information processing and are believed to occur in 40-50% of all traumatic brain injuries.⁵⁷ As axons are responsible for the transmission of information throughout the brain,⁵⁶ and any damage to these structures resulting in slowed information processing could cause clinically noticeable functional impairments, such as balance deficits or deficits in the visual system. The extent of these functional impairments, and whether changes in one sensory system alone would cause the impairments, is not known.

Visual attention and working memory processes are known to be affected by a concussive injury.⁵⁸ Visual attention is mediated through the relationship between the frontal lobe and visual pathways⁵⁹ and involves the ability to focus on an object while in the presence of multiple objects. Working memory allows an individual to remember and identify a single object.⁵⁹ Selective attention and working memory are frequently affected following concussion⁵⁸ and are both traditionally tested through the use of

neuropsychological assessments.⁶⁰ The link between selective attention and working memory is reciprocal, in that one process relies heavily on the other. Recent researchers have demonstrated that working memory relies on selective attention to function fully and that selective attention receives information about the object from memory in order to help make the determination of importance.⁶¹ A normal functioning selective attention process allows the individual to focus on the desired object or goal while disregarding the remaining stimuli.⁶¹ Selective attention is regarded mostly as a ‘top-down’ process where information about what is important about the object is transmitted from structures in the frontal lobe to the visual pathways where the information will be gathered and processed for further action. Damage in the frontal lobe and visual pathways from TBI greatly impacts all components of visual processing⁶².

Visual processing areas of the brain are vulnerable to the wide-spread damage following a concussion.³⁰ Researchers have demonstrated deficits in visual processing in children similar to that of an elderly population^{30,63} which is thought to be the result of the widespread damage caused by DAI. The axonal damage⁵⁶ caused by a concussion can produce a wide variety of possible visual perception problems³⁰ including: double vision, blurred vision, sensitivity to light, slowed visual processing speed, and deficits in visual working memory.^{5,24,64} Athletes experiencing these visual perception problems may also experience challenges in performing common activities of daily living. Areas of the brain that initiate visual processing also have connections to areas of the frontal lobe⁵⁹, which are primarily responsible for conscious balance control and movement. Therefore, any changes that affect visual processing may be partially responsible for impairments noted in balance along with the delayed information processing.

Challenging the visual system while simultaneously requiring an athlete to maintain stable balance will provide health care providers a better understanding of how the visual system contributes to balance and how dysfunction of visual processing may impair balance.

Simple visual processing testing protocols³⁰ can help identify deficits in visual processing and visual performance but have yet to be investigated among concussed athletes. Testing protocols that consist of first-order (i.e. simple or linear)³⁰ stimuli are defined by the luminance and color of the stimuli, and second-order (i.e. complex, non-linear) stimuli are defined by their contrast, texture and depth.⁶⁵ *Optical flow* refers to complex motion information representing the body moving through the environment.^{66,67} Athletes must use all these stimuli (simple/linear, complex/non-linear, and optical flow) to generate an image of their surroundings and allow them to properly navigate through the environment without difficulty. Problems arise for athletes when the ability to cognitively map their surroundings is impaired resulting in delayed motor responses and impairments in fluid movements.^{68,69} Current approaches to concussion assessment do not address visual processing deficits directly, but rely on the resolution of self-reported visual (and other somatic, cognitive, and behavioral) symptoms to determine if recovery has occurred. Researchers have identified delayed perceptual deficits during complex visual tasks despite normal neurological examination findings and resolution of self-reported symptoms in children after a concussion.³⁰ Deficits in visual processing have been demonstrated in children ages 8 to 16 years during first- and second- order stimuli testing following a concussion.³⁰ There is no published research on how these processes are affected following a concussion in an older (ages 16 to 24 years) athletic population.

The investigation of visual processing deficits and the influence that these deficits have on upright balance in athletes will help to better understand the underlying pathophysiologic mechanisms for balance deficits and why altered visuo-motor processing may be related to postural instability typically seen following a concussion.

The Problem

The maintenance of upright balance requires the integration of afferent information from the visual, vestibular, and somatosensory systems.²⁴ Interference with one or more of these systems can negatively affect an individual's ability to maintain upright balance. Currently, there is a lack of published research concerning: (1) balance following an acute concussion while in the presence of visual perturbation, and (2) visuo-motor processing in concussed athletes. Traditionally, balance assessments following concussion have focused on standard balance assessments in a controlled laboratory environment, with no concern for identifying the ecological validity or the underlying neurophysiologic processes that are causing these balance impairments. The role of the visual processing system and how it may be negatively affected following a concussion warrants further investigation. The overall research question to be addressed in this dissertation is: To what extent is visual processing altered following acute sport-related concussion and does this have an effect on upright balance?

Purpose

The overall objective of this research study is to determine the relationship between visual processing deficits and balance impairments following concussion in athletes. The purposes of the research study are to: (1) identify the nature and extent of visuo-motor processing impairments; (2) establish the relationship between altered visuo-

motor processing and upright balance; and (3) establish the influence that a visual perturbation stimulus has on upright balance among acutely concussed athletes.

Experimental Aims and Hypotheses

Specific Aim 1: To determine if visuo-motor processing differs among concussed and non-concussed subjects.

Hypothesis: Concussed athletes will have increased reaction time, decreased accuracy, and an increased number of errors during a visuo-motor processing task compared to healthy control subjects.

Specific Aim 2: To establish the relationship between altered visuo-motor processing and upright balance deficits among acutely concussed athletes.

Hypothesis: Acutely concussed athletes whom perform poorly on a visuo-motor processing task will demonstrate a negative correlation with postural instability compared to non-concussed athletes.

Specific Aim 3: To determine the influence of a visual perturbation on upright balance in athletes following concussion.

Hypothesis: The inclusion of a visual perturbation during standardized balance testing will result in a decrease of upright dynamic and static balance scores (i.e. impaired balance) among acutely concussed subjects compared to healthy subjects.

Clinical Implications

The validation of a hypothetical model linking visuo-motor processing and balance impairments in acutely concussed athletes will improve the sports medicine clinician's overall understanding of balance impairments following concussion and the

role that the visual system has postural instability. Using laboratory methods of balance assessment that are similar to the types of visual environments encountered by athletes during competition and practice will challenge the athlete in a more realistic manner, thereby identifying athletes who may perform within normal limits on standard balance assessments yet demonstrate subtle impairment when a visual perturbation stimuli is used during testing. Demonstrating balance impairments during the more challenging task of a simultaneous visual perturbation presentation may help to identify athletes who are still recovering from the acute effects of concussion and who need more time before being allowed to return to competition. Furthermore, if visual processing is affected by an acute sport-related concussion, balance and visual processing training programs could be developed and tested to assess their effectiveness in enhancing recovery.

The identification of impairments in visuo-motor processing and their impact on postural control will provide a plausible, although not necessarily inclusive, explanation for balance dysfunction following concussion. Balance is maintained as a result of contributions of the visual, vestibular, and somatosensory systems,²⁴ however there is a lack of evidence to identify: (1) the extent to which each of these sensory systems, either individually or in combination, contribute to upright balance, (2) how the sensory systems may be adversely affected by the concussive injury, and (3) the neurophysiologic changes that occur in the hours and days post-injury. The outcomes of this research will improve our understanding of balance impairments following concussion and help to identify how deficits in visuo-motor processing impede upright balance.

Operational Definitions

Computer Dynamic Posturography: a method validated by controlled research studies to isolate the functional contributions of vestibular inputs, visual inputs, somatosensory inputs, central integrating mechanisms, and neuromuscular system outputs for postural and balance control using forceplate technology.⁷⁰

Sensory Organization Test (SOT): a test designed to cause a systematic disruption of the sensory selection process to identify balance deficits.³⁹ The systematic disruption causes alterations of an individual's ability to use somatosensory, visual, and vestibular information to maintain static standing balance and can help identify deficits in a particular sensory system or combination of systems.⁷¹

Modified Clinical Test of Sensory Interaction and Balance (mCTSIB): a simplified test derived from the Clinical Test of Sensory Interaction on Balance (CTSIB)⁴⁶ used to measure an individual's functional balance control. The mCTSIB consists of two visual conditions (eyes open and eyes closed) and two surface conditions (foam and firm) using a double limb stance.

SOT Composite Equilibrium Score: a weighted average of the center of gravity (COG) sway during each of the three trials for the six conditions and characterizes the subject's overall level of performance on a 100 point scale.⁷¹

SOT Sensory Analysis: identifies impairments of individual sensory systems by using a ratio of the composite equilibrium score. The sensory analysis ratios are automatically computed by comparing average scores achieved on the 6 SOT testing conditions, and include (a) a *vestibular ratio* (comparison of condition 5 to condition 1), (b) a *visual ratio* (conditions 4 and 1), (c) a *somatosensory ratio* (conditions 2 and 1) and (d) *preference* (conditions 3+6 and conditions 2+5).⁷¹

Simple Visuo-Motor Processing Task (SVMP): a test using single motion stimuli (adapted from Pinkus and Pantel (1997)⁷²) to examine baseline motion perception.⁷³

SVMP Accuracy: proportions of correct perceptual judgments of the direction (left or right) of the unambiguous single motion steps were computed for each observer.⁷³

SVMP Reaction Time: length of time (ms) from stimuli motion occurring to subject making decision about direction of motion and entering answer.⁷²

SVMP Ambiguous Trial: perceived motion occurring as a result of the sine-wave grating stimuli moving 180° to the left or to the right resulting in ambiguous trial.⁷²

SVMP Unambiguous Stimulus: perceived motion occurring as a result of sine-wave grating stimuli moving 90° to the left or to the right.⁷²

SOT Sway-Referenced: indicates either the support surface, visual surround or both move in response to the subject's postural sway.⁷¹

mCTSIB Mean Center of Gravity Sway Velocity: identifies the speed of COG displacement over a given time during the mCTSIB; values closer to zero represent minimal sway.⁷¹

First Order Stimuli: Allows for visual perception of simple visual stimuli which are defined by differences in luminance and color.³⁰

Second Order Stimuli: Allows for visual perception of simple visual stimuli which are identified by their contrast, texture, or depth.³⁰

Balance or Postural Stability: the ability of an individual to control their center of mass in relationship to the base of support.³¹

Concussion: A complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces. Common features include: it is caused by a direct blow

to the head, face, neck, or elsewhere on the body with an ‘impulsive’ force transmitted to the head; it typically results in rapid onset of short-lived impairment of neurological function that resolves spontaneously; it may result in neuropathological changes but the acute clinical symptoms largely reflect a functional disturbance rather than structural injury; it results in a graded set of clinical symptoms that may or may not involve loss of consciousness; and the resolution of clinical and cognitive symptoms typically follows a sequential course.⁷⁴

Selective Attention: the cognitive ability to choose relevant visual information (color, luminance, texture, depth) from visual stimuli while ignoring the less relevant information.⁷⁵

Visual Attention: the ability to take information from physical environment and learn from it.⁷⁵

Visual Discrimination: the ability to detect distinctive and invariant features of a visual stimuli.⁷⁵

Visual Memory: the ability to retain and recall visual experiences.⁷⁵

Visual Perception: the ability to interpret what an individual observes as an outcome behavior reflective of the interaction between specific visual and cognitive skills.⁷⁶

Visual Processing or Cognitive Analysis Skill: information gained from the eye which is then transferred to the cognitive areas of the central nervous system.⁶¹ Included in these skills are: visual attention (selection of visual input), visual memory (integration of visual information with previous experiences), and visual discrimination (ability to detect features of stimuli for perceptual differentiation).⁷⁵

Visuo-motor Processing or Visual Information Analysis: the association of information obtained from the eyes and transferred to the motor systems to coordinate motion.^{61,76}

Visual Stimuli: includes objects (three-dimensional forms present in the environment), space (three-dimensional space), the basic level of perception of depth and distance, events (happenings over time and through space), representations (two-dimensional pictures or drawings or objects, space, or events), and symbols (coded stimuli, designed to correspond with some other set of stimuli).⁷⁷

Assumptions

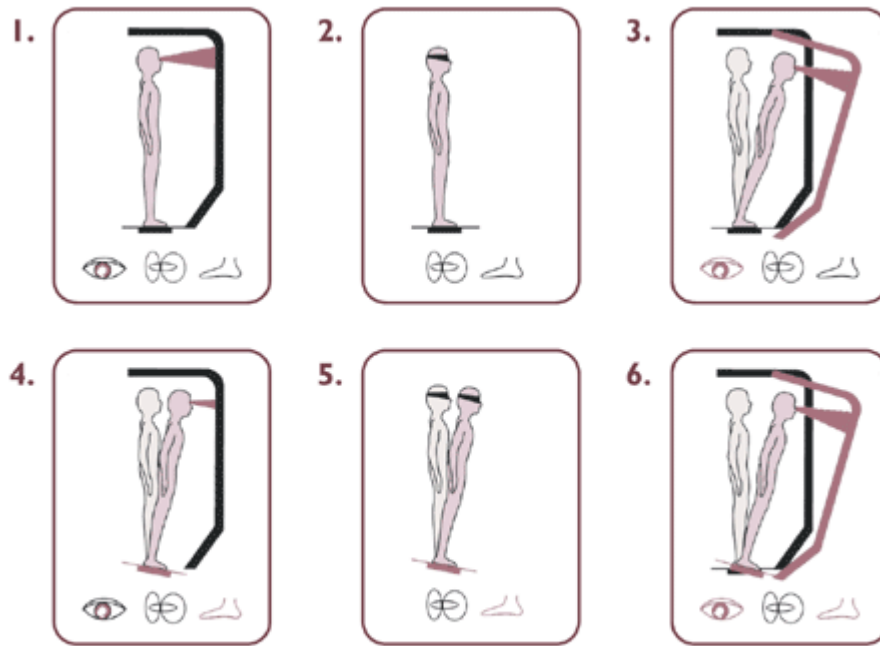
1. Subjects will be accurately diagnosed with an acute cerebral concussion by physician or certified athletic trainer.
2. Subjects will demonstrate their best effort during balance testing.
3. Subject will be honest of their reporting of medication intake, previous medial history, and current neurological problems.

Delimitations

1. Subjects will be males and females between the ages of 12-24 years with an acute concussion sustained in a sporting-related activity (practice, scrimmage or game);
2. Subjects will have no self-reported: lower extremity injury, vestibular system deficits, spine or peripheral nerve injury causing difficulty with standing balance;
3. Subjects will not have sustained concussion within the 6 months prior to the most recent injury.
4. Subject's balance will be assessed on the Sensory Organization Test and the Modified Clinical Test of Sensory Interaction and Balance.
5. Visual processing will be assessed using the simple Visuo-Motor Processing Task.
6. Subjects will have sustained a concussion within the previous 48 hours before testing.
7. Subjects will have no self-reported pre-existing or concurrent medical conditions, nor will they be taking medications, which may impair their balance.

Somatic	Neurobehavioral	Cognitive
<ul style="list-style-type: none"> • Headache • Nausea • Vomiting • Balance difficulty/dizziness • Numbness/tingling • Sensitivity to light and noise 	<ul style="list-style-type: none"> • Fatigue • Trouble falling asleep • Sleeping more than usual • Drowsiness • Sadness • Nervousness 	<ul style="list-style-type: none"> • Feeling “slowed down” • Feeling “in a fog” • Difficulty concentrating • Difficulty remembering

Figure 1.1 Common Self-Reported Post-Concussion Symptoms



Sensory Organization Test

Figure 1.2 The Sensory Organization Test (SOT) six sensory conditions

Chapter 2 Balance Assessment Following Concussion: A Systematic Review & Vision Mini Review

Introduction

The incidence of concussions among athletes have been reported between 1.6 to 3.8 million annually,¹ with as many as 50% of concussions going unreported by athletes.⁷⁸ The challenge that health care professionals face is diagnosing and managing the athlete with a concussion, regardless if the injury was reported. The difficulty in diagnosing a concussion relates to a variety of issues, (1) lack of evidence of the nature and extent of injury from standard neuroimaging techniques,¹³ (2) lack of a standardized and universally-accepted definition of concussion, (3) the wide variation of clinical signs and symptoms reported by the athlete, and (4) the lack of standardized, validated assessment approach. Currently, athletic trainers have been advised to use a battery of assessment tools to aid in the diagnosis and assessment of sport-related concussion; these tools include: symptom reporting, neuropsychological testing, and balance testing.⁶⁻¹²

Self-reported symptom inventories, neuropsychological assessments and balance testing are often included in the assessment and management of concussions. Self-reported symptom inventories, such as the Head Injury Scale,⁷⁹ concussion symptom inventory,⁸⁰ and the Cantu grading scale,⁸¹ are subjective in nature and may be manipulated by the athlete to avoid being withheld from participation.¹⁴

Neuropsychological assessments can be conducted using either paper and pencil assessments or computer-based assessments.¹⁷ While neuropsychological measures are more objective in nature than self-reported symptoms, most require a trained

neuropsychologist to interpret the results, making the tools ineffective for initial sideline or clinical assessment. Additionally, the results of neuropsychological tests may be affected by the type of test (paper and pencil or computer) and the period of time the test is administered from the initial injury.¹⁵ Balance assessments are routinely recommended in current concussion management position statements and guidelines.⁸² Symptoms such as vertigo, dizziness, and inability to maintain upright balance are often reported following the injury^{7,9-12,38,41,83,84} and may assist the athletic trainer in the diagnosis of a concussion. Balance assessments are an objective tool that can be used to detect the effects of a concussion and as a guide for making return to play decisions.^{7,26,43}

Balance assessments are commonly performed on the sidelines and repeated over the course of the first few days post—injury until balance performance returns to within normal limits.^{7,26-28} Traditional side-line assessments such as the Balance Error Scoring System (BESS)^{34,43} are cost-effective, quick and easy to administer in any environment.³⁵ This type of sideline balance assessment protocol is classified as a low-technology assessment tool. High-technology tools, such as computerized dynamic posturography (CDP),²⁴ biomechanical studies, and virtual reality tools are expensive, time-consuming and not practical for use on the sideline or many clinical settings. Regardless of which type of balance assessment is used, the purpose of any balance assessment is to identify impairments in the athlete's ability to maintain upright balance.

Postural control impairments are believed to result from a failure of the visual, vestibular, and somatosensory systems to properly integrate information to maintain upright balance.^{24,29,31} Balance deficits have been reported in up to 30% of athletes following a concussion regardless of assessment tool used. Typically, deficits in postural

control resolve between three to ten days following the injury.²⁴ The majority of research studies that have been conducted on balance deficits following a concussion^{7,9-12,16,26-28,38,41,42,64,83-86} have a small sample size making it difficult to generalize the results to different populations. The overall purpose of this systematic review was to determine the role of balance assessment in concussion diagnosis and management and to determine if; (1) balance deficits can be detected using current assessment approaches, and (2) similar balance deficits are noted with various assessment tools.

Hypothesis

It was hypothesized, based upon the above purposes that 1) following concussion in collegiate athletes, balance deficits will be detected using current balance assessment approaches and 2) similar balance deficits will be noted using various assessment tools.

Description of outcomes

Outcome measures were restricted to balance and postural stability outcomes. All outcome measurements are reported in **Table 2.1**.

Type of study designs used

There were no restrictions on the types of research designs that were included in the study. Any published study that met the inclusion/exclusion criteria was included.

Study populations

Research papers were restricted to those conducted on athletic populations. There were no other population restrictions. The demographics of the study populations can be found in **Table 2.2**.

Methods

Search Strategy and Manuscript Selection

The search and selection of published papers to be included in the analysis an initial search (title and abstract reviewed) followed by a forward and a hand search with the titles and abstracts being reviewed. A flow chart with the number of research papers identified at each step in the search process can be found in **Figure 2.1**.

Literature search

PubMed, Medline, CINAHL, and SPORTDiscus were used for the initial search. The investigators conducted searches with the results reported in **Table 2.3**. The search strategy was limited to articles published in English between the years 1990 and the current year (2013).

Article inclusion and exclusion criteria

The initial PubMed search resulted in 85 articles, the CINAHL search resulted in 20, the Medline search resulted in 41, and SPORTDiscus database research resulted in 93 articles found. Of the total 239 articles found, 152 of those articles were duplicates leaving 87 articles whose titles and abstracts reviewed to determine if the study fit into the inclusion criteria. For the article to be included in the systematic review the article must have assessed balance immediately following a concussion in athletes and a team physician or certified athletic trainer must have diagnosed the concussion. Included at this phase of the study were nine published papers.

Forward and hand search

From the above nine articles, references were searched for articles that may not have been included in the initial search. The forward search revealed 104 articles in which

70 were identified as duplicates of the initial search. From the forward search, one additional article was included. The hand search resulted in 64 articles found. After reviewing the titles and abstracts for the articles, two additional articles were included in the analysis.

Quality Assessment

Quality assessment for this study was done using the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement scale.⁸⁷ All studies were assessed by the investigators on the 21 point STROBE scale by two independent raters. After the initial review, the scores were compared and any large discrepancies among the reviewers were identified. Studies with large discrepancies (scores greater than T1 SD above the mean) were again independently reviewed. We used these final results as the quality score. The rating items include: (a) title and abstract (item 1), (b) introduction (items 2 and 3, background/rationale and objectives), (c) methods (items 4-12, study design, setting, participants, variables, data sources/measurement, bias, study size, quantitative variables, and statistical methods), (d) results (items 13-17, participants, descriptive data, outcome data, main results, and other analysis), (e) discussion (items 18-21, key results, limitations, interpretation, and generalizability) and (f) other information (item 22, funding). The STROBE scale reports items that should be included on observational studies. The STROBE scale was selected as the included studies were observational in nature, which allowed all items on the STROBE to be included.

RESULTS

Identification of Subjects Characteristics

Characteristics of both the 11 published papers that were included in the review and the subject demographics are reported in **Tables 2.1** and **2.2**, respectively. All characteristics were extracted from the body of the article in either the method sections or where the inclusion/exclusion criteria were stated. Additionally, days of measurement after the concussion and, if any baseline measurements were performed, were recorded. As indicated in **Table 2.1**, the day of measurement and the balance assessment tools were not consistent across all the papers reviewed. A summary of the most significant outcomes are presented in **Table 2.3** for each of the reviewed papers.

Quality Assessment

The STROBE scale was ideal for all articles included in this systematic review. The scores for each of the papers evaluated by the two reviewers remained fairly consistent with the scores ranging from 16 to 20 on a 21 point scale. The results of the quality assessment are presented in **Table 2.1** as quality scores on the STROBE scale and indicate that all studies included in the analysis were of high level (above 16 point) of study quality.

DISCUSSION

Our initial analysis of the articles revealed that following a concussion athletes experience balance impairments as measured on a variety of assessment tools. The findings of the current study support the recommendations for the use of balance assessments in the diagnosis and management of following sports-related concussion. No standardized protocol, however, has been established for implementing post-concussion

balance assessment or which balance assessment instruments should be used. This lack of a standardized protocol may be partially due to the limited scientific evidence to support the effectiveness of various balance assessments. Furthermore, due to the variety of balance assessments currently available for use in the laboratory and clinical settings, health care providers may question which tool to use and if balance assessments are even necessary in the assessment of sport-related concussions. The results of the current paper suggest that a variety of tools can be used in the successful assessment of balance following a concussion and that health care providers should use the tool that is more accessible to them. The purpose of this systematic review was to determine the role of balance assessment in concussion diagnosis and management and to determine if; (1) balance deficits can be detected using current assessment approaches, and (2) similar balance deficits are noted with various assessment tools. The results of this systematic review indicate that balance deficits can be detected using current assessment approaches and balance can be assessed using a variety of examination tools. Additionally, the published papers included in this systematic review suggest that balance impairments are the most pronounced 1 day following the injury.²⁴ While the majority of the papers suggest that balance recovers 3 to 5 days following the injury,⁴¹ multiple researchers suggest that balance may continue to be impaired up to 10 days following a single episode of concussion.^{16,88} Some of the included studies^{12,16,64} in this review confirm previous research that balance impairments may last longer than the initial 10 days after the injury. The articles that showed balance deficits lasting for longer than ten days varied between the assessment tool (SOT, BESS, and motion analysis forceplate) suggesting that while balance impairments can be noted following a concussion on a

variety of tools, the results of these studies should be replicated to validate the findings. If balance impairments do last for longer than 10 days following the injury, health care providers need to be made aware of these findings to ensure recovery occurs before athletes are allowed to return to participation in athletics.

Control parameters varied considerably among the published papers reviewed. Some of the research studies compared post-injury balance assessments to a control group^{7,12,16,26,41,43,64,83,86} and many studies made comparisons between baseline values and post-concussion balance scores.^{8,12,13,24,26,41,79,80,85} Impairments in balance were noted between both baseline measures and control subjects. Recommendations from the National Athletic Training Association and National Collegiate Athletic Association have recommended that preseason baseline measurements be done as health care professionals are unlikely to have control subjects data readily available at the time of injury.⁸² The results of the systematic review agree with the recommendation and the investigators advise health care providers to administer baseline balance assessments to assist in make decisions regarding balance impairments following a concussion.

The limitations to this systematic review include: the lack of randomized controlled trials (RCTs) included in the review, timeframe when balance assessments were conducted, how concussion was defined, and the setting in which balance testing was completed. While the quality of the included studies was consistent across all studies, there were no RCTs included in the analysis. Additionally, the timeframe between concussive injury and balance assessment in each of the selected studies varied which made comparisons between studies difficult. The operational definition of concussion varied among the studies and, in some cases, was not mentioned in the article

at all. Some of the studies compared balance after injury to baseline measures^{8,12,13,24,26,41,79,80,85} while others compared balance measures post-concussion to a control group.^{7,12,16,26,41,43,64,83,86} The lack of a standardized comparison between baseline and control subjects makes interpreting impairments difficult and may have resulted in differences in recovery time. The generalizability of the systematic review is limited because the papers reviewed only included collegiate athletes with sport-related concussions; the results may be different for younger athletic populations (e.g. youth sports and interscholastic athletics). Finally, all of the studies included in the analysis assessed athletes' balance in a laboratory setting, which may have affected the results of the individual studies. No published studies conducted in a clinical setting (e.g. side-line, athletic training room) are available.

The results of the present systematic review are significant in terms of validating previously published papers suggesting that balance is impaired following sport-related concussions and the current assessment approaches are able to detect impairments as well as balance impairments can be assessed using a variety of tools including low-technology measures such as the BESS. This systematic review will help health care professions justify the use and importance of balance assessments in concussion diagnosis and management.

CONCLUSION

Following a sport-related concussion, a collegiate athlete may experience balance deficits during the acute post-injury period. The deficits typically resolve within 10 days following the injury; some individuals, however, may continue to experience impairments after that time frame. Pre-season baseline balance testing should be an

integral component of the pre-participation examinations. Baseline measures of an athlete's balance test performance can then be compared to post-concussion balance scores to aid in diagnosis, prognosis, and return-to-play decision making. The overall result of the systematic review suggest that health care providers should focus on administering the balance assessments serially immediately following a concussion and should continue until the athlete returns to or exceeds baseline values using whichever balance tool is easily accessible for them.

FUNDING

The authors of the systematic review have no funding to report.

Table 2.1 Study inclusion criteria, STROBE (quality) score, subjects, time points, and outcome variables

Authors	Quality Score	Stated Inclusion Criteria/Exclusion Criteria	Injured Subjects (n)	Uninjured Subjects (n)	Postural Control Instrument	Time Points	Outcome Variables
Broglia et al. ³⁸	19	Completion of baseline SOT test; diagnosis of concussion by a certified athletic trainer followed by the team physician	32	0	SOT	baseline; 48 post	mean stability; composite equilibrium score; vestibular ratio; somatosensory ratio
Catena et al. ⁶⁴	18	Grade II Concussion diagnosed by athletic trainer; no loss of consciousness but disoriented for greater than 15 min; no abnormal gait; no common concussion symptoms for uninjured subjects	10	10	Motion Analysis, Force plate	> 2Days; Day 6; Day 14; Day 28	Center of Mass, Center of Pressure
Cavanaugh et al. ⁸³ 2006	19	No lower limb musculoskeletal injury sustained eiyher earlier in the season or at the time of concussion, completion of baseline testing; concussion diagnosed by certified athletic trainer followed by a team physician	18	29	SOT	Baseline; >48 hours; 48-96 hours	mean approximate entropy; equilibrium score; composite equilibrium score; vestibular ratio; somatosensory ratio

Cavanaugh et al. ⁴¹ 2005	20	No prior concussion history; diagnosed with a concussion by a certified athletic trainer or team physician	27	30	SOT	Baseline; 48hours post	mean approximate entropy; equilibrium score; composite equilibrium score; vestibular ratio; somatosensory ratio
Covassin et al. ⁸⁵	20	Inclusion: Age 14-25 years, sports related concussion diagnoses by a sports medicine professional. Exclusion: history of treatment for substance abuse, psychiatric disorder, special education, years repeated in school, speech problems	222	0	BESS	Baseline: 2, 4, 7, 14 days after injury	# Errors
Guskiewicz et al 2001. ⁷	17	Concussion sustained during either practice or competition; diagnosed by certified athletic trainer; completed baseline testing; control subjects had no history of concussion (within 6 months), no vestibular deficit or an acute musculoskeletal injury that affected postural equilibrium	36	36	SOT; BESS	Baseline; Day 1; Day 3; Day 5	mean approximate entropy; equilibrium score; composite equilibrium score; vestibular ratio; somatosensory ratio; # errors

Guskiewicz et al. 1996 ²⁶	17	Inclusion: Age 15-25 years Exclusion: history of mild head injury within the previous 6 months, history of any severe visual, vestibular, or balance disorders	10	10	Chattecx Balance System	Day 1, 3, 5, 10 and 30 after injury	Center of Balance, Sway Index (cm).
McCrea et al. ⁹⁻¹²	18	Collegiate football player; completed baseline test; no lower limb injury; diagnosed by certified athletic trainer	94	56	BESS	Baseline; immediate; 3 hours; Day 1; Day 2; Day 3; Day 5; Day 7; Day 90	Mean BESS score (# errors)
Peterson et al. ¹⁶	17	Inclusion: Collegiate athlete who participated in sports as identified as high-risk for a concussion Exclusion: Second concussive injury during the same season	24	18	SOT	Baseline; 1, 2, 3, 10 days after injury	Composite Equilibrium Score, Vestibular ratio
Register-Mihalki et al. ⁸⁶	16	Concussion diagnosed by a certified athletic trainer or physician; no history of migraine	26	82	SOT	Baseline; post-injury (1.44±0.90 days)	composite equilibrium score; vestibular, and visual ratio score

Reimann et al. ^{27,28}	17	Exclusion: history of musculoskeletal injury which may affect their ability to balance or a head injury with the previous year.	16	16	BESS	Day 1, 3, 5, and 10 post injury	# Errors
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Table 2.2 Subject Characteristics

<u>Author</u>	<u>Previous Concussion</u>	<u>Athlete</u>	<u>Scale</u>	<u>Gender</u>	<u>Age Injured</u>	<u>Height Injured (cm)</u>	<u>Weight Injured (kg)</u>	<u>Age Control</u>	<u>Height Control (cm)</u>	<u>Weight Control (kg)</u>
Broglio et al.	No	Yes	Not stated	M/F	19.7	179.8	89.9	n/a	n/a	n/a
Catena et al.	Not stated	Yes	*AAN Grade 2	M/F	21	173.6	71.7	20.7	172.7	72.6
Cavanaugh et al. 2006	No	Yes	Not stated	M/F	19.1	179.5	84.4	n/a	n/a	n/a
Cavanaugh et al. 2005	Possibly	Yes	Not stated	M/F	19.5	181.7	90	n/a	n/a	n/a
Covassin et al.	Possibly	Yes	Not stated	M/F	15.6 M HS, 15.43 F HS, 19.52 M College, 18.94 F College	69.81 M HS, 65.55 F HS, 72.25 M College, 67.29 F College	168.64 M HS, 140.67 F HS, 206.42 M College, 146.83 F College	n/a	n/a	n/a
Guskiewicz et al. 1996	No	Yes	Not stated	M/F	17.4	183.8	87.7	18.6	185.7	84.5
Guskiewicz et al. 2001	No	Yes	Not stated	M/F	19.5	180.34	83.43	20	179.07	81.5
McCrea et al.	No	Yes	Not stated	M	20.04	186.69	105.87	19.2	184.79	98.33
Peterson et al.	No	Yes	AAN	M/F	20.17	181.29	92.93	19.28	183.16	92.73
Register-Mihalki et al.	Not stated	Yes	Not stated	M/F	18.83	180.92	83.29	n/a	n/a	n/a
Riemann et al.	No	Yes	Cantu Scale ⁸⁹	M/F	19.2	183.1	84.3	22.5	183.1	88.7

*AAN - American Academy of Neurology, M –Male, F – Female, HS – High School

Table 2.3 Individual Study Results

Study	Results
Broglio et al.	Significant correlations were found between subjects experience balance symptoms and scores on SOT composite equilibrium score ($r=-0.52$), somatosensory ratio($r=-0.41$), visual ratio ($r=-0.39$), vestibular ratio ($r=-0.57$) when examined 48 hours following injury.
Catena et al.	Concussed athletes shifted to a more conservative balance strategy immediately following the injury ($p=0.006$). The normal control of balance wasn't resumed until 28days following the concussion. Day 5 following the injury, concussed subjects were not significantly different from the control group in anterior peak velocity center of mass, suggesting that while balance strategy may still be affected, no functional changes in balance were noted.
Cavanaugh et al. 2006	96 hours after initial injury, anterior-posterior and medial-lateral approximate entropy values remained significantly different from preseason values ($F_{5,4,147}=3.0$, $P=0.01$).
Cavanaugh et al. 2005	Following injury (48 hours) medial-lateral approximate entropy values declined in all sensory organization test conditions ($F_{1,55}=6.36$, $p=0.02$) in athletes who demonstrate normal postural stability.
Covassin et al.	Significant differences were noted for time (Wilks $\lambda=0.621$, $F_{2,110}=33.54$, $P=0.000$) on the BESS. Scores on the BESS were highest 1 day after the concussion and significantly improved by Day 2($P=0.001$) and again from Day 2 to Day 3($P=0.001$).
Guskiewicz et al. 1996	Significant differences were found on sway index between day and platform ($F_{8,288}=3.36$) and group by day ($F_{4,144}=6.74$). Additionally, depending on platform surface and visual input (eyes open, eyes closed, dome) impairments in balance may be noted up to 3-5 days following injury when compared to matched controls. Ten days following injury concussed subjects mimicked control subjects sway index on all surfaces and visual conditions.
Guskiewicz et al. 2001	Concussed subjects demonstrated balance impairments as measured on the BESS and SOT immediately following injury (day 1) when compared to baseline values and matched controls. When compared to matched controls, concussed subjects demonstrated impairments on balance measures (SOT and BESS) on days 1,3,& 5 days following the injury ($F_{3,210}=10.17$, $P<0.01$ & ($F_{3,210}=2.68$, $P<0.05$ respectively).
McCrea et al.	Immediately following a concussion athletes demonstrated significantly more balance problems (BESS score 5.81 points higher 95%CI, -0.67 to 12.30) when compared to control subjects. Balance impairments dissipated within 3 to 5 days after injury. No significant differences were noted between the concussed and control group 90 days after injury.

Peterson et al.	Significant differences in balance were noted on the following days; 1(P=0.011), 2 (P=0.004), 3(0.009) and 10 days (P=0.025) following concussion between groups.
Register-Mihalki et al.	Balance deficits were noted following concussion when compared to preseason measures (P<0.05). Subjects reporting posttraumatic headache demonstrated a greater impairment in balance scores compared to subjects no reported posttraumatic headache (P<0.05)
Riemann et al.	Significant differences were found in concussed subjects compared to control subjects in double-leg ($t_{15}=-3.10$, $p=0.01$), single-leg ($t_{15}=-3.11$, $p=0.01$) and tandem stances ($t_{15}=-4.01$, $p=0.00$) on foam surfaces on day 1. Concussed subject recovered balance by day 3 of testing when compared with control subjects.

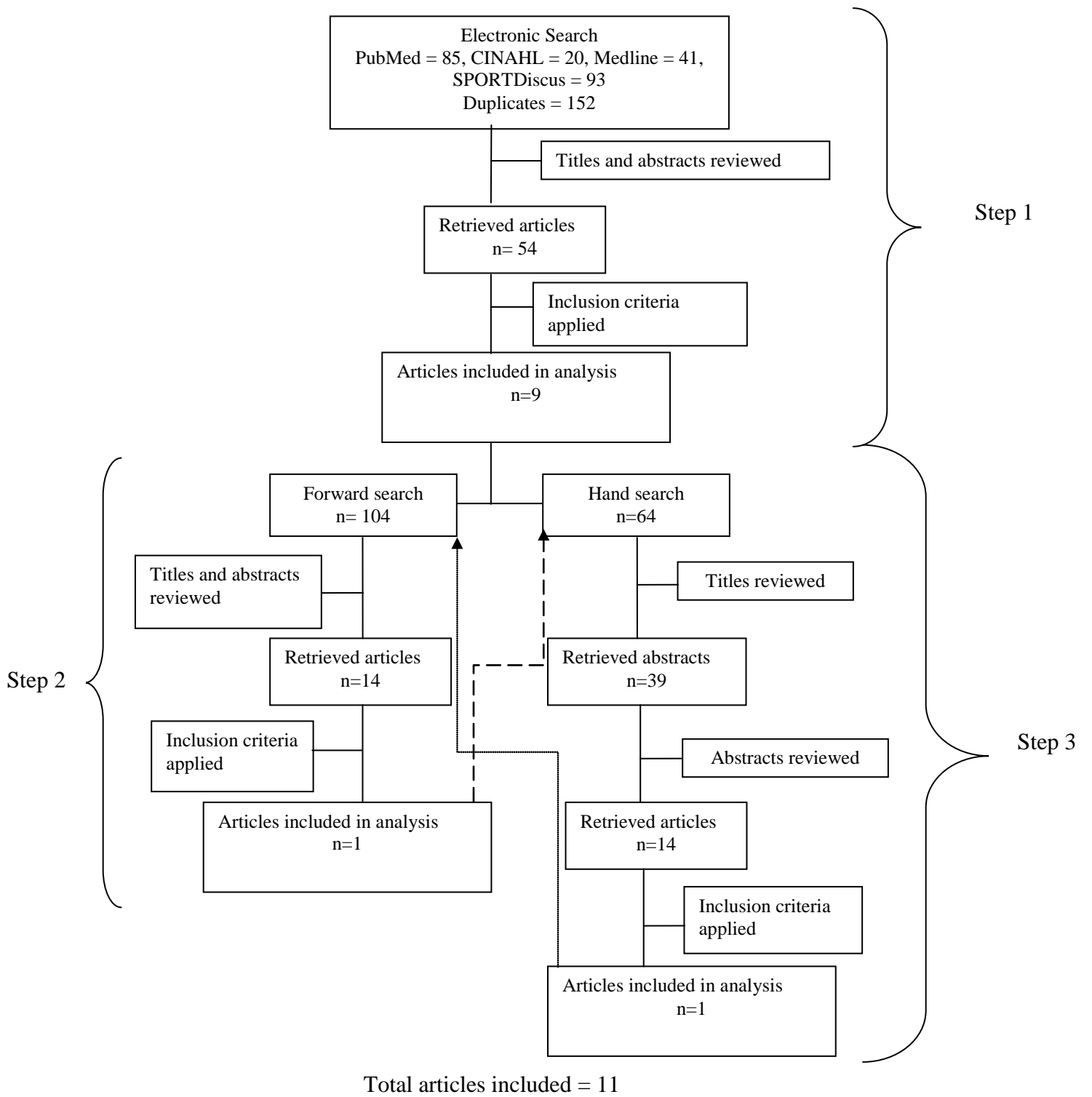


Figure 2.1 Flow chart for article review process.

Visual Cortices and their Impact on Sport-Related Concussion: A Review

Introduction

Concussion rates among athletes occur are estimated to be 1.6-3.8 million annually in the United States.¹ Concussions represent 13.2% of all sports injuries in high-school athletics.⁴ The challenge that health care providers face is in accurately diagnosing, managing, and making safe return to play decision following a concussive injury. Research on concussion has grown exponentially in recent years; many gaps remain in the literature regarding diagnosis and treatment of concussion. Current concussion researchers and experts in the field recognize that a battery of assessments are helpful to diagnose a concussion, although most assessment tools fails to explain underlying cause(s) for concussion signs and symptoms. Current post-concussion assessment protocols include self-reported symptom inventories, neuropsychological testing, and balance assessments.^{6-8,90} Balance assessments identify balance deficits in approximately 30% of all concussed athletes,⁵⁴ and are used to monitor recovery of balance performance following a concussion. Balance deficits typically resolve within 3-10 days of the initial injury.^{7,26,91} Researchers have suggested that balance impairments following a concussion result from either a failure of the somatosensory, visual, and vestibular systems to properly integrated information correctly.²⁴ Healthy individuals (including athletes) tend to rely more heavily on one sensory system (typically the visual system).²⁹ Healthy individuals tend to rely most heavily on the visual system to maintain upright balance, therefore, any changes in the visual system's ability to process visual information would greatly impair the individual's ability to maintain upright balance. The

presence of visual system changes and how these may have an adverse effect on balance following a concussion is not well understood. Literature has been mostly conducted in primate studies and focuses on the function of the dorsal and ventral pathways. The information gained from primate studies is critical for understanding how a concussion may affect the visual system, and may help to explain, at least in part, balance impairments following traumatic brain injury.

In primate studies, thirty separate visual cortical areas have been identified as being represented on the entire cortex, accounting for almost one-half of the total area of the cortex.⁹² Visual cortices are made up of two main pathways, the dorsal stream and ventral stream. Combined, these streams encompass 90% of the axons that leave the retina⁹³ and little to no vision survives in incidences where both pathways are destroyed.⁹⁴ Considerable debate exists as to whether the streams function independent from one-another. In order to understand the contributions and workings of the individual pathways, it is important to understand the central visual pathways as a whole to help comprehend the drivers of ‘perception’ and ‘action,’ and to help justify the suggestion of two independent pathways. The purposes of this article are to: (1) provide an overview of the two anatomical pathways of the human visual cortices, (2) describe the implications for differential effects of brain damage in the dorsal and ventral pathways of individuals who have sustained a mild traumatic brain injury, and (3) explain how frontal cortex function or dysfunction modulates perception and action that are accomplished in posterior parts of the brain.

Central Visual Pathways

The eye is an extremely complex biological system, having the most representation on the cortex of any of the senses⁹⁵ with the primary relay center being the lateral geniculate nucleus (LGN) of the thalamus. The LGN is comprised of six layers of cells which map the contralateral visual field. However, topographical representations of areas on the map are not equally distributed. High-acuity vision, for example is represented on the LGN to a much higher degree than vision which requires lower detail, such as vision in the peripheral fields.⁹⁶ Layers of the LGN are separated into two main groups: the magnocellular and parvocellular layers.⁹⁷

Researchers believed that the start of the perception and action streams (which will be discussed later) were the result of the divisions in the magnocellular and parvocellular layers of the LGN partially due to the function of the layers. The magnocellular layers (M-layers) involve the first two layers of the LGN. Cells contained within the M-layer contain large diameter cell bodies and large dendritic fields, causing rapid, transient response. Cells contained within the M-layer function to identify coarse detail, and motion analysis. M-cells typically have high temporal resolution and low spatial resolution. Information from the magnocellular layers are mainly sent via the dorsal stream to the parietal lobe and are believed to describe the ‘where’ of an object, although signals are sent elsewhere in the cortex, including the occipital lobe. Parvocellular layers (P-layers) are located on the third to sixth layer of the LGN. Cells within the P-layer contain small diameter cell bodies and dendritic fields which result in slowed sustained responses. Recognition of color sensitivities and fine detail occur within the P-layers because they tend to have low temporal resolution and high spatial resolution. Visual responses in the P-layers travel via the ventral stream and are referred

to as the ‘what’ stream, although signals from the P-layer are sent to other parts of the visual cortex as well. Each of the layers in the LGN remains separate in the initial stages of cortical processing, resulting in varying information processing deficits if individual pathways are damaged.

Damage in the magnocellular pathway results in inability to perceive quickly moving stimuli, while damage in the parvocellular pathway results in impaired visual acuity and color perception.⁹⁸ Observations in primates have lead researchers to believe that visual processing occurs in two distinct pathways with little to no communication between the two streams.^{95,99,100} Additionally, areas in the occipital, temporal, and parietal lobes have been observed to be greatly involved in visual processing. Areas shown in **Figure 2.2**⁹⁸ contain a map of visual space which is dependent on the primary visual cortex for its activation and each area responds to different stimuli (e.g. middle temporal (MT) neurons respond solely to a moving edge direction, while neurons contained within visual area V4 (V4) respond to color without regard to movement). Functional MRI studies have reported similar visual space maps in humans (**Figure 2.3**).⁹⁸ Individual areas of the visual cortex respond to different stimuli; therefore, damage to individual areas of the primary visual cortex or visual processing areas cause distinct impairments in primates depending on the areas damaged

Investigations involving individuals suffering from varying visual impairments resulted in the belief that the visual system is organized into two separate pathways. These two pathways mainly transmit information to the cortical association areas in the

temporal and parietal lobes.⁹⁸ Information from the striate cortex to inferior part of the temporal lobe is sent via the ventral stream. Information processed through this pathway includes references about high-resolution and object recognition. The dorsal stream terminates in the parietal lobe and contains the MT area which processes spatial aspects of vision.^{95,98,101} Considering the functional capacities of the streams, it is easy to see why the ventral stream is deemed the ‘what’ stream while the dorsal stream is termed the ‘where’ stream.

Organization and Function

Originally, scientists believed that the ventral and dorsal pathways formed as a result of the two cytological subdivisions of retinal ganglion cells (parvocellular and magnocellular layers). However, because there is more overlap between the layers than originally believed, another explanation of how the ventral and dorsal pathways function separately is needed. A more plausible explanation of separate pathways can be obtained by exploring the organization and function of the individual streams.

Organization

The ventral and dorsal pathways are arranged in such a manner that will optimize the area of the cortex. Areas of the cerebral cortex which have strong connections to each other are located a short distance from one another when compared to areas in which no connections occur; these cortical area are situated at opposite locations (**Figure 2.4**).

Organization of the macaque cortical visual system is shown in **Figure 2.5**. This organization highlights the varying distances of connections which are dependent on function and location. Additional organizational features are consistent within the visual matrix; structures tend to follow a posterior-anterior or inferior-superior distribution.¹⁰²

An example of this organization is the areas of the posterior parietal cortex which is concentrated in the top part of the diagram. There is a lack of connections between portions of the ventral and dorsal stream with some areas having no connections (**Figure 2.6**). Both streams do, however, have projections leading to area 46 and to the superior temporal polysensory area (STPa). Area 46 helps to determine what an object is, where it is, an object's movement in visual space, its color, and its relation to movement of the eyes; all of these roles are primarily performed initially in one of the two tracks. There may be a distinct visual track system which has no 'cross-talk' to a certain point, but eventually the streams come back together to help visual processing and help in identifying the 'what' and 'where' of objects.¹⁰²

Optimizing the area of the visual cortex provides justification for two separate pathways; however, an additional organizational pattern of a hierarchical organization may be more important. Hierarchical organization is present in both the dorsal and ventral streams as well as throughout the entire visual cortex. Visual signals are transformed into more useful representations of information at each ascending level. Additionally, as the levels increase from inferior to superior, the size of the receptive fields increase, the neuronal response latencies increase, and neuronal response complexities increase.⁹⁵ **Figure 2.6**¹⁰³ shows a representation of the visual cortical hierarchy as well as the ventral and dorsal streams. The complexity of the visual hierarchical organization allows for a better understanding of the increased functional demands within higher levels of the CNS.

Function

Perception and action are extremely complex processes that are processed through the visual system to help both humans and animals achieve desired goals such as movement, visual memory, and selective attention. These processes are located within the top levels of the hierarchical organization scheme and that damage at any lower level of the system can lead to drastic impairments in visual processing. The function of each of the ventral and dorsal streams leads to a better understanding of how visual process works and why impairments such as cerebral concussion may lead to impairments in visual processing. The ventral stream is critical for perception of objects^{101,104,105} while the dorsal stream is critical for visually- guided actions mediated at the level of the somatosensory system.^{106,107} Furthermore, each stream uses visual information for separate functions; the ventral visual stream uses information for perception and recognition of objects; information in the dorsal visual stream determines the details of the objects and helps to control goal-oriented motion. Each visual stream has distinct characteristics and functions but work together in the visual system to assist with visual perception and action (or ‘what’ and ‘where.’)

‘What’ vs. ‘Where’ pathways

Research in animal models, specifically primates, has revealed two distinct processing pathways with little overlap and communication between them¹⁰². Initially, evidence supporting the idea of two separate pathways arose from research conducted in primates in which lesions in a particular stream resulted in impairments related to the visual streams’ function. Lesions in the temporal pathways, for example, resulted in impaired visual discrimination tasks; lesions in parietal pathways resulted in impairments

in spatial visual processing. Additionally, in patients where lesions were present in only one stream, full functional capacity remained intact of the other stream. The importance of the ‘what’ and ‘where’ pathways for visual perception are apparent during activities of daily living and competitive sports.¹⁰⁸ Visual perception allows individuals to attach significance and meaning to objects and events in their visual environment.¹⁰⁹ From birth the visual system is actively using visual processing to identify objects and events for future use. In order for visual perception to actively encode information, the information needs to remain fairly consistent (such as the shape, size, color, and location of objects); thus, from various vantage points or in different environmental situations the individual is able to correctly recall the information regardless of the surrounding environment. The ‘action’ or dorsal visual pathway is very different from the ventral pathway because the action system is goal-directed and the transformation of information requires a ‘viewer-center’ analysis to make connection.¹⁰⁹ A ‘viewer-center’ analysis focuses on the goal object and the orientation of the object in relation to the observer, which can become a challenge due to the inconsistent nature in which visual orientation and visual processing goals occur. Due to the variety of functions occurring in each of the ventral and dorsal systems, visual informatics coding will vary within the visual systems in order to achieve the systems overall goals.¹⁰¹

The action system

The action or dorsal visual stream is the ‘where’ stream, which terminates in parts of the posterior parietal lobe, has functional roles in visual fixation, pursuit and saccadic eye movements, visually guided reaching, and the in-hand manipulation of objects.¹⁰⁴ The dorsal stream includes both sensory and movement-related activity,

although the activity is always short duration due to the motion of the animal or human. Additionally, cells in the dorsal stream fire during tasks in which an object is manipulated by the primate.⁹⁶ The dorsal stream is sensitive to the structure of the objects (such as orientation and size). Furthermore, action-dependent cells located within the medial superior temporal area (MST) area of the cortex are an imperative component of self-motion through an environment. The dorsal action stream is an integral part of determining where visual motion is occurring, as well as influencing where an individual needs to move his/her body to intercept an object or event. Although the posterior parietal lobe is extremely important in visual motion perception, connections to other motor areas of the brain allows the most efficient movement execution.

The posterior parietal lobe is where the majority of the action stream terminates and is strongly linked to areas in the frontal cortex, specifically prefrontal cortex where motions initiation begins. Links between the dorsal stream and the prefrontal cortex assist with reaching movements of the upper limb, as well as grasping objects by the hands and fingers. The ability to correctly move the limb toward a directed visual target and identify where the object is allows an individual to live without disabilities; in sports this connection is extremely important for catching a ball or swinging a racket towards a moving object.¹⁰⁸ Damage to either the dorsal visual stream or the prefrontal cortex would greatly diminish an athlete's performance. Additionally, because the prefrontal cortex is strongly involved in planning complex cognitive behaviors, decision making, and moderating social behavior,^{110,111} damage to this portion of the cortex would cause deficits in visually-guided decision making in the dorsal stream as well as deficits in complex cognitive visual tasks. The ability to move the body towards an object (e.g. ball,

goal) and intercept a moving ball is extremely important in sports and requires a working action and perceptual system to be successful.

The perception system

Information from both the M and P pathways contribute to the ventral perception system, ensuring that a great amount of visual detail is managed by the ventral stream.¹⁰¹ Neurons in the ventral system have a columnar arrangement similar to that of the primary visual cortex which helps to organize the system into areas of similar receptive areas and functions. The functions of the ventral visual stream have been investigated mainly in primates.¹⁰⁰ As previously mentioned, the ventral stream has longer-lasting responses due partly because of the larger receptive field; this makes the ventral stream more concerned with the consistency (texture, color, orientation) of the object rather than the action of the object which is more a function of the dorsal stream. Early phases of visual processing occur in the V4 area, a part of the ventral stream, in which learning-based upon orientation, form, and color/hue of the object or environment occurs.¹⁰⁴ Additionally, whereas the ventral system is more concerned with identifying objects, visual memory takes place primarily in the ventral visual system and in the surrounding areas of the limbic system. The majority of initial research performed on the normal functioning of the ventral visual stream was performed with lesion analysis in primates; lesioned primates ventral stream do not affect their ability to maintain spatial awareness and correct hand position for grasping, but did impact the primate ability to recognize objects, faces, and spaces. Thus, damage in the ventral stream provides evidence of the two stream hypothesis.¹⁰¹ Overall, damage, as a result of a concussion, in either the ventral or dorsal streams would cause dramatic effects on vision and visual processing.

Effects of concussion on ventral and dorsal pathways

Following a mild traumatic brain injury, there are typically no structural changes visible on standard neuroimaging studies;¹³ rather, the effects are physiological and occur as a result of the mechanical forces that are imparted on the brain during the rapid acceleration/deceleration motion.¹¹² Due to the rapid forces that are transmitted through the cranium, both widespread and focal damage to the brain can occur. Both shearing and stretching micro-trauma occurs at the cellular (axonal) level which results in widespread pathophysiological changes. Giza and Hovda (2001)⁵⁵ developed an animal model of these changes that occur in the brain immediately following a concussion; this ‘neurometabolic cascade’ of events will assist with explaining possible mechanisms for visual disturbances in athletes following a head injury and, more specifically, what occurs in the dorsal and ventral visual pathway. Following a concussion there is, “An abrupt neuronal depolarization, release of excitatory neurotransmitters, ionic shifts, changes in glucose metabolism, altered cerebral blood flow, and impaired axonal function.”⁵⁵ Given the vulnerability of the brain to changes in its normal physiology, any of the neurometabolic changes could lead to impairments in the visual system. Stress on the energy system cause by decreases in cerebral blood flow and hyperglycolysis immediately following concussion may cause an imbalance in energy use by the neurons, possibly leading to impairments in visual processing and cognition⁵⁵. Calcium influx, mitochondrial dysfunction, and delayed glucose hypometabolism occur immediately following the concussive hit and may last for several days after the initial injury, even if clinical symptoms have resolved. The cycle that occurs with increased levels of calcium, problems with mitochondrial dysfunction and glucose hypometabolism cause neuronal energy failure, which hinders recovery and impairs cognitive function. In addition to the

ongoing neurometabolic changes that are brought about by a concussive injury, there is evidence for widespread diffuse axonal injury (DAI) that accompanies these physiologic changes.⁵⁶

“The principle mechanical force responsible for diffuse axonal injury is rotational acceleration of the brain, resulting from unrestricted head movement including dynamic shear, tensile, and compressive strains within the tissue.”(Johnson, 2012)⁵⁶ Axons are responsible for transmitting information and impairments at the cellular level would result in membrane disruption and depolarization of the cell; this may present itself clinically as delayed information processing. ⁵⁶ Due to the speed at which visual processing occurs and the complexity of the visual pathways within the CNS, even a minor delay in neuronal processing would cause a significant decrease in the time in which an individual could process visual information. This may help explain the clinical symptoms often experienced by an athlete following a concussion, such as blurred vision, disorientation, and memory difficulties. Additional clinical symptoms (such as difficulty concentration, headache, and cognitive problems) may be from the result of DAI or potentially from focal damage to affected cerebral lobes proper. According to Bigler (2007), the frontal and temporal lobes are more susceptible to injury.⁶⁰ This may provide additional evidence for dorsal and ventral pathway impairments in athletes following a concussion.

The definition of a concussion, as defined by the International Concussion in Sport Group (2002, 2009), is a complex pathophysiological process affecting the brain, induced by biomechanical forces. Common features of concussion include the following: (1) it may be caused by a direct blow to the head, face, neck, or elsewhere on the body

with in 'impulsive' force transmitted to the head; (2) it typically results in rapid onset of short-lived impairments of neurological function that resolve spontaneously; (3) it may result in neuropathological changes but the acute clinical symptoms largely reflect a functional disturbance rather than structural injury; and (4) it results in a graded set of clinical symptoms that may or may not involve loss of consciousness, symptoms typically follow a sequential course.^{5,113} A concussion results in a functional disturbance that results in graded symptoms. Symptoms of dorsal and ventral visual pathway impairments may be observed in concussed individual who experience delayed visual memory processing and impaired memory recall.⁵⁸ Such impairments may be caused by the widespread injury (DAI and the neurometabolic cascade), and may also be caused by focal damage to the pathways. Cerebral concussion in sports commonly occurs following a direct hit to the head or from the hitting directly on an object, and there is the potential for focal damage in any of the cerebral lobes. The primary visual cortex is located in the occipital lobe at the posterior-inferior portion of the brain. Damage to the visual system would become apparent in the athlete as a result of potential minor brain bleeds or swelling. Additionally, the frontal lobe, which is located at the most anterior portion of the cerebrum, could easily suffer from a concussive blow by either a direct hit (*coup* injury) or from the secondary jarring of the brain against the skull (*contre-coup* injury). Damage to the frontal lobe would cause focal functional impairments and deficits among the connecting dorsal visual pathways. Dorsal visual pathway lesions would lead to impairments in smooth pursuit movements towards a visual target and impairments in cognition (as mentioned earlier).

Temporal Lobe

Memory and language are the main functions of the temporal lobe¹¹² of the cerebrum and damage here should always be suspected following concussion where an athlete has difficulty with speech or memory. Recent evidence during visual and verbal memory testing indicates that 75% of all patients sustaining a concussion suffer damage in the temporal lobe.¹¹² The temporal lobe is the termination point for the majority of the ventral visual pathway and damage from either widespread physiological changes or focal injury would cause delayed processing for all functions of the ventral pathway. These ventral visual pathway functions include visual memory and object recognition. Information from the ventral pathway merges with information from the dorsal/parietal pathway to activate functions, (movement initiation, decision making, and emotional state) of the frontal lobe.

Parietal Lobe

Although the parietal lobe of the cerebrum is unlikely to sustain a focal injury caused by an athletic concussion, widespread physiological changes may cause physiologic alterations. Injuries to the areas surrounding the parietal lobe may cause swelling and herniation into the parietal lobe. The parietal lobe is considered the main coordination point for vision and movement.¹¹⁴ Smooth pursuits movement towards a visual target would not be possible in cases where parietal lobe damage occurs.¹¹² Other common clinical symptoms that an individual may experience as a result of damage to the parietal lobe are disorientation, difficulty identifying objects, and clumsiness of the hands.¹¹⁴ Athletic performance is strongly dependent on hand-eye coordination and, therefore, any damage to the parietal lobe could lead to a drastic decrease in athletic

performance. The parietal lobe is closely linked with the motor cortex of the frontal lobe, which provides the basis of movement throughout the body.

Frontal Lobe

The frontal lobe is commonly affected by concussion⁶² and is clinically manifested as neurocognitive impairments. The frontal lobe is highly linked to the visual areas of the cortex ; the large majority of higher-order visual processing tasks involve areas in the frontal lobe and many visual processing tasks could never be accomplished without the connections between the frontal lobe and visual pathways. An example of this inter-relationship is the connection between areas in the ventral and dorsal pathways (neurons in V4 and inferotemporal cortex) and attention.¹¹⁵ Although the frontal lobe is commonly affected following a concussion, typically the resulting impairments are short-lived and the individual returns back to functional levels within approximately one week following injury.¹¹² Recovery may be protracted in cases of repeat concussions, a history of migraine headaches, and possibly because of learning deficits or other developmental disorders.¹¹⁶ Stuss (2011) linked dysfunction in the frontal lobe into 4 main categories: (1) speed of processing, (2) executive functioning, (3) emotional reactivity/personality, and (4) empathy/metacognition.¹¹⁷ These types of dysfunctions mainly occur with moderate to severe brain injuries, but there is evidence to support the same deficits following a mild traumatic brain injury. Following a sport-related concussion, many of the symptoms can be related to these four categories of impairments, although not all of the symptoms correlate with the ventral and dorsal pathways specifically. Deficits such as decreased reaction time or lethargy may be caused by slowed speed of processing or executive functioning. The link between damage in the frontal lobe and functions at

lower levels, such as in the ventral and dorsal pathways, help establish that the frontal lobe as part of the ‘top-down processing’ system occurring in the cerebral cortex.⁶⁰ The frontal lobe is the main center for attention and memory and, therefore, damage to this area following a concussion could lead to deficits for athletes both on and off the field.

Selective attention and working memory as part of top-down processing

Selective visual attention is mediated through the relationship between the frontal lobe and visual pathways⁵⁹ and involves the ability to focus on an object while in the presence of multiple objects. Selective attention and working memory are frequently affected following concussion⁵⁸ and are both traditionally tested through the use of neuropsychological assessments.⁶⁰ The link between selective attention and working memory is reciprocal, in that one process relies heavily on the other. Recent research has demonstrated that working memory rely on selective attention to function fully, and that selective attention receives information about the object from memory in order to help make the determination of importance.⁶¹ The receptive fields in the ventral pathway are large in nature and they function to distinguish between a target object and additional distractors or more accurately selective attention.⁵⁹ The selective attention process allows an individual to focus on the desired object/goal while disregarding the remaining stimuli.⁶¹ Working memory allows the object to be remembered while the distractors are often forgotten. Selective attention is regarded mostly as a ‘top-down process’ where information in regards to what is important about the object is sent from structures in the frontal lobe to the visual pathways where the information is gathered and processed for further action. Damage in the frontal lobe and visual pathways, as discussed previously, greatly affects these processes. Visual processing is modulated in the visual cortex with

the assistance of the ventral and dorsal visual pathways. Visual information is received in V1 and then transmitted to structures in the higher cortical areas to be further processed. This system is termed ‘top-down processing’ and functions throughout the frontal-parietal-visual networks during visual processing.⁶¹ Researchers using transcranial magnetic stimulation (TMS)⁶¹ have added to the evidence that visual processing is a ‘top-down’ action in the visual cortex, as when repetitive TMS was applied to areas of the frontal lobe, functions at lower level were temporarily impaired. When the TMS was applied to lower cortical levels, function at the highest level of the cortex were not affected.⁶¹ Overall, ‘top-down processing’ includes more than selective attention and working memory; these two processes are extremely important to the visual system.

Conclusion

The overall purpose of the paper was to provide an anatomical and physiological description of the two separate visual pathways for perception and action. A general overview of the dorsal and ventral pathway in the visual cortices was presented, a description of how athletes who suffer a cerebral concussive injury would have problems in the perception and action pathways, and finally description of the relationship between frontal top-down processing and perception and action streams was presented. The visual system is an extremely complex entity in which damage to any of the systems or areas can lead to drastic changes elsewhere in the brain and body. There has been considerable debate in the literature about two separate pathways for perception and action, and an understand the relationship between the two separate pathways begins in the lateral geniculate nucleus and terminates in the parietal, and temporal lobes. Both the ventral and dorsal visual pathways function independently to help identify the ‘what’ and

'where' of objects and events. Following identification of the target object, further processing takes place at higher-order processing centers throughout the frontal lobe, including visual memory and selective attention. A concussion can cause damages in focal or wide-spread areas throughout the cortex and, following injury, athletes may demonstrate deficits in functions related to the injured cortical areas. Damage to the ventral and dorsal visual pathway would be revealed as impairments during pathway-dependent tasks such as visual memory or visually guided reach, while damage in the frontal lobe would lead to deficits in more cognitive-based tasks such as selective visual attention and visual memory recall. Overall, the visual system is an extremely interconnected functional area of the cerebrum within individual areas specialize in performing specific tasks; macroscopic or microscopic damage to any specific area or the cerebrum will cause specific and often overlapping impairments.

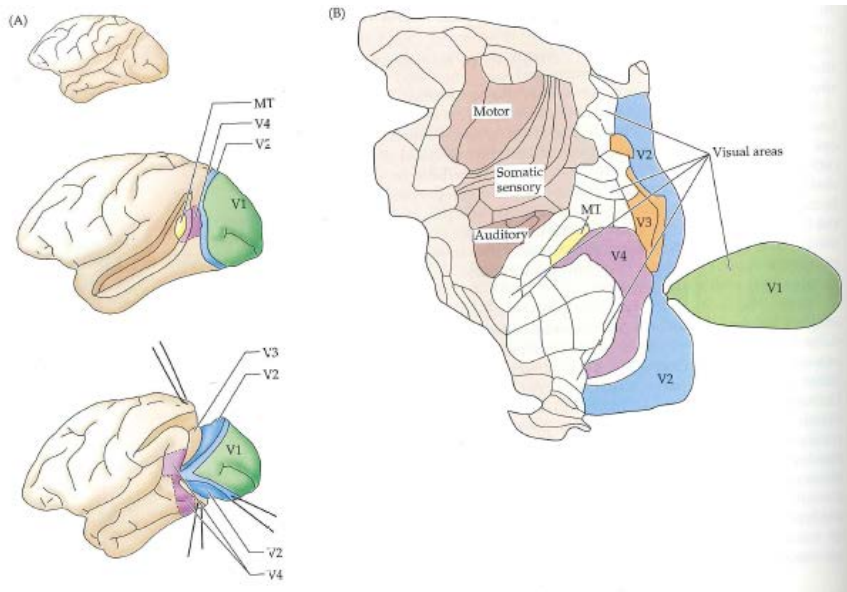


Figure 2.2 Subdivision of the extrastriate cortex in the macaque monkey

(A) Each of the subdivisions indicated in color contains neurons that respond to visual stimulation. Many are buried in sulci, and the overlying cortex must be removed in order to expose them. Some of the extensively studied extrastriate areas are specifically identified (V2, V3, V4, and MT). V1 is the primary visual cortex; MT is the middle temporal area. (B) The arrangement of extrastriate and other areas of neocortex in a flattened view of the monkey neocortex. There are at least 25 areas that are predominantly or exclusively visual in function, plus 7 other areas suspected to play a role in visual processing. Used with permission¹¹⁸

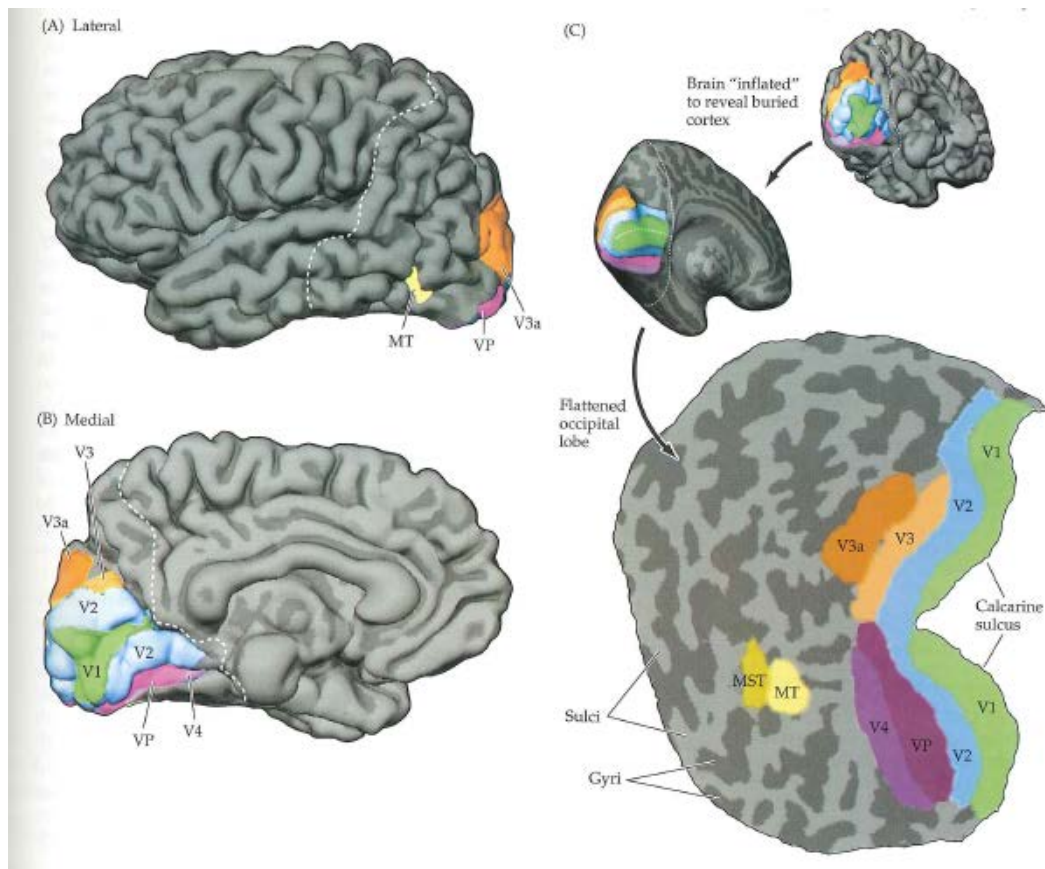


Figure 2.3 Localization of multiple visual areas in the human brain using fMRI

(A,B) Lateral and medial views (respectively) of the human brain, illustrating the location of primary visual cortex (V1) and additional visual areas V2, V3, VP (ventral posterior area), V4, MT (middle temporal area), and MST (medial superior temporal area). (C) Unfolded and flattened view of retinotopically defined visual areas in the occipital lobe. Dark grey areas correspond to cortical regions that were embedded in sulci; light regions correspond to regions that were located on the surface of gyri. Visual areas in humans show a close resemblance to visual areas originally defined in monkeys. Used with permission from (a)¹¹⁹ and (b).¹²⁰

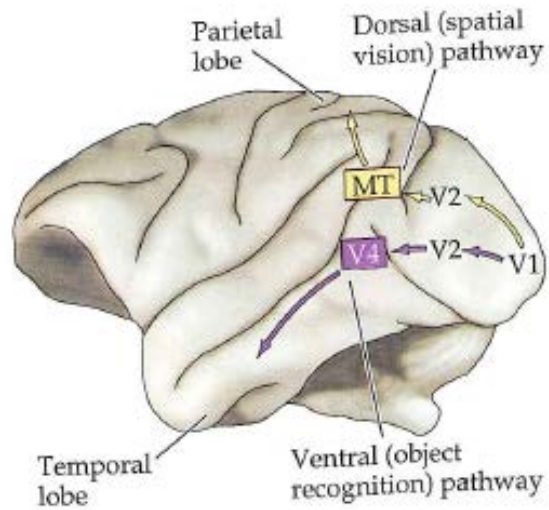


Figure 2.4 The visual areas beyond the striate cortex

The visual areas beyond the striate cortex are broadly organized into two pathways: a ventral pathway that leads to the temporal lobe, and a dorsal pathway that leads to the parietal lobe. The ventral pathway plays an important role in object recognition, the dorsal pathway in spatial vision. Used with permission. ⁹⁸

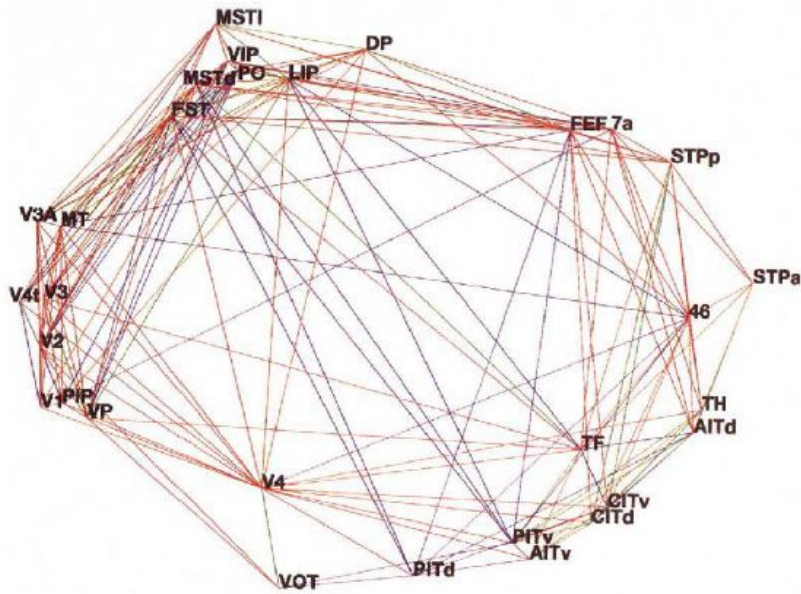


Figure 2.5 The topological organization of the macaque cortical visual system

Reciprocal connections are colored red, one-way projections going from left to right are colored blue and one-way projections going from right to left are green. A total of 301 connections is represented, of which 62 are one-way. This non-arbitrary structure is a best-fit representation in 2 dimensions of the connectional topology of this system, in which the position of areas are specified by their positions being ones that minimize the distance between connected areas and maximize the distance between areas that are not connected. Used with permission.¹⁰²

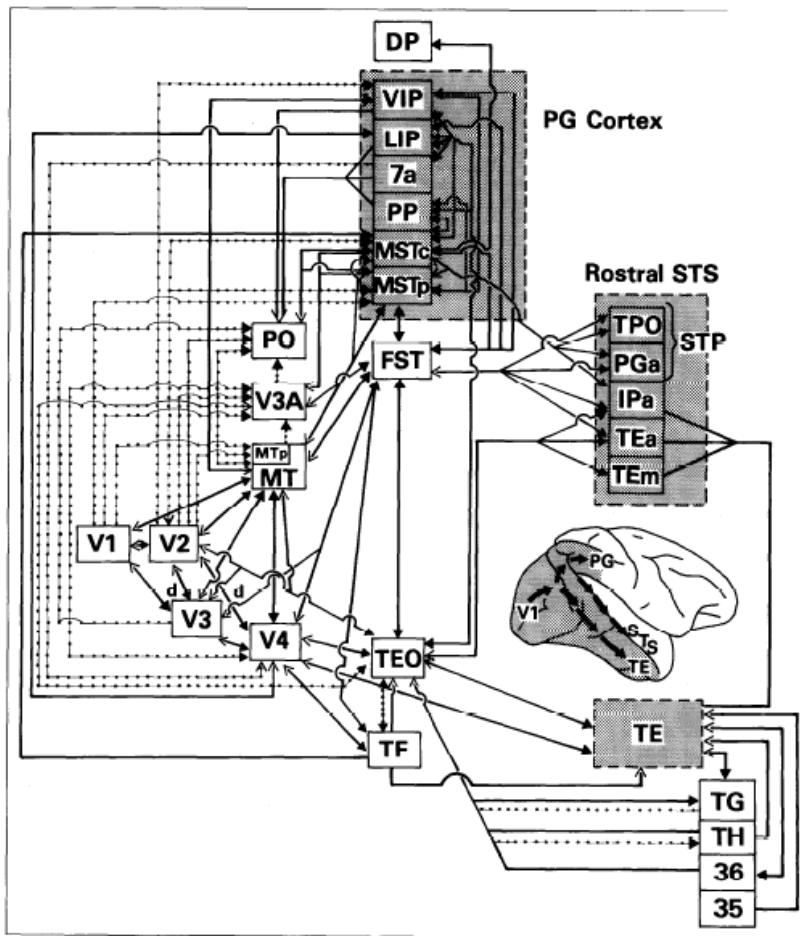


Figure 2.6 Summary diagram of the visual cortical hierarchy

Solid lines indicate connections originating from both central and peripheral field representations, where dotted lines indicate connections restricted to peripheral field representations. Solid arrowheads indicate feed-forward connections, open arrowheads indicate feedback connections, and reciprocal solid arrowheads indicate intermediate-type connections. The diagram demonstrated the divergence in the flow of visual information into ventral and dorsal streams directed toward the inferior temporal (TE) and inferior parietal (PG) cortex, respectively, and possibly sites for interaction between the two within the rostral superior temporal sulcus (STS). Used with permission.¹⁰³

Chapter 3 Visuo-Motor Processing Impairments Following Concussion in Athletes

Introduction

Sport-related concussion rates in the United States have been reported as 300,000 concussions annually.^{121,122} Approximately 50% of all concussions going unreported⁷⁸ by the athlete, so the true number of concussions may be much higher. Health care providers are faced with the intimidating task of diagnosing, managing, and making return to play decisions following sport-related concussions. The obstacle that health care professionals encounter in diagnosing concussion arises from the lack of biological markers or standardized assessment protocols which accurately detect a concussion.⁷⁸ Concussion symptoms are highly variable among individual athletes and even among separate incidents in the same athletes, which poses a challenge for even the most experienced athletic trainer or sports medicine clinician to determine whether an athlete has sustained a concussion or not. Adding to the challenge is the lack of consensus of the definition of concussion. While most allied health providers believe that a concussion is synonymous with a mild traumatic brain injury, there are some professionals who believe concussion is a distinct injury and therefore requires its own definition.⁵ The most widely accepted definition of concussion is defined by the Concussion in Sport Group (2009) as, “A complex pathophysiological process affecting the brain, induced by biomechanical forces. Common features of concussion include; may be caused by a direct blow to the head, face, neck, or elsewhere on the body with in ‘impulsive’ force transmitted to the head; typically results in rapid onset of short-lived impairments of neurological function that resolve spontaneously; may result in neuropathological changes but the acute clinical symptoms largely reflect a functional disturbance rather than structural injury; and result

in a graded set of clinical symptoms that may or may not involve loss of consciousness, symptoms typically follow a sequential course.”^{5,113 5}

A concussion is a result of forces transmitted to the brain which cause both focal and widespread damage at the neuronal level.⁵⁵ The mechanism of injury that causes stretching and shearing of the axons results in diffuse axonal injury (DAI)⁵⁶ and triggers the onset of a neurometabolic cascade of concussion (NCC).⁵⁵ Both DAI and NCC have been noted to cause impairments in axonal transmission speed.⁵⁶ Axons are responsible for transmitting information, including sensory information, throughout the brain and body. Any delay in the speed of transmission of neural signals may result in problems in sensory information integration, including information to and from the visual system. DAI results in disruption and depolarization of the cellular membrane and widespread damage to the axons in the brainstem, parasagittal white matter of the cerebral cortex, and corpus callosum,⁵⁵ which result in functional impairments at the systems level. Cognitive deficits (e.g. disorders in memory), possible changes in, vision,¹²³ visuo-motor processing³⁰ and delays in information processing⁵⁷ may arise as a result of the changes at the physiological level.

The visual system relies on the ability to perceive and process visual stimuli quickly, and to cognitively interpret the stimuli to usable information; any delay in this process would likely cause clinical functional impairments. The human visual system uses visual information from the surrounding environment as well as cognitive information to interpret visual stimuli and to navigate through the environment.⁷⁶ The ability of an individual to maintain upright balance and gait is dependent on their capacity to accurately interpret their visual environment and objects in the environment. The ability

of the visual system to identify objects and integrate that information into a *sensory map* involves information from the visual system, as well as information from the somatosensory and vestibular systems. Information from the vestibular system provides information about the position of the head and neck in space,¹²⁴ while the somatosensory system provides information about the support surface.³¹ Following a concussion, an athlete may suffer from several visual system impairments including:^{30,125-127} (1) *visual attention* (defined as their ability to maintain gaze on an object while disregarding other objects or stimuli),¹²⁸ (2) *visual memory* (the ability to perceive an object visually, then store and retrieve that information at a later time)¹²⁹, (3) *working memory* (the ability to hold or retain information while focusing on another task),¹³⁰ (4) *selective attention* (the ability to choose relevant visual information and ignore distracting or irrelevant information)⁷⁶ and (5) *visual discrimination* (the ability to identify features of a stimuli and distinguish its identity).⁷⁶ Each of these components are key aspects of the visual processing system. Visual processing is the foundation for *visuo-motor processing*, which is defined as the ability to integrate visual information with motor skills to produce functional movement patterns.¹³¹ In athletes, the ability to integrate information about their surrounding environment (e.g. the location and movement of opposing players, location on the field, velocity of ball, etc.) is a fundamental component to successful sports participation. Following a concussion, an athlete may be unable to successfully incorporate visual information with information gained from other sensory systems (vestibular, somatosensory, cognitive) resulting in functional impairments (e.g. balance deficits, gait impairments). Visuo-motor processing may be impaired following

concussions and health care professionals need to be able to properly identify and manage these impairments before an individual is allowed to return to participation.

Simple visuo-motor processing (SVMP) testing protocols³⁰ can help identify deficits in *visual processing* and *visual perception* but have yet to be investigated among concussed athletes. SVMP uses stimuli that measures visual processing in 2D motion, in contrast with a complex visuo-motor processing task which measures visual processing in a 3D rotational motion. Stimuli used in computer-based SVMP testing are defined by their luminance (i.e. simple or first-order stimuli³⁰) and are used in conjunction with second-order stimuli (defined by contrast, texture, and depth)⁶⁵ to help generate an image of an individual's surroundings. When an athlete is able to successfully generate a visual map of their surroundings, they can navigate through those surroundings without much difficulty. The effects of an acute sport-related concussion on an athlete's ability to successfully visually 'map their surroundings' have not been systematically investigated. Examining visuo-motor processing following a sport-related concussion using a simple visuo-motor processing task may provide insight for into the pathophysiologic processes and clinical recovery following concussion, which will allow health care professionals to make a more informed return to play decision. The primary purpose of this study was to identify if visuo-motor processing is altered in athletes following sports-related concussion. The secondary purpose was to determine the test-retest reliability of a simple visuo-motor task in a healthy athletic population.

Methods

Design

A longitudinal cohort study design was used. The independent variables included time (with 2 levels: days 1 and day 10 following injury) and group (with 2 levels: concussed and control subjects). The dependent variables were derived from a simple visuo-motor processing task which included: reaction time, number of errors, number of responses right/left, and number of ambiguous responses (left and right directions).

Subjects

The target number of subjects necessary, based on a power analysis using visual processing data derived from Brosseau (2008)³⁰, using an *a priori* level of significance equal to 0.10, was a minimum of 12 subjects per group. This design achieves 80% power to test for mean differences in average reaction times between concussed and control subjects and 99% power to test for mean differences in average reaction times between day 1 and day 10 (effect sizes of 0.52 and 0.90, respectively). Additionally, this design achieves 98% power to test for significant interaction differences between concussed and control subjects over the 2 time points (with an effect size of 0.90). All statistical analyses assume a Wilk's-Lambda test was implemented with a 10% significance level.

Seven acutely concussed subjects [age (17.1 ± 3.0 years), height (174.0 ± 74.2 cm), weight (73.3 ± 23.8 kg)] participated in the study. Subjects were included in the concussed group if they participated in an intercollegiate, interscholastic, or club sport and had been diagnosed with a concussion by a certified athletic trainer or physician sustained within the previous 48 hours. Concussion was defined as: "A complex pathophysiological process affecting the brain, induced by biomechanical forces. Common features include;

caused by a direct blow to the head, face, neck, or elsewhere on the body with an ‘impulsive’ force transmitted to the head; typically results in rapid onset of short-lived impairment of neurological function that resolves spontaneously; may result in neuropathological changes but the acute clinical symptoms largely reflect a functional disturbance rather than structural injury; result in a graded set of clinical symptoms that may or may not involve loss of consciousness; resolution of clinical and cognitive symptoms typically follows a sequential course.”⁷⁴ Seven control subjects [age (17.3 ± 3.1 years), height (178.8 ± 11.6 cm), weight (77.9 ± 23.4 kg)] with similar age, sport, and gender participated. All subjects were volunteers whom signed a written informed consent or assent form. Human subject’s approval was obtained from the Office of Research Integrity at the University of Kentucky (IRB#12-0509) prior to beginning the study.

Control subjects had no self-reported history of a concussion within the previous year, were not taking any medications that may affect balance (e.g. NSAIDS, antidepressants, anticonvulsants, vestibular suppressants, neurostimulants, antimetics)¹³² taken within 2 hours of the scheduled testing, or vision less than 20/20 (corrected or uncorrected) as measured during the static visual acuity testing using the NeuroCom® InVision program (see Testing Procedures below).

Instrumentation

E-prime V1.2 software (Psychology Software, Pittsburgh PA), and a Dell laptop computer with an external keyboard were used for the visual processing test. To limit the number of errors from subjects using incorrect keys, a modified keyboard was used in which all of the keys except the keys required for responses (‘a’, ‘l’, and ‘spacebar’) were

removed. Visual acuity testing was conducted with the NeuroCom® InVision software, a component of the NeuroCom Smart Balance System (NeuroCom® International, Inc; Clackamas, OR). The hardware for the visual acuity testing included a head-mounted tracking device (**Figure 3.2**) that determines the angle, distance, and velocity of head motion during the testing procedures.

Procedures

Subjects reported to the research laboratory on two separate occasions: 24 to 48 hours and 10 days following injury. These testing time points were chosen based upon previous published research demonstrating initial deficits in postural stability and recovery of postural stability comparable to control subjects within 24 hours to 10 days following a concussion.^{24,26-28} Control subjects were assessed at the same time intervals but not necessarily on the same day as their matched concussed subjects. All subjects were screened using a self-reported medical screening form containing questions about their health and medical history. Demographic information (e.g. height, weight, age, handedness, gender, and sport) was collected using standard techniques and entered into the E-prime software data files.

To determine if visuo-motor processing was affected by the concussion, subjects complete a visual processing task, as developed by Pinkus and Patel (1997),⁷² in which they were seated at a distance of 24 inches from the computer screen with a modified keyboard positioned on a desk directly in front of the subject. The validity and reliability of the SVMP task had not been established prior to the initiation of this study, the study was based upon previously published work of Pinkus and Patel⁷² which showed good face validity. A secondary purpose of this study was to determine the reliability of the

measure in athletes, as this has not been evaluated. Subjects were shown a series of sine-wave gratings on a computer monitor with a refresh rate of 75 Hz and a screen resolution of 1024 X 768 pixels. Mean luminance for the stimuli was 14cd/m². **Figure 3.1** represents ‘motion jumps’ that subject were asked to identify during the visuo-motor testing sequence.

Each trial began with a neutral stimuli (0°) followed by a second frame presented in one of three orientations: +90°, -90°, and 180°. Orientations of +90° and -90° were ambiguous right or ambiguous left motion while motion in the 180° was an unambiguous stimulus with no correct response. Right and left motion shifts are associated with +90° and -90° stimulus respectively, while 180° motion shifts represent a counter-phase shift with no correct response. Unambiguous trials were included to help determine if visual processing at higher levels of the brain are affected. Subjects completed 120 trials (40 trials in each orientation) in a random order as determined by E-prime software. The stimuli were constructed as in the 2D motion priming experiments reported by Pinkus and Pantle (1997)⁷². A 5-second inter-trial interval was used to diminish the effects of motion priming [influence of a previously perceived moving object on the subsequent perception of the motion of another moving object]¹³³ occurring between each trial.

Subjects were instructed to look at the whole screen (“look globally”) and not to focus on one individual place on the screen. Subjects were instructed to respond to each motion jump as quickly and accurately as possible. If the motion is in the left directions subjects are to press the ‘a’ button on the keyboard and if motion jump is to the right, subjects are to press the ‘l’ button in the keyboard. If a subject failed to respond within 5-seconds of the motion jump, the trial was marked as non-response and the next trial

began automatically. If subjects were unsure of which direction the motion occurred, they were instructed to press both the 'l' and 'a' buttons together. Testing lasted approximately 5 minutes and ended automatically after the completion of all 120 trials (40 per direction, ambiguous, unambiguous right, unambiguous left). Data derived from this test included: reaction time (msec), number of errors, number of overall responses (left and right directions), and number of ambiguous responses (left and right directions). All data were automatically extracted for analysis into an Excel spreadsheet by the Eprime software at the conclusion of the session. The order of the testing was counterbalanced between days and testing sequence to limit the potential influence of fatigue on the subject.

All subjects completed standardized visual acuity testing using the NeuroCom *InVision* system to determine their static and dynamic visual acuity. Subjects sat 10 feet (3 meters) away from a computer monitor adjusted to eye level. To determine static visual acuity, subjects completed the Static Visual Acuity (SVA) and Perception Time Test (PTT) protocols in which subjects were asked to correctly identify the orientation of an optotype (capital letter 'E'); the direction of the optotype could be up, down, left or right. Perception time was defined as the shortest presentation time that the optotype could be accurately determined.⁷¹ During the PTT the length of time of the optotype stimulus presentation was automatically decreased from 240 msec to 20 msec until either the final speed (20 msec) was achieved or the subject failed to identify the orientation of the optotype at a faster speed. SVA was determined by reducing the size of the optotype until the subject was unable to correctly identify its correct orientation in 3 out of 5 consecutive trials. SVA was reported as a LogMAR score (logarithm of minimum angle

of resolution) and later converted to a Snellen fraction. LogMAR scores represent the apparent size of an image based on a ratio of its absolute size to the distance from the eye⁷¹ while the Snellen fraction is a representation of visual acuity where the numerator is the distance and the denominator is the smallest Snellen letter read by the eye. While the Snellen fraction is more commonly used clinically, logMAR scores represent data which can be manipulated and interpreted in research studies.¹³⁴

Dynamic visual acuity was assessed using the Dynamic Visual Acuity (DVA) and the Gaze Stabilization Test (GST) protocols. The initial size of the optotype for assessing dynamic visual acuity was 0.2 logMAR greater than what was determined on the SVA test. The DVA test is a measure of the subject's ability to correctly identify the orientation of the optotype while the head is actively moving; this test assesses the functional integrity of the vestibular ocular reflex (VOR).⁷¹ During the DVA test, subjects were fitted with a head mounted sensor (**Figure 3.2**) which tracks the velocity and degree of head movement. Subjects were asked to move their head in a side-to-side motion, 20° to the right and left directions in a horizontal plane at 85 degrees/second while maintaining their visual gaze on the computer screen positioned 10 feet away. Subjects were required to correctly identify the orientation of the optotype when presented by verbally responding to the investigator who then manually entered the subject's responses on the NeuroCom system. The number of trials varied between subjects depending on the number of correct/incorrect responses given. When a subject failed to correctly identify 3 out of 5 successive orientations, the test was automatically stopped. In contrast to the DVA, the GST measured the subject's ability to maintain an acceptable level of acuity while moving the head at higher speeds. The same head

mounted sensor was placed on the head of the seated subject. Subjects were then asked to rotate their head 20° in each direction in a horizontal plane at varying speeds ranging from 10 to 150°/sec. The velocity of head rotation began at 70°/sec and either increased (in response to a correct response of the otype presented) or decreased (in response to an incorrect response of the otype presented). Subjects were required to correctly identify otype orientation until they failed to correctly identify three out of five presentations. The number of responses required varied depending on the number of correct and incorrect responses given by the subject.

Practice trials for the PTT, GST, and DVA were administered prior to all testing to ensure subjects understood the task and to account for potential practice effects. Practice on these tests was permitted until the subject verbally articulated to the tester that he/she felt comfortable with the test and understood the directions.

Data Reduction

All data derived from the visuo-motor task were summarized by E-prime software and automatically exported into an Excel datasheet for data processing. Data derived from the DVA test included: DVA loss left, and DVA loss right; data derived from the GST included: perception time, static acuity, maximum velocity achieved left and maximum velocity achieved right. DVA and GST data were expressed as a LogMAR score. LogMAR scores represent a measure of visual acuity loss and were used for primary analysis but were later converted, with the assistance of a standard visual acuity chart,¹³⁴ to a Snellen fraction for interpretation.

Statistical Analysis

Descriptive statistics, measures of central tendency and variability were calculated to summarize the demographic characteristics of the sample. A repeated measures ANOVA, using a Bonferroni correction to control for the familywise error rate, was used to assess for differences between groups (concussed and control), and testing sessions (day 1, and day 10) on subjects' performance of the visuomotor processing task. To determine the stability of subjects' performance on the visuomotor processing task over time, interclass correlations coefficients (ICC, version 2,1)¹³⁵ were calculated. ICCs¹³⁶ were interpreted as per Fleiss' criteria: below 0.4 is considered poor reliability, 0.4 to 0.75 is considered moderate to good reliability, and above 0.75 is considered excellent reliability.¹³⁷ On the basis of the reliability coefficients, the minimum detectable change (MDC) for each condition was calculated using the following formula:

$$\text{MDC} = 1.96 \times \text{SEM} \times \sqrt{2}^{138} \text{ [where the standard error of the measurement (SEM)}$$

will be computed using the following formula:

$$\text{SEM} = S_x \sqrt{(1-r_{xx})}^{138} \text{ where } S_x \text{ is the standard deviation of the equilibrium scores}$$

and r_{xx} is the reliability coefficient (r).

All statistical analyses were performed with SPSS software (PASW Statistics version 18.0, SPSS Inc., Chicago, IL). An *a priori* alpha level of $p < .10$ was applied to all data to determine significant differences. An alpha level of $p < .10$ was chosen because the research question was exploratory in nature and the testing procedures (i.e. visual processing task) have not been used previously in the selected population or with the same outcomes.

Results

Descriptive statistics for the SVMP task and visual acuity testing (GST and DVA) are presented in **Tables 3.1** and **3.3**, respectively. The results of the reliability analysis and MDC values for the SVMP task are presented in **Table 3.2**.

Simple Visuo-Motor Processing Task

Separate two-way ANOVAs with repeated measures on the factor ‘time’ revealed a significant day by group interaction for: overall reaction time ($F_{1,6}=3.780$, Wilk’s $\lambda=0.759$, $p=0.076$, $\omega^2=0.241$, $1-\beta=0.577$), and reaction time for trials 81-100 ($F_{1,6}= 5.475$, Wilk’s $\lambda=0.687$, $p=0.037$, $\omega^2=0.313$, $1-\beta=0.712$). Independent pairwise post-hoc analysis for these interactions revealed significant differences in the concussed group between day 1 and day 10. Overall reaction time was significantly faster on day 10 in the concussed group (496.18 ± 52.85 , 439.01 ± 20.62 , $p=0.013$) and reaction time on trials 81-100 was significantly faster on day 10 (532.31 ± 107.37 , 421.00 ± 25.92 , $p=0.017$). Reaction time on trials 81-100 was also significantly different on day 1 of testing between the concussed and the control group (concussed = 532.31 ± 107.37 , control = 422.35 ± 80.04 , $p=0.051$). No other significant interactions were noted for the SVMP outcomes.

A significant main effect on the variable ‘day’ was detected in the concussed group’s performance on the SVMP task. Pairwise post-hoc analysis showed significant differences between day 1 and day 10 on: SVMP reaction time left (day 1 = 484.97 ± 64.60 , day 10 = 429.35 ± 34.19 , $p=0.023$), SVMP reaction time right (day 1 = 474.88 ± 44.44 , day 10 = 413.76 ± 28.79 , $p=0.014$), SVMP reaction time ambiguous (day 1 = 530.22 ± 62.74 , day 10 = 472.30 ± 226.98 , $p=0.034$).

Significant main effects on the variable 'group' were noted for several SVMP test variables on days 1 and 10 of testing; concussed athletes were significantly different than control subjects on day 1 for SVMP reaction time for trials 101-120 (concussed = 500.12 ± 54.17 , control = 439.81 ± 59.05 , $p=0.089$), and SVMP reaction time ambiguous trials (concussed = 530.22 ± 62.74 , control = 452.58 ± 81.13 , $p=0.069$). On day 10 of testing, concussed subjects were significantly different from control subjects for SVMP reaction time trials 101-120 (concussed = 484.77 ± 43.10 , control = 427.76 ± 68.77 , $p=0.089$). No other significant differences were noted between day or group (see **Table 3.1**).

Visual Acuity

Results of the repeated measures ANOVA demonstrated no significant interactions for any of the visual acuity outcomes. Significant main effects were noted for differences in concussed athletes between day 1 and day 10 of testing for GST static acuity (day 1 = -0.01 ± 0.04 , day 10 = -0.11 ± 0.13 , $p=0.058$). Significant main effects on the variable 'group' were determined on day 1 of testing; concussed athletes were significantly different than control subjects on GST static acuity (concussed = -0.01 ± 0.04 , control = -0.15 ± 0.13 , $p=0.031$). No other significant differences were noted between day or group as shown in **Table 3.3**.

Discussion

In this pilot study we investigated the effects of a single episode of sports-related concussion on visuo-motor processing. We hypothesized that there would be significant differences in SVMP task reaction time, total number of responses to the right and left, and number of ambiguous stimuli responses to the left and right when comparing acutely

concussed athletes to healthy matched controls. Additionally, we hypothesized that concussed subjects would demonstrate slower reaction time and a greater number of incorrect responses (right, and left) on day 1 and improvement (i.e. faster reaction time and fewer errors) on day 10.

Acutely concussed athletes demonstrate functional differences in SVMP task performance between days. The results of this study support the theory of delayed visual information processing immediately following a concussion.³⁰ Concussed athletes had significantly delayed reaction time on day 1 of testing compared to day 10 (day 1 = 496.18 ± 52.85 , day 10 = 439.01 ± 20.62) (**Figure 3.4**). Furthermore, concussed athletes demonstrated significantly slower reaction time to the left (day 1 = 484.97 ± 64.60 , day 10 = 429.35 ± 34.19), right (day 1 = 474.88 ± 44.44 , day 10 = 413.76 ± 28.79), and ambiguous trials (day 1 = $530.62.74 \pm 62.74$, day 10 = 472.30 ± 26.98). **Figure 3.3** depicts the differences in reaction time for each stimuli type.

Additional significant findings were observed between groups on reaction time trials 81-100 (concussed = 531.31 ± 107.37 , control = 422.35 ± 80.04), reaction time trials 101-120 (500.12 ± 54.17), and reaction time ambiguous stimuli (concussed = 530.22 ± 62.74 , control = 452.58 ± 81.13). Visual processing is an essential attribute that athletes require to be successful in their sport. Any delay in visual information processing may lead to other functional impairments because areas of the brain which are responsible for visual processing are also partially responsible for coordinated movements, visually guided actions, and balance coordination.^{106,107} These visual processing functions are extremely important in sports performance and participation. Additionally, visual processing is responsible for making a cognitive map of the

surrounding environment. Therefore, an athlete suffering from a concussion may experience slowed visual processing caused by deficits in effective cognitive mapping, leading to difficulties navigating through space.¹³⁹

The significant differences in overall reaction time on the SVMP task suggests that visual processing is initially impaired following a concussion (i.e. day 1 post-injury $\mu = 496.18 \pm 52.85\text{ms}$), but this impairment is short-lived (i.e. reaction time day 10 $\mu = 439.01 \pm 20.62\text{ms}$) and should recover to values comparable to control subjects ($\mu = 433.14 \pm 66.60\text{ms}$) within ten days following the injury. Concussed subjects were not statistically different than control subjects on day one for SVMP reaction time (concussed = 496.18 ± 52.85 , and control = $436.32 \pm 74.37\text{ms}$). Although not statistically significant, these results are clinically meaningful because symptoms of altered visuo-motor processing would likely be noticeable in a clinical setting and should be evaluated in future research. **Figure 3.3** depicts the average reaction time on the SVMP task in 20-trial increments. The graph demonstrates that concussed athletes are not different in comparison to the control group on day 1 for overall SVMP task reaction time and continue to show no difference until 80 trials have been completed. During trials 81-100, concussed subjects were significantly different from control subjects (concussed = 531.31 ± 107.37 , control = $422.35 \pm 80.04\text{ms}$) on day 1 of testing suggesting that fatigue may be a factor following a concussion. Furthermore, reaction time on trials 101-120 was significantly difference between concussed and control subjects on day 1 and day 10 (concussed, day 1 = 500.12 ± 54.17 , day 10 = $439.81 \pm 59.05\text{ms}$ and control day 1 = 484.77 ± 43.10 , day 10 = $427.76 \pm 68.77\text{ms}$) suggesting that following a concussion the physiological changes occurring in the brain cause functional deficits which present

during prolonged activity. Concussed subjects demonstrated faster reaction times on day 10 of testing, although they remained significantly slower than control subjects on trials 101-120, which may suggest that full recovery in subject's reaction time had not occurred. Finally, the reaction time for ambiguous trails was significantly slower on day 1 of testing than the control group (concussed = 530.22 ± 62.74 ms, control = 452.55 ± 81.13 ms) and compared to day 10 (day 1 = 530.22 ± 62.74 ms, day 10 = 448.89 ± 77.21 ms) as depicted in **Figure 3.5**. Ambiguous trials require the subject to make a decision about the direction of the motion, having a delayed reaction time following a concussion provides support for delayed processing immediately following a concussion.

A secondary purpose of the study was to determine the test-retest reliability of the SVMP task. Reaction time for SVMP trials 61-80 (ICC=0.78) demonstrated excellent reliability. The reliability between days of testing was moderate to good on the following SVMP variables;: overall reaction time (ICC=0.63), RT trials 21-40 (ICC=0.36), RT trials 41-60 (ICC=0.42), RT trials 81-100 (ICC=0.65), RT trials 101-120 (ICC=0.73), RT left (ICC=0.72), RT ambiguous (ICC=0.61), number responses left/right (ICC=0.51, ICC=0.64 respectively), number incorrect left (ICC=0.65), number ambiguous left/right (ICC=0.47, ICC=0.54 respectively), and number unanswered (ICC=0.65). Poor reliability was observed for the following SVMP variables: RT trials 1-20 (ICC=0.36), RT right (ICC=0.32) and number incorrect responses right (ICC=0.38). The MDC values for the SVMP reported in the current study (**Table 3.2**) can be used to identify meaningful clinical changes for the SVMP outcomes. Determining the MDC values for the SVMP test in healthy non-concussed athletes will aid clinicians to

understand the minimum differences in test performance that indicated significant change not due to measurement error or some other confounding effects.

Visual acuity testing was performed to: (1) ensure that athletes had normal 20/20 vision prior to beginning the study, and (2) to ensure visual acuity didn't change over time. The results of the visual acuity testing demonstrate impairment in static visual acuity among the concussion group on day 1 post-injury (mean +/- SD) compared to the control group (mean +/- SD). Static visual acuity among the concussed subjects improved by day 10 (mean +/- SD) and was comparable to control subject's SVA (mean +/- SD). Impairments in visual processing may be the result of visual acuity of less than 20/20 and, while the initial purpose of visual acuity testing was to test the precision and accuracy of each subject's lens condition, the dorsal pathway (which is responsible for identification stimuli orientation) was tested. The primary pathway tested during SVMP testing was the dorsal visual pathway suggesting that there is a connection between concussion and deficits in the dorsal pathway as subjects suffered from deficits in identifying optotype orientation. Further investigation into the dorsal visual pathway may reveal a relationship between static visual acuity and visuo-motor processing. The results of the current study are consistent with previously published research conducted in patients suffering from moderate to severe traumatic brain injuries.^{123,140} Greater visual acuity loss was observed following a more severe brain injury, although the majority of the individuals who were included in the study had static visual acuity of 20/20 or better. Following a brain injury patients should be examined using a complete battery of visual testing, including static visual acuity, which may help explain functional impairments such as balance impairments, post-concussive symptoms, and cognitive impairments.¹²³

Currently used assessment protocols for concussed athletes do not require any assessment of vision or visual acuity. Establishment of a visual acuity testing protocol may assist health care providers in identify why functional impairments are noted following a concussion.

This study was the first to examine visuo-motor processing changes in acutely concussed athletes in an attempt to better understand the physiological changes occurring in the brain following injury and the impact that these impairments have on a SVMP task. Visuo-motor processing includes components of working visual memory, visual attention, visual discrimination, and selective attention.¹³⁹ These components work collaboratively to help an individual form a visual representation of their surroundings, which in turn in helps them navigate through space. Athletes are continually receiving visual information regarding other players, the location of the ball, and the fans or surrounding environment during athletic practice or competition, so it is imperative they be able to make the visual representation immediately to avoid possible collisions and intercept the ball or other players. Additionally, previous research¹⁰¹ conducted on the ventral and dorsal pathways of the brain have linked visual perception and action to visual processing. This connection ultimately impacts how an individual responds to external visual perturbations for making a correct visual representation and how this ultimately influences functional movements. By identifying how these visual processing interactions are possibly affected following a concussion, our understanding of the functional deficits resulting from sport-related concussions will be greatly enhanced.

The SVMP task conducted in the current study was based on the visual stimulus research done by Pinkus and Patel (1997).⁷² This type of visual stimuli has been

investigated in healthy adult subjects but has not been studied among acutely concussed athletes. The results of the current study demonstrated moderate test-retest reliability of the SVMP task, but the generalizability of the study is limited to acutely concussed athletes between the ages of 13 and 20. Additionally, prior concussion history was not a criteria for matching control subjects to concussed subjects because the cumulative effects of concussion on visuo-motor processing are not known at the present time; the outcomes of this research may have been affected by prior concussion history.

Furthermore, subject history of learning disorders, attention deficit disorder, and psychiatric history were not criteria for matching control subjects, and it is not currently known if visuo-motor processing may be impaired by those confounding factors.

Following an acute concussion, athletic trainers and sports medicine clinicians should assess both static visual acuity and visual processing through a SVMP task. Assessing visual processing and visual acuity following a concussion will help to identify impairments in the visual system which may be the underlying cause of other functional impairments (e.g. balance deficits).

Conclusion

Acutely concussed athletes demonstrate impairments in reaction time during a simple visuo-motor processing task between 1 and 10 days following the injury. The results of the study suggest that athletes have delayed visual information processing following a concussion. An athlete's ability to navigate through their environment is imperative for successful and safe participation in athletics as sports have a highly dynamic and constantly changing environment. The ability to change and adapt quickly to the environment is one of the most important skills an athlete must possess for

successful participation in athletics. This ability arises partially from the visual system which takes information about the surrounding environment and transfers that information to workable, usable information regarding orientation, speed, motion, color and trajectory. Current concussion assessment protocols do not incorporate visual testing approaches, but including visual processing and visual acuity testing in the post-concussion assessment battery will help in identifying impairments in visual processing. Through the process of identifying these visual processing impairments, the underlying cause for functional balance impairments that are common following the injury may be revealed.

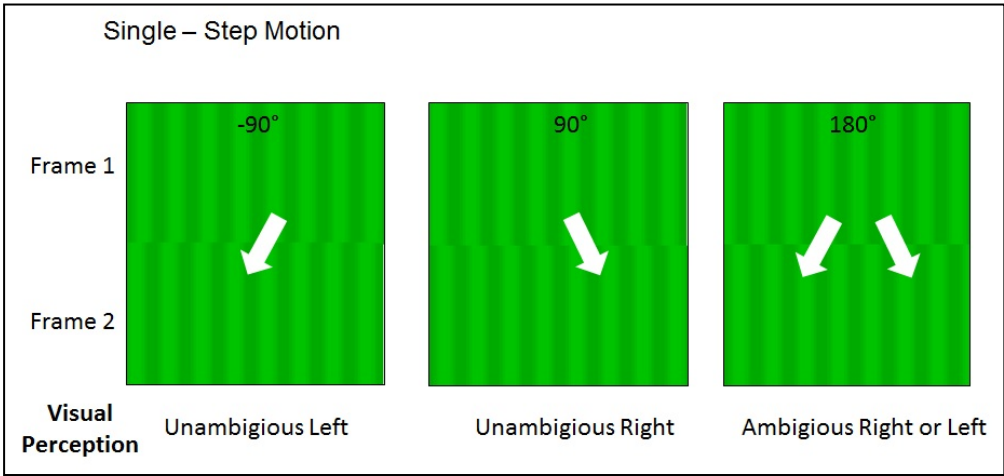


Figure 3.1 Visual stimuli for single motion sine wave gratings

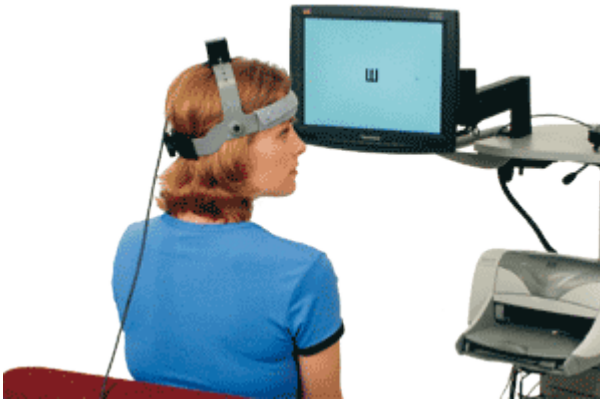


Figure 3.2 Example of the head mounted tracker and optotype stimulus. Used with permission

Table 3.1 Descriptive Statistics for SVMP variables by Day and Group (mean ± SD)

SVMP Variable	Concussed (n=7)		Control (n=7)	
	Day 1	Day 10	Day 1	Day 10
Overall Reaction Time ^a	496.18±52.85*	439.01±20.62*	436.32±74.37	433.14±66.60
Reaction Time Trials 1-20 ^a	500.13±74.85	431.67±62.80	445.72±122.08	438.02±37.11
Reaction Time Trials 21-40 ^a	451.05±73.82	437.63±34.82	432.13±96.70	430.19±87.48
Reaction Time Trials 41-60 ^a	466.92±58.61	427.02±36.87	451.54±68.30	422.10±81.32
Reaction Time Trials 61-80 ^a	530.24±147.81	431.30±17.82	434.06±70.05	436.24±89.89
Reaction Time Trials 81-100 ^a	532.31±107.37*†	421.00±25.92*	422.35±80.04†	424.70±56.97
Reaction Time Trials 101-120 ^a	500.12±54.17†	484.77±43.10†	439.81±59.05†	427.76±68.77†
Reaction Time Left ^a	484.97±64.60*	429.35±34.19*	448.98±91.32	431.15±71.51
Reaction Time Right ^a	474.88±44.44*	413.76±28.79*	421.55±68.88	413.71±51.90
Reaction Time Ambiguous ^a	530.22±62.74*†	472.30±26.98*	452.58±81.13†	448.89±77.21
Number Responses Left	59.00±8.52	58.86±11.36	59.29±7.30	54.71±12.02
Number Responses Right	60.14±8.28	59.71±11.22	60.43±5.83	65.00±12.08
Number of Incorrect Responses Left	1.43±0.98	0.86±0.90	1.00±1.30	1.29±1.38
Number of Incorrect Responses Right	1.14±1.77	0.71±0.95	1.14±1.22	0.14±0.38
Number of Amb Responses Left	19.71±8.18	18.71±11.18	17.57±6.27	16.14±11.64
Number of Amb Responses Right	19.86±8.13	20.86±10.24	22.14±6.67	24.29±11.95
Number Unanswered	0.86±1.07	1.29±1.38	1.29±1.80	0.29±0.76

^aReaction Time measures in ms

‡p<0.10; significant interaction group*day

*p<0.10; significant difference between days of testing

†p<0.10; significant differences between groups (concussed & control)

Table 3.2 Test-Retest Reliability Coefficient and Minimal Detectable Change Values for the SVMP Task

Outcome	Standard Deviation	ICC	Fleiss' Criteria	Standard Error of the Measurement	MDC
Overall Reaction Time	40.81	0.625	moderate	24.9909	69.27129
Trials 1-20	107.68	0.36	poor	86.1440	238.779
Trials 21-40	83.65	0.423	moderate	63.5410	176.1266
Trials 41-60	60.72	0.467	moderate	44.3298	122.8758
Trials 61-80	147.07	0.777	excellent	69.4507	192.5075
Trials 81-100	114.74	0.653	moderate	67.5896	187.3487
Trials 101-120	58.82	0.732	moderate	30.4504	84.40409
Reaction Time Left	50.41	0.715	moderate	26.9116	74.59508
Reaction Time Right	35.68	0.323	poor	29.3575	81.37486
Reaction Time Amb	57.8	0.613	moderate	35.9570	99.66769
Number Responses Left	9.91	0.514	moderate	6.9086	19.14974
Number Responses Right	8.4	0.637	moderate	5.0610	14.02826
Number Incorrect Left	1.4	0.653	moderate	0.8247	2.285935
Number Incorrect Right	2.37	0.382	poor	1.8631	5.164326
Number Amb Left	10.07	0.472	moderate	7.3172	20.28231
Number Amb Right	9.02	0.524	moderate	6.2231	17.24968
Number Unanswered	1.99	0.65	moderate	1.1773	3.263309

Table 3.3 Descriptive Statistics for GST variables

Assessment	Visual Acuity Variables	Concussed		Control (n=7)	
		Day 1(n=5) ^a	Day 10(n=7)	Day 1	Day 10
GST	Perception Time	23.33±8.17	20.00±0.00	20.00±0.00	20.00±0.00
	Static Acuity (logMAR)	-0.01±0.04*†	-0.11±0.13*	-0.15±0.13†	-0.22±0.10
	Maximum Velocity Left (deg/sec)	157.80±28.23	161.60±20.91	143.15±52.11	151.57±38.53
	Maximum Velocity Right (deg/sec)	191.40±28.19	159.60±44.30	162.00±57.04	176.14±28.67
DVA	Visual Acuity Loss Left (logMAR)	0.13±0.11	0.16±0.05	0.14±0.11	0.21±0.14
	Visual Acuity Loss Right (logMAR)	0.13±0.11	0.16±0.05	0.14±0.11	0.21±0.14

GST; Gaze Stabilization Test, DVA; Dynamic Visual Acuity Test

^a Two subjects were unable to complete the test as it provoked symptoms

*p<0.10; significant difference between days of testing (day 1 and day 10)

†p<0.10; significant differences between groups (concussed & control)

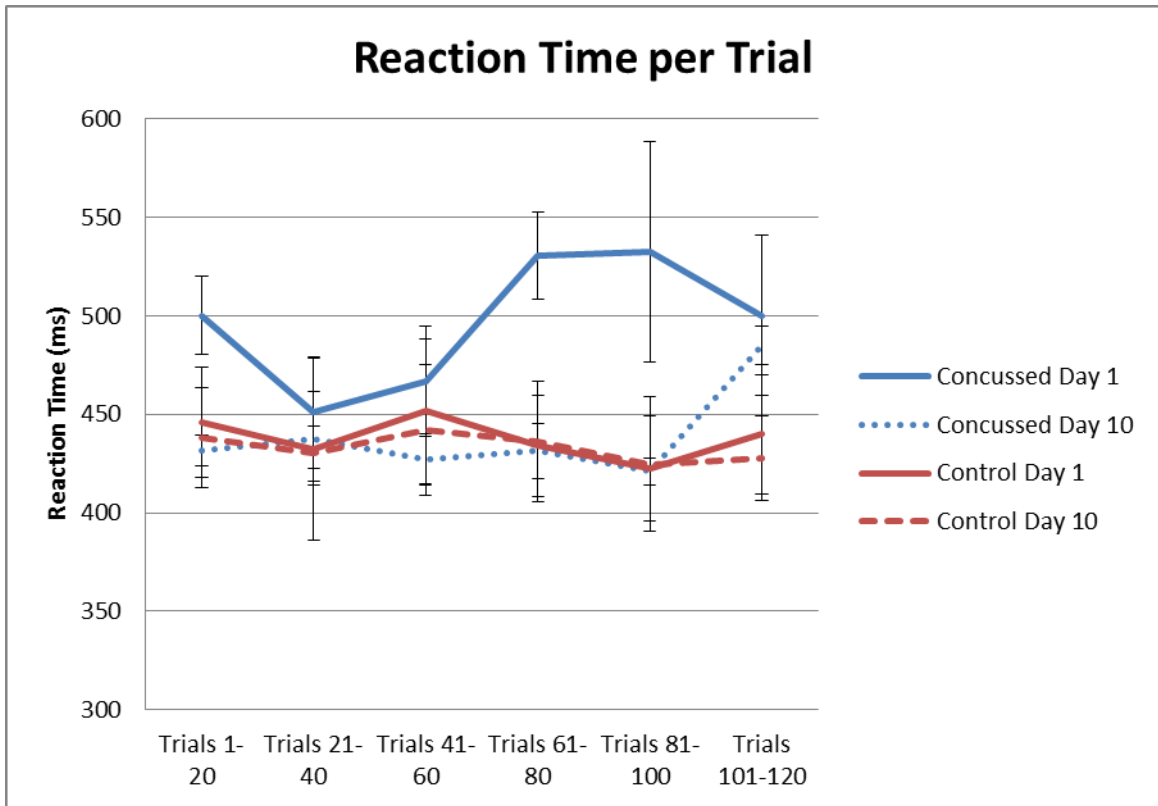


Figure 3.3 SOT Composite Equilibrium Score Reaction Time per Trial

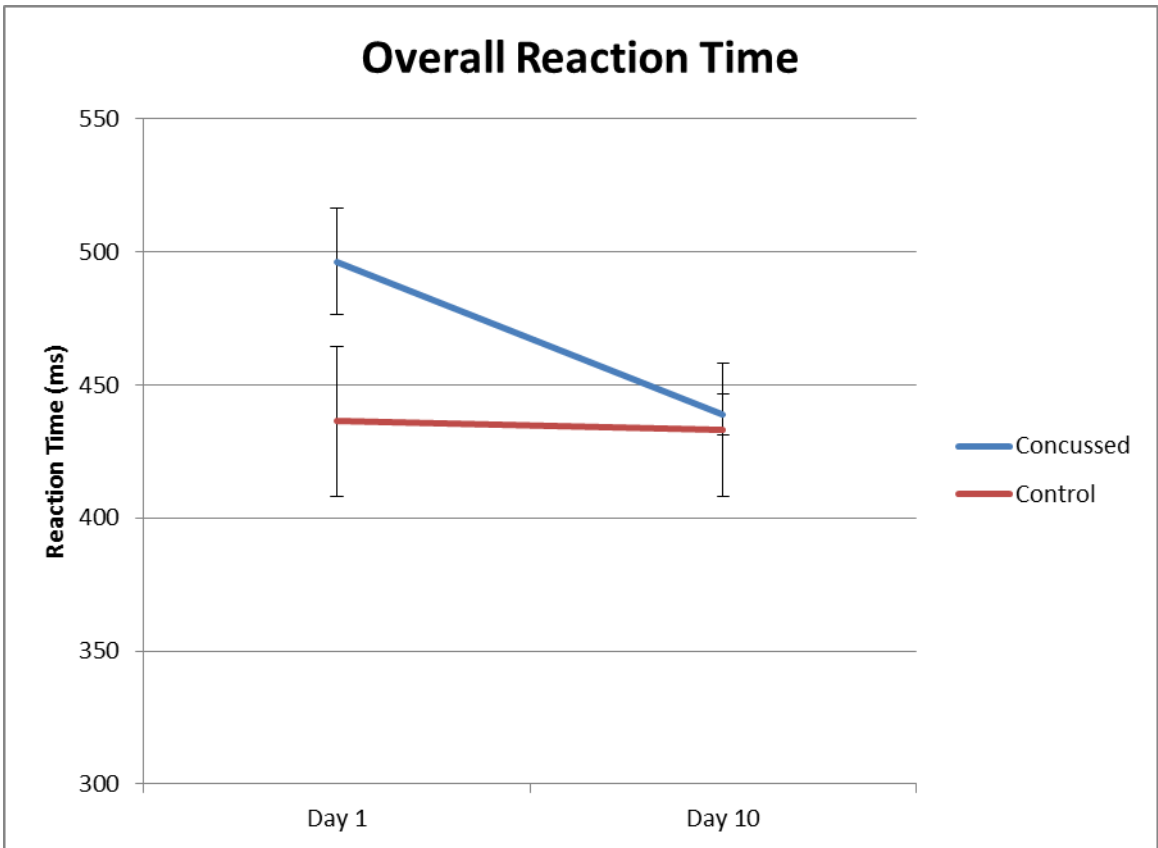


Figure 3.4 SOT Composite Equilibrium Score Mean Reaction Time

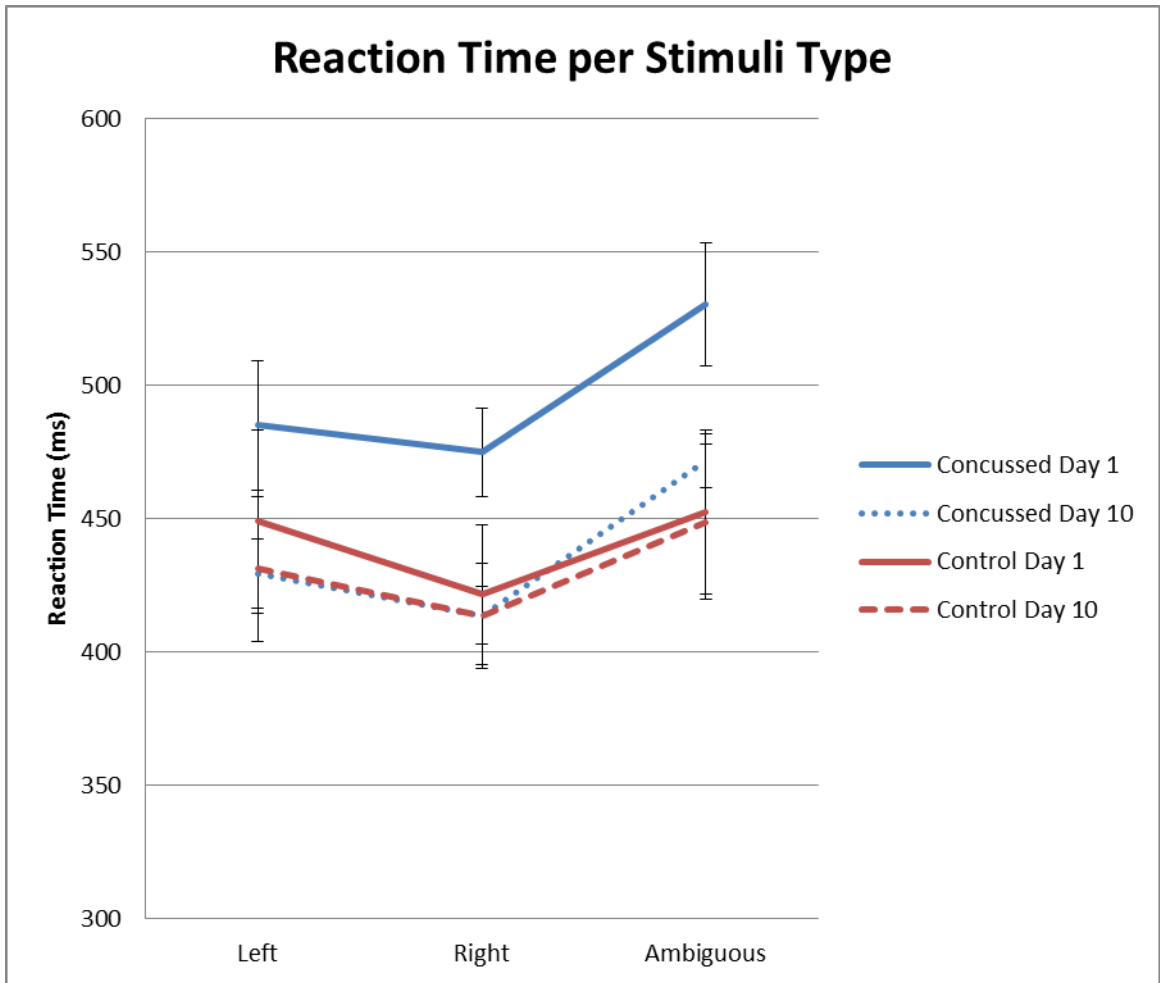


Figure 3.5 Reaction Time by Stimuli Type

Chapter 4 The Relationship of Visuo-Motor Processing and Upright Postural Stability in Acutely Concussed Athletes

Introduction

Sport-related concussion diagnosis and management pose a great challenge to health care providers. Although there is no universally accepted definition of concussion, the International Concussion in Sport Group has defined the injury as, “A complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces.”¹⁴¹ Concussion is not a structural injury that can routinely be noted on standard neuroimaging techniques such as computed tomography (CT) or magnetic resonance imaging (MRI).¹³ With the lack of standardized assessment protocols, health care professionals must rely on subjective and other objective assessment tools to make the initial diagnosis and return to play decision.

Commonly administered tools used by athletic trainers following a concussion include self-reported symptom inventories, neuropsychological assessments, and balance assessments. While self-reported symptom inventories have been used extensively in the past, the subjective nature of the assessment often results in misleading data¹⁴ because many athletes may under-report symptoms. As approximately one-third of all undiagnosed concussions may result from the athlete not being aware of the signs and symptoms.¹⁴ Relying solely on symptom inventories is not recommended and athletic trainers are encouraged to use more objective assessments tools to aid in the diagnosis and management of concussion. Neuropsychological assessments are widely used in the use of diagnosis and management of concussion;^{17,18} however, a trained neuropsychologist is often required to interpret the results of the testing, making the test

results less clinically meaningful for the athletic trainer. An additional challenge to health care providers who are dealing with acutely concussed athletes is the potential for visual and visuo-motor processing impairments to negatively affect neuropsychological test performance. The final component of the battery of testing for suspected concussions includes balance assessments. Researchers have identified alterations in balance following sport-related concussion^{6,22-25} and have observed that these deficits typically resolve between 3 to 10 days after the injury.^{7,26,91} Impairments in balance following a concussion have been related to either (1) a failure of sensory (visual, vestibular, somatosensory) information to properly integrate together,²⁴ or (2) an individual relying too heavily on one of the individual systems to compensate for another sensory system that may be impaired.²⁹ The primary objective of balance assessments following a concussion is to identifying alterations within the three primary sensory systems which may be contributing to the balance impairments.

Current approaches to balance assessment following concussion can be classified as high-technology²⁴ measures which often use computerized dynamic posturography (CDP),⁷⁰ or low-technology²⁴ measures which are inexpensive and available to the majority of health care professionals. Balance measures such as the Sensory Organization Test (SOT),^{7,43,142} and modified Clinical Test of Sensory Interaction on Balance (mCTSIB)^{24,33} are CDP measures classified as high-technology assessments and are typically conducted in a research laboratory setting. The SOT has been used extensively to identify post-concussion balance deficits in athletes^{7,23,24,26,38,91} and is a clinical test designed to systematically disrupt the sensory selection process by altering the information available to the somatosensory, vestibular and/or visual systems.^{29,39} The

SOT was developed to isolate which sensory system is most involved in regulating balance and to determine how the interactions between these systems affects postural control.⁴⁰ The SOT is a valid test of balance impairments among athletes with mild TBI.^{26,142} The testing protocol objectively identifies abnormalities related to the individual's use of the somatosensory, visual and vestibular systems contributing to balance by systematically eliminating visual input and/or support surface (somatosensory) information and creates conflicting sensory situations.

Another CDP measure commonly used to detect balance impairments is the mCTSIB, which was modified from the original Clinical Test of Sensory Interaction on Balance (CTSIB). The mCTSIB resulted from the removal of the dome conditions and is an effective test for determining balance deficits in an elderly population;⁴⁸⁻⁵⁰ the pediatric version of the test has been used in determining balance deficits among children with concussions,¹⁴³ however it has not been studied in an acutely concussed athletic population. The mCTSIB could be beneficial to identify balance problems among concussed athletes and, thereby, provide the clinician with the information required to support further post-concussion assessment. Finally, the mCTSIB is a laboratory measure that represents clinical (or sideline) measures such as the BESS,⁵³ making the results of the mCTSIB more clinically meaningful for health care providers. The Balance Error Scoring System (BESS)^{7,90} is a commonly used sideline assessment tool following concussion and is classified as a low-technology approach to balance testing. The BESS moderate to good reliability³⁵ and has been shown to be correlated with measures of CDP. As the intention of all of the aforementioned balance assessment is to identify underlying sensory impairments it is vital to determine the relationship that these

measures of balance have with underlying causes of sensory impairments such as changes in visuo-motor processing.

Balance deficits arise as a result sensory information integration impairments²⁴ when sensory information processing is delayed. Information from the sensory systems may be delayed following a concussion as a result of the physiological changes that occur within the brain. Both a neurometabolic cascade⁵⁵ and diffuse axonal injuries⁵⁶ are believed to occur following a concussion and these may help to partially explain why information processing is delayed. The physiological changes that occur following a concussion take place at both a focal and wide-spread level, and can occur at the level of the brainstem up to the cortex.⁵⁵ This widespread damage will lead to impairments in information transmission via the axons (which are primarily responsible for transmission of information). Stemming from the delayed information processing are possible impairments in balance as a result of a failure integrating of sensory information (vestibular, visual, and somatosensory). The somatosensory system is responsible for information regarding the support surface. Following a concussion, an individual may experience delayed information processing in proprioception and touch.³³ Vestibular information contributes to balance by transmitting information about where the head and neck are in space, as well as keeping the eyes fixed on a target.³¹ Finally, as the visual system contributes to balance by transmitting information about the external environment to determine where the body is in space, any impairment in the visual system may lead to symptoms of impaired balance (e.g. disequilibrium or imbalance). In addition to balance impairments attributable to visual system dysfunction, other visual symptoms (such as double vision, blurred vision, or sensitivity to light) may be experienced by the athlete following concussion.³⁰

Vision is directly linked to several cognitive processes including attention, working memory, reasoning, judgment, problem-solving, sensory abilities, perceptual abilities, and information processing.¹⁴⁴ All of these cognitive processes are required for successful participation in sports and have been reported to be affected following a concussion.⁵⁸ Furthermore, visual attention is mediated through the relationship between the frontal lobe and visual pathways⁵⁹ and involves the ability to focus on an object while in the presence of multiple objects, an ability that is extremely important in athletics. Working memory allows an individual to remember and identify a single object.⁵⁹ Selective attention and working memory are frequently affected following concussion⁵⁸ and are both traditionally tested through the use of neuropsychological assessments.⁶⁰ The link between selective attention and working memory is reciprocal, in that one process relies heavily on the other. Recent researchers have demonstrated that working memory relies on selective attention to function fully and that selective attention receives information about the object from memory in order to help make the determination of importance.⁶¹ A normal functioning selective attention process allows the individual to focus on the desired object or goal while disregarding the remaining stimuli.⁶¹ Selective attention is regarded as a 'top-down' (hierarchical) process where information about what is important about the object is transmitted from structures in the frontal lobe to the visual pathways where the information will be gathered and processed for further action. Damage in the frontal lobe and visual pathways from TBI greatly impacts all components of visual processing⁶² and may cause challenges in performing common functional activities of daily living. Areas of the brain that initiate visual processing also have connections to areas of the frontal lobe,⁵⁹ and these areas are primarily responsible for

conscious balance control and movement. Therefore, any changes that affect visual processing may be partially responsible for impairments noted in balance along with the delayed information processing.

Determining the relationship between visuo-motor impairments and impairments in balance following a concussive injury will allow clinicians to conduct a more thorough assessment of vision and balance and could potentially identify if a visual training protocol should be established. Simple visual processing testing protocols³⁰ can help identify deficits in visual processing and visual performance but have not been investigated among concussed athletes. Testing protocols that consist of first-order (i.e. simple or linear)³⁰ stimuli are defined by the luminance and color of the stimuli, and second-order (i.e. complex, non-linear) stimuli are defined by their contrast, texture and depth.⁶⁵ *Optical flow* refers to complex motion information representing the body moving through the environment.^{66,67} Athletes must use all these stimuli (simple/linear, complex/non-linear, and optical flow) to generate an image of their surroundings and allow them to properly navigate through the environment without difficulty. Current approaches to concussion assessment do not address visual processing deficits directly, but rely on the resolution of self-reported visual (and other somatic, cognitive, and behavioral) symptoms to determine if recovery has occurred. Researchers have identified delayed perceptual deficits during complex visual tasks despite normal neurological examination findings and resolution of self-reported symptoms in children after a concussion.³⁰ Deficits in visual processing have been demonstrated in children ages 8 to 16 years during first- and second- order stimuli testing following a concussion.³⁰ There is no published research on how these processes are affected following a concussion in an

older (ages 16 to 24 years) athletic population. The investigation of visual processing deficits and the relationship that these deficits have on upright balance in athletes will help to better understand the underlying pathophysiologic mechanisms for balance deficits and why altered visuo-motor processing may be related to postural instability typically seen following a concussion. The purpose of this study was to analyze the relationship between visuo-motor processing and upright postural stability in acutely concussed athletes through a simple visuo-motor processing task and computerized dynamic posturography.

Methods

Design

A longitudinal, matched cohort study design was used to assess the correlation between scores on a visuo-motor processing task with scores on standardized balance assessments. The independent variables included time (with 2 levels: day 1 and day 10) and group (with 2 levels: concussed and control subjects). The dependent variables included: (a) reaction time on a visuo-motor processing task, (b) composite equilibrium score and sensory analysis on the SOT, and (c) mean center of gravity sway velocity on the mCTSIB.

Subjects

The target number of subjects necessary, based on a power analysis using data derived from a visuo-motor processing task [Brosseau (2008)]³⁰ and the SOT and mCTSIB assessments [Guskiewicz (2001)],⁷ using an *a priori* level of $P < .10$, was a minimum of 12 subjects per group.

Seven acutely concussed subjects [age (17.1 ± 3.0 years), height (174.0 ± 74.2 cm), weight (73.3 ± 23.8 kg)] participated in the study. Subjects were included in the concussed group if they participated in an intercollegiate, interscholastic, or club sports and had been diagnosed with a concussion by a certified athletic trainer or physician trained sustained within the previous 48 hours. Concussion was defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces common features of a concussion include:(1) an injury caused by a direct blow to the head, face, neck, or elsewhere on the body with an ‘impulsive’ force transmitted to the head, (2) a concussion typically results in rapid onset of short-lived impairment of neurological function that resolves spontaneously, (3) the injury may result in neuropathological changes but the acute clinical symptoms largely reflect a functional disturbance rather than structural injury, (4) a concussion results in a graded set of clinical symptoms that may or may not involve loss of consciousness, and (5) resolution of clinical and cognitive symptoms typically follows a sequential course.⁷⁴ Seven control subjects [age (17.3 ± 3.1 years), height (178.8 ± 11.6 cm), weight (77.9 ± 23.4 kg)] matched according to age, sport, and gender also participated. All subjects were volunteers who signed a written informed consent or assent form. Human subject’s approval was obtained from the Office of Research Integrity at the University of Kentucky (IRB#12-0509) prior to beginning the study.

Control subjects had no self-reported history of a concussion within the previous year. Additional exclusion criteria for subjects included any medications that may affect balance (e.g. NSAIDs, antidepressants, anticonvulsants, vestibular suppressants, neurostimulants, antimetics)¹³² taken within 2 hours of the scheduled testing, and lower

extremity injury that may impair balance (e.g. ankle sprain), a previous concussion within the previous year, or vision less than 20/20 (corrected or uncorrected) as measured during the static visual acuity testing using the NeuroCom® InVision program (see Testing Procedures below).

Instrumentation

E-prime V1.2 software (Psychology Software, Pittsburgh PA), and a Dell laptop computer with an external keyboard were used for the visual processing task. To limit the number of errors from subjects using incorrect keys, a modified keyboard was used, in which all of the keys except the keys required for responses ('a', 'l', and 'spacebar') were removed. Visual acuity testing was conducted with the NeuroCom® InVision software (NeuroCom® International, Inc.; Clackamas, OR). The hardware for the visual acuity testing included a head-mounted tracking device that determines angle, distance, and velocity of head motion.

The NeuroCom SMART Balance System was used for all balance and visual acuity assessments. Subjects were tested using two standard protocols pre-established by NeuroCom: the SOT and the mCTSIB.⁷¹ The SOT was performed using the standard SOT protocol as described by Guskiewicz (2001)⁷. Subjects also performed the mCTSIB on the long forceplate of the NeuroCom. Both the SOT and mCTSIB are valid and reliable techniques for assessing balance deficits.^{48,145}

Procedures

Subjects reported to the Laboratory on two separate occasions: 24 to 48 hours and 10 days following injury. These testing time points were chosen based upon previous published research demonstrating initial deficits in postural stability and recovery

comparable to control subjects within 1-10 days following a concussion.^{24,26,91} Control subjects were assessed at the same time intervals but not necessarily on the same day as their matched concussed subjects. All subjects were screened using a self-reported medical screening for their eligibility to participate in the research study. Demographic information (i.e. height, weight, age, handedness, gender, and sport) was collected using standard techniques and entered into the E-prime and NeuroCom software data files.

Subjects' balance was assessed on the SOT and the mCTSIB following the NeuroCom® protocols. All subjects underwent testing in a counter-balanced order for test (SOT, mCTSIB, DVA/GST, and day (24-48 hours, 10 days). Subjects were barefoot for all of the balance testing procedures and each subject's stance position was standardized according to the NeuroCom® protocol based upon their own height. All subjects were fitted with a safety harness prior to the start of the SOT and secured to the overhead frame to ensure their safety during testing. The SOT is designed to systematically disrupt the sensory selection processing by altering available visual, vestibular, and somatosensory information. The SOT test protocol consists of 18 total trials (20 seconds per each trial) in each of 6 conditions. Subjects were presented with three different visual conditions (eyes closed, eyes open, and sway referenced surround), and two different somatosensory conditions (fixed and sway referenced) comprising the 6 different testing conditions. 'Sway- referencing' refers to the tilting of the support surface (i.e. force platform) or visual surround, or both.²⁸ During each of the testing conditions, subjects were asked to stand as motionless as possible. **Figure 4.2** depicts each of the 6 SOT conditions. Outcome measures from the SOT included: a composite equilibrium

score, and sensory analysis ratio (visual, vestibular, somatosensory, and preference ratios).

The mCTSIB⁴⁵ is a simplified test derived from the original CTSIB⁴⁶ that attempts to replicate clinical assessments of balance such as the Balance Error Scoring System.⁴³ The mCTSIB is a measure of a patient's functional balance control and consists of two visual conditions (eyes open and eyes closed) and two surface conditions (foam and firm). During the foam surface testing conditions, subjects are asked to stand on an 18 in X 18 in X 5 in foam pad. Twelve 10-second duration trials are conducted for each of the four testing conditions: eyes open firm, eyes open foam, eyes closed firm, and eyes closed foam. During each of the testing conditions, subjects were asked to remain as motionless as possible. During the mCTSIB, subjects were supervised by the investigator at all times to deter a fall from occurring. Outcome measures for the mCTSIB include: mean center of gravity (COG), sway velocity (deg/sec), composite score, and COG alignment.

For the visuo-motor processing task subjects were seated at a distance of 24 inches from the computer screen with a modified keyboard on a desk in front of the subject. Subjects were shown a series of sine-wave gratings on a computer monitor with a refresh rate of 75 Hz and a screen resolution of 1024 X 768 pixels. Mean luminance for the stimuli was 14cd/m². **Figure 4.1** represents the 'motion jumps' subjects were tasked with identifying. During the task, subjects were asked to identify the direction (right or left) of each 'motion jump' and respond by pressing the corresponding key on the keyboard ('a' for left, 'l' for right)

Each trial of the visuo-motor processing task began with a neutral stimuli (0°) followed by a second frame presented in one of three orientations: $+90^\circ$, -90° , and 180° . Orientations of $+90^\circ$ and -90° were ambiguous right or ambiguous left motion while motion in the 180° was an unambiguous stimulus with no correct response. Right and left motion shifts are associated with $+90^\circ$ and -90° stimulus respectively, while 180° motion shifts represent a counter-phase shift with no correct response. Unambiguous trials were included to help determine if visual processing at higher levels of the brain are affected. Subjects completed 120 trials (40 trials in each orientation) in a random order as determined by E-prime software. The stimuli were constructed as in the 2D motion priming experiments reported by Pinkus and Pantle (1997).⁷² A 5-second inter-trial interval was used to diminish the effects of motion priming [influence of a previously perceived moving object on the subsequent perception of the motion of another moving object]¹³³ occurring between each trial.

Subjects were instructed to look at the whole screen (“look globally”) and not to focus on one individual place on the screen. Subjects were instructed to respond to each motion jump as quickly and accurately as possible. If the motion is in the left directions subjects are to press the ‘a’ button on the keyboard and if motion jump is to the right, subjects are to press the ‘l’ button in the keyboard. If a subject failed to respond within 5-seconds of the motion jump, the trial was marked as non-response and the next trial began automatically. If subjects were unsure of which direction the motion occurred, they will be instructed to press both the ‘l’ and ‘a’ buttons together. Testing lasted approximately 5 minutes and ended automatically after the completion of the all 120 trials. Data derived from this test included: reaction time, reaction time for 20 trials, and

reaction time left/right/ambiguous. All data was extracted for analysis into an excel spreadsheet by the software at the conclusion of the session.

All subjects underwent standardized visual acuity testing using the NeuroCom *InVision* system to determine their static and dynamic visual acuity. Subjects sat 10 feet (3 meters) away from a computer monitor adjusted to eye level. To determine static visual acuity, subjects completed the Static Visual Acuity (SVA) and Perception Time Test (PTT) protocols in which they were asked to correctly identify the orientation of an optotype (capital letter 'E'); the direction of the optotype could be up, down, left or right. During the PTT (the shortest presentation time that the optotype can be accurately determined)⁷¹ the length of presentation of the optotype was automatically decreased from 240 msec to 20 msec until either the final speed (20 msec) is achieved or the subject failed to identify the orientation of the optotype at a faster speed. Static visual acuity (SVA) was determined by reducing the size of the optotype (measured as a Snellen fraction and expressed as a logMAR score) until the subject was unable to correctly identify its correct orientation in 3 out of 5 trials.

Dynamic visual acuity was measured on two assessments: the Dynamic Visual Acuity (DVA) test and the Gaze Stabilization Test (GST) protocols. The initial size of the optotype was 0.2 logMAR greater than what was determined on the SVA test. The DVA test is a measure of the subject's ability to correctly identify the orientation of the optotype while the head is actively moving; this test assesses the functional integrity of the vestibular ocular reflex (VOR).⁷¹ During the DVA test, subjects were fitted with a head mounted sensor (**Figure 4.3**) which tracks the velocity and degree of head movement. Subjects were asked to move their head in a side-to-side motion, 20° to the

right and left directions, in a horizontal plane at 85 degrees/second while maintaining their visual gaze on the computer screen positioned 10 feet away. Subjects were required to correctly identify the orientation of the optotype when presented by verbally responding to the investigator who then manually entered the subject's response on the NeuroCom system. When a subject failed to correctly identify 3 out of 5 successive orientations, the test was automatically stopped. In contrast to the DVA, the GST measured the subject's ability to maintain an acceptable level of acuity while moving the head at higher speeds. The same head mounted sensor was placed on the head of the seated subject. Subjects were then asked to rotate their head 20° in each direction in a horizontal plane at varying speeds ranging from 10 to 150°/sec. The velocity of head rotation began at 70°/sec and either increased (in response to a correct response of the ototype presented) or decreased (in response to an incorrect response of the ototype presented). Subjects were required to correctly identify the orientation of the ototype presented until they failed to correctly identify three out of five orientations. Practice trials for the PTT, GST, and DVA were administered prior to all testing until the subject verbally articulated to the tester that he/she felt comfortable with the test and understood the directions; this helped to ensure subjects understood the task and to account for potential practice effects.

Data Reduction

All data was summarized by NeuroCom software and exported into an Excel datasheet for data processing. Data derived from the DVA test included: DVA loss left, and DVA loss right; data derived from the GST included: perception time, static acuity, maximum velocity achieved left and maximum velocity achieved right. DVA and GST

data was expressed as a log of the minimal angle of resolution (LogMAR) score. LogMAR scores represent a measure of visual acuity loss and were used for primary analysis but were later converted, with the assistance of a visual acuity chart,¹³⁴ to a Snellen Fraction for interpretation.

Statistical Analysis

Descriptive statistics, measures of central tendency and variability were calculated to summarize the demographic characteristics of the sample. Separate repeated measure ANOVAs (with a bonferroni correction to account for the familywise error rate) were used for within-subject comparisons of scores of the SVMP (reaction time), SOT (composite equilibrium score, sensory analysis) and mCTSIB (mean COG sway velocity) for each of the days of testing (day 1 and day 10). The between-subject factor was group (concussed and control). Post-hoc analyses were conducted for any significant interaction effects among the independent variables 'group,' 'condition,' or 'day.'

Bivariate correlations (Pearson product moment correlation (r) coefficients) were conducted to determine the relationship between simple visuo-motor processing and balance in concussed and control subjects. All statistical analyses were performed with SPSS software (PASW Statistics version 18.0, SPSS Inc., Chicago, IL). An *a priori* alpha level of $p \leq .10$ was applied to all data to determine significant differences. An alpha level of $p < .10$ was chosen because the research question was exploratory in nature and the testing procedures (i.e. visual processing task) have not been used previously in the selected population or with the same outcomes.

Results

Descriptive statistics for the SVMP task, SOT, mCTSIB and visual acuity testing are presented in **Table 4.1, 4.2, and 4.3** respectively. Pearson correlations revealed significant correlations for a number of outcomes in both groups (concussed and control) and for both days (day 1 and day 10) which are presented in **Table 4.4**. SVMP variables not included in the table did not show significant correlations for either group or day when compared with SOT and mCTSIB outcomes.

Simple Visuo-Motor Processing Task

Separate two-way ANOVAs with repeated measures on the factor ‘time’ revealed a significant day by group interaction for: overall reaction time ($F_{1,6}=3.780$, Wilk’s $\lambda=0.760$, $p=0.076$, $\omega^2=0.240$, $1-\beta=0.575$), and reaction time for trials 81-100 ($F_{1,6}=5.475$, Wilk’s $\lambda=0.687$, $p=0.037$, $\omega^2=0.251$, $1-\beta=0.712$). Independent pairwise post-hoc analysis revealed significant differences in the concussed group between day 1 and day 10. Overall reaction time on the SVMP task was significantly slower on day 10 in the concussed group (496.18 ± 52.85 ms) compared to the control group (439.01 ± 20.62 ms, $p=0.039$) and reaction time on trials 81-100 was significantly slower on day 10 (concussed = 532.31 ± 107.37 ms, control = 421.00 ± 25.92 ms, $p=0.017$). Finally, on day 1 of testing reaction time on trials 81-100 concussed subjects were significantly slower than control subjects (532.31 ± 107.37 ms, 422.35 ± 80.04 ms, $p=0.051$). No other significant interactions were observed for the remaining SVMP variables.

Significant main effects on the variable ‘day’ were observed among concussed athletes for; SVMP reaction time left (concussed = 484.97 ± 64.60 ms, control = 429.35 ± 34.19 ms, $p=0.031$), SVMP reaction time right (concussed = 474.88 ± 44.44 ms, control = 413.76 ± 28.79 ms, $p=0.040$), and SVMP reaction time ambiguous trials (concussed =

530.22 ± 62.74 ms, control = 472.30 ± 226.98 ms, p=0.034). On day 1 of testing, a significant main effect was observed between the groups for reaction time on the ambiguous trails (concussed = 530.22 ± 62.74, control = 452.58 ± 81.13, p= 0.068). Concussed subjects were significantly slower than control subjects. No other significant main effects were noted for the remaining SVMP variables.

Computerized Dynamic Posturography Measures

Analysis on the CES data from the SOT revealed a significant day x group interaction ($F_{1,6}=7.02$, Wilk's $\lambda=0.631$, $p=0.02$, $\omega^2=0.369$, $1-\beta=0.803$). Independent post-hoc analysis revealed a significant improvement in the concussed subjects CES between days 1 and 10 (day 1 = 73.14 ± 5.73, day 10 = 78.71 ± 7.74 p=0.000). Repeated measures ANOVA revealed a significant day x group interaction for SOT somatosensory ratio ($F_{1,6}=0.0431$, Wilk's $\lambda=0.651$, $p=0.026$, $\omega^2=0.349$, $1-\beta=0.772$). Pairwise post-hoc analysis revealed significant differences in the concussed group between days (day 1 = 1.09 ± 0.07, day 10 = 1.03 ± 0.04, p=0.044) and on day 1 of testing concussed subjects were significantly different than control subjects (concussed = 1.09 ± 0.07, control = 1.00 ± 0.00, p=0.009). There was a significant day x group interaction for the SOT VEST ratio ($F_{1,6}=8.054$, Wilk's $\lambda=0.598$, $p=0.015$, $\omega^2=0.402$, $1-\beta=0.848$). Post-hoc analysis revealed a significant improvement between concussed subjects between day 1 and day 10 of testing (day 1 = 0.61 ± 0.09, day 10 = 0.80 ± 0.05, p=0.000), as well as a significant improvement between groups on day 1 (concussed = 0.61 ± 0.09, control = 0.71 ± 0.12, p=0.095). There were no other significant interactions for the CDP variables. Analysis of the SOT VIS ratios revealed significant main effects for day and group; concussed subjects were significantly better between day 1 and day 10 of testing (day 1 = 0.88 ± 0.10,

day 10 = 0.97 ± 0.03 , $p=0.038$) and concussed and control subjects were significantly different on day 10 of testing (concussed = 0.97 ± 0.03 , control = 0.93 ± 0.04 , $p=0.046$). There were no significant differences notes for the SOT PREF and mCTSIB mean COG sway velocity.

Visual Acuity

The repeated measures ANOVA did not reveal any significant interactions for any of the visual acuity outcomes. Significant main effects were noted for between days of testing among the concussed athletes for the following variables: GST static acuity (day 1 = -0.01 ± 0.04 , day 10 = -0.11 ± 0.13 , $p=0.058$). Significant main effects for group were also observed on day 1 of testing; concussed athletes were significantly different than control subjects on GST static acuity (concussed = -0.01 ± 0.04 , control = -0.15 ± 0.13 , $p=0.031$). No other significant differences were noted between day or group as shown in **Table 4.3**.

Discussion

This pilot study investigated visuo-motor processing and measures of CDP to analyze the relationship between the measures. We hypothesized that acutely concussed athletes, whom perform poorly on a SVMP task, would demonstrate a negative correlation with postural stability compared to healthy control subjects. The results indicate a trend towards a relationship between the SVMP overall RT and SOT CES on day 1 of testing in a concussed population. **Figure 4.4** depicts a trend towards significant among the concussed group, as the scores on the SOT were impaired (lower score), the score on the SVMP was increased (higher score). Following a concussion a battery of assessments has been recommended that should be administered to assist the health care

provider with making a concussion diagnosis and monitoring the clinical course of recovery.⁸² Included in the battery of assessment are athlete-reported post-concussion symptoms, cognitive performance, and balance.^{7,74,90,146} Measures of balance reveal deficits immediately following the injury which may last anywhere from 3 to 10.^{7,26,91} The deficits that occur in balance following a concussion are believed to occur as a result of impairments in the sensory systems to properly integrate information.³¹ The objectives of using CDP measures are to identify which sensory system(s) are affected following a concussion and to track the recovery of the balance impairments. However, the standard balance assessments using CDP do not address the underlying physiological changes which may be causing the balance impairments nor do they address impairments in the individual sensory systems separate from balance. Additionally, the human visual system uses visual information from the surrounding environment, as well as cognitive information to interpret what is being seen and to navigate through the environment.⁷⁶ Problems arise for athletes when the ability to cognitively map their surroundings is impaired, resulting in delayed motor responses and impairments in fluid movements.^{68,69} The ability of an individual to maintain upright balance and participate in normal gait is dependent on the individual's capacity to interpret their visual environment and objects in the environment. The visual system integrates that information into a sensory map which involves information from the visual system as well as information from the somatosensory and vestibular systems. The vestibular system provides information about where the head and neck are in space, as well as keeping the eyes fixed on a target.³¹ The somatosensory system provides information regarding the support surface.³³ The purpose of this study was to analyze the relationship between visuo-motor processing and upright

postural stability in acutely concussed athletes through a simple visuo-motor processing task and computerized dynamic posturography. We hypothesized that acutely concussed athletes would demonstrate impairments in both visuo-motor processing and balance, while healthy control subjects would demonstrate no impairments in either visuo-motor processing or balance.

The balance assessments used in the current study (SOT and mCTSIB) attempt to determine the integrity of integration of sensory information in an effort to identify impairments in the sensory systems following concussion. The SOT evaluates the interdependence of the sensory systems and how they function to maintain upright postural stability by having the subject complete 6 different conditions using different visual conditions (eyes open, eyes closed, and inaccurate visual surround information) and altering somatosensory information (providing inaccurate support surface information). Results of SOT CES revealed significant improvement in the concussed group between day 1 and day 10 of testing (day 1 = 73.14 ± 5.73 , day 10 = 83.57 ± 2.15) which is similar to previous results of balance recovery between day 1-10 following concussion.^{7,26,91} Similar results were also found on the SOM, VIS, and VEST ratio suggesting that immediately following a concussion physiological changes occurring in the brain are causing functional impairments but when the physiological changes begin to recover so do the functional changes. Contrary to what is published, no difference was found between groups on the SOT CES however as the CES is a weighted average of all trials, it is possible the CES is not sensitive to subtle changes in balance. Additionally, the variability between all subjects on day 1 of testing was higher than compared to day 10 confirming a learning effect on the test. Significant differences were noted on day 1 of

testing between the concussed and control group on the SOT SOM and SOM VEST ratio. Concussed athletes scored higher on the SOM ratio compared to controls but scored lower on the VEST ratio. These impairments suggest that following a concussion athletes may experience impairments in vestibular functioning and rely more heavily on input from the somatosensory system to maintain upright balance. While the SOT and mCTSIB are successful in removing visual information, the result of the current study may have been influenced by involvement of the vestibular and somatosensory systems which cannot be truly isolated during the testing session future research should consider including methodology which attempts to provide altered vestibular inputs, e.g. using the Head Shake Sensory Organization Test (HS-SOT) to delineate vestibular dysfunction, to determine if there is a stronger relationship between concussion and vestibular function.

Acutely concussed athletes demonstrate functional differences between days while completing a SVMP task. The results of this study support the theory of delayed visual information processing immediately following a concussion.³⁰ Concussed athletes had significantly delayed reaction time on day 1 of testing compared to day 10 (day 1 = 496.18 ± 52.85 , day 10 = 439.01 ± 20.62). Furthermore, following a concussion concussed athletes demonstrated significant impairments on day 1 of testing in reaction time on left (day 1 = 484.97 ± 64.60 , day 10 = 429.35 ± 34.19), right (day 1 = 474.88 ± 44.44 , day 10 = 413.76 ± 28.79), and ambiguous trials (day 1 = 530.62 ± 62.74 , day 1 = 472.30 ± 26.98). Improvements in balance following a concussion, were noted in the study as measured by the SOT CES (day 1 = 73.14 ± 5.73 , day 10 = 78.71 ± 7.74) which is consistent with the previously reported recovery pattern of 3 to 10 days;^{7,26,91} however, the deficits in visuo-motor processing is a novel approach that has not been previously used for assessing

acutely concussed athletes. SVMP task outcome measures including overall reaction time, reaction time left, reaction time right, and reaction time ambiguous all noted a significant improvement in the concussed group between day 1 and day 10. Improvement in reaction time may suggest that recovery of the neurometabolic cascade of concussion may be recovered by day 10 following the injury. Additionally, as the greatest impairments were noted on day 1 following the injury, it would suggest that the physiological changes are worst during that time. Additional significant findings were observed between groups on reaction time trials 81-100 (concussed = 531.31 ± 107.37 , control = 422.35 ± 80.04), reaction time trials 101-120 (500.12 ± 54.17), and reaction time ambiguous stimuli (concussed = 530.22 ± 62.74 , control = 452.58 ± 81.13). Visual processing is an essential attribute that athletes require to be successful in their sport. Any delay in visual information processing may lead to other functional impairments because areas of the brain which are responsible for visual processing are also partially responsible for coordinated movements, visually guided actions, and balance coordination.^{106,107} These visual processing functions are extremely important in sports performance and participation. Additionally, visual processing is responsible for making a cognitive map of the surrounding environment. Therefore, an athlete suffering from a concussion may experience slowed visual processing caused by deficits in effective cognitive mapping, leading to difficulties navigating through space.¹³⁹

We hypothesized that concussed athletes who exhibited impairments in visuo-motor processing would also demonstrate deficits in balance deficits, but the correlation analysis did not demonstrate a statistically significant relationship on day 1 of testing; however, the results of the correlation analysis trended towards a significant relationship

between SVMP and SOT measures on day 1 (**Figure 4.4**). Scores on the SOT CES in the concussed group on day 10 of testing were negatively correlated ($r = -0.741$, $p = 0.057$) with SVMP overall reaction time suggesting that as balance improves, reaction time improves as well (**Figure 4.5**). Additionally, SOT CES was negatively correlated with SVMP RT on trials 101-120 ($r = -0.830$, $p = 0.021$) suggesting that as scores on balance decrease, reaction time increases. The investigators used CDP measures when attempting to investigate the interactions among the sensory systems to identify if one or more of the systems were affected, the SVMP task determines if delayed information processing occurred and is therefore indirectly measuring physiological changes following a concussion. Assessment of balance is an integral component of assessment following a concussion,^{5,82,113} and we recommend that visuo-motor processing testing should also be evaluated to aid in decision making. A possibility exists that even if a concussed athlete demonstrates no impairments on balance; visuo-motor processing may be affected. Two subjects included in the analysis demonstrated deficits in SVMP overall reaction time but did not demonstrate deficits in balance as measured on the SOT. Future research should establish if the SVMP task can be used to diagnose concussion and make return-to-play decisions.

A limitation of this pilot study relates to the age of the subjects tested in the study, as the age of subjects (13 to 20 years) indicates that the results should only be generalized to that population. Future research should focus on identifying the relationship between SVMP and balance measures in different age populations. Other factors which may have influenced the results of the study relate to the prior concussion history of the subjects and the type of visuo-motor stimuli used. Prior concussion history (>6months) was not

determined among the control subjects and no attempts were made to match subjects (concussed to controls) based on prior concussion history, as the cumulative effects of concussion have been previously reported,¹⁴⁷ this may have influenced the results as athletes suffering from multiple previous concussions may exhibit additional impairments in balance and visuo-motor processing. The type of visual stimuli used in the current study during the SVMP task was based upon the work done by Pinkus and Patel (1997).⁷² To our knowledge, this test has not been previously investigated in acutely concussed subjects outside the investigator laboratory, however in unpublished work moderate reliability (ICC = 0.4-0.75) of the SVMP task was established. Balance assessment and SVMP task performance appear to be measuring two different underlying constructs which are independent from each other and both provide valuable information for identifying specific deficits following a concussion.

Conclusion

Acutely concussed athletes demonstrate impairments in visuo-motor processing and balance on day 1 of testing, as measured by the SVMP, and SOT tests respectively. The ability of an athlete to maintain upright balance and make a visual representation of the surrounding environment is essential for successful participation in athletics. The relationship between balance and SVMP task performance suggests that while the tests may be evaluating different underlying independent constructs, both measures revealed specific deficits among concussed athletes compared to control athletes and trended towards a significant correlation. Balance is an important component of the post-concussion evaluation, and the addition of a simple visuo-motor processing task may

provide further information about the nature and extent of deficits athletes experience in the initial 10 days following injury.

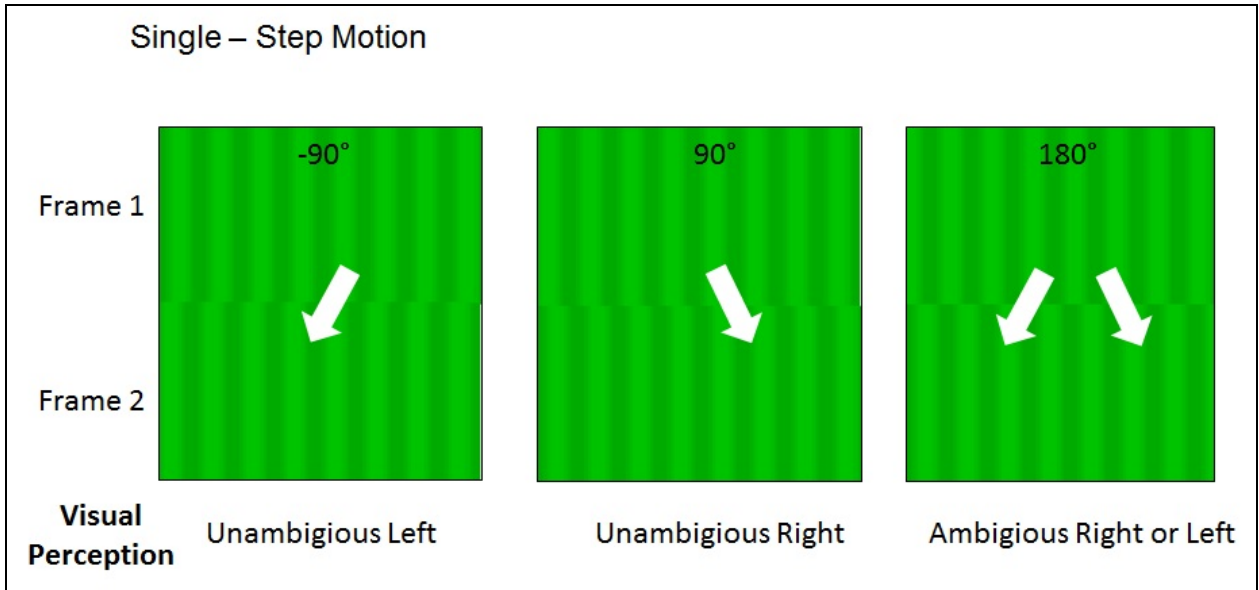
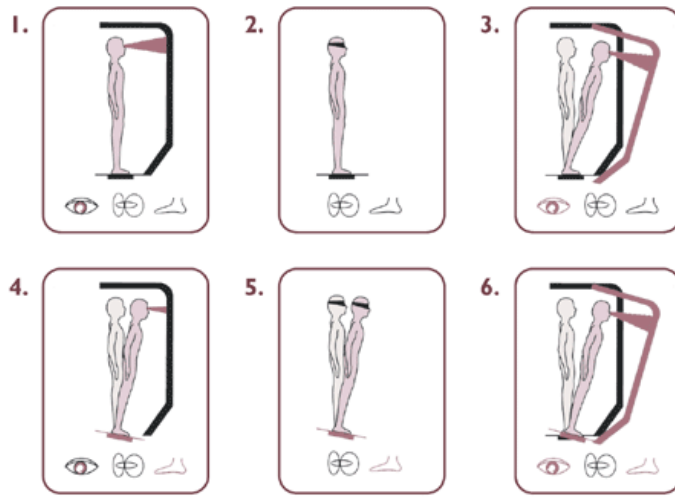


Figure 4.1 Visual stimuli for single motion sine wave gratings



Sensory Organization Test

Figure 4.2 The Sensory Organization Test (SOT) six sensory conditions. Used with permission



Figure 4.3 Example of the head mounted tracker and optotype stimulus. Used with permission

Day 1

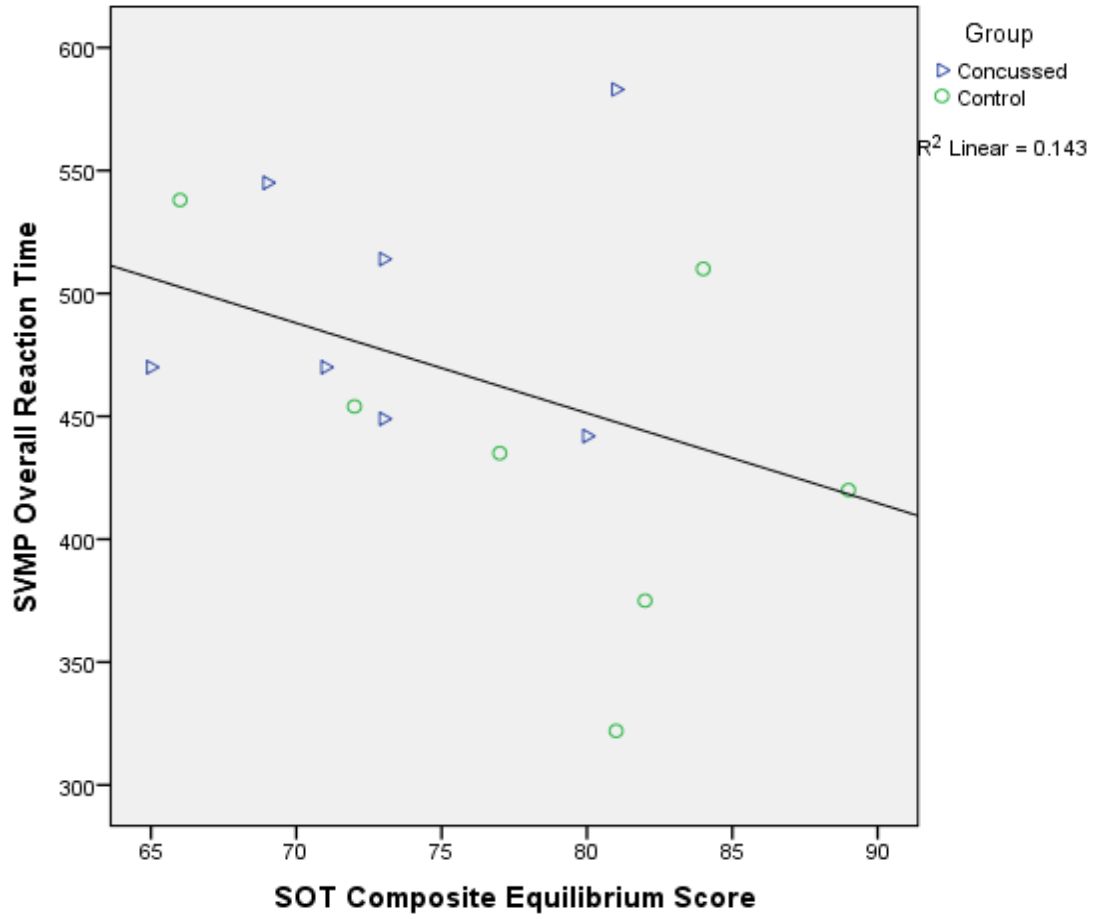


Figure 4.4 SVMP and SOT Correlation Day 1

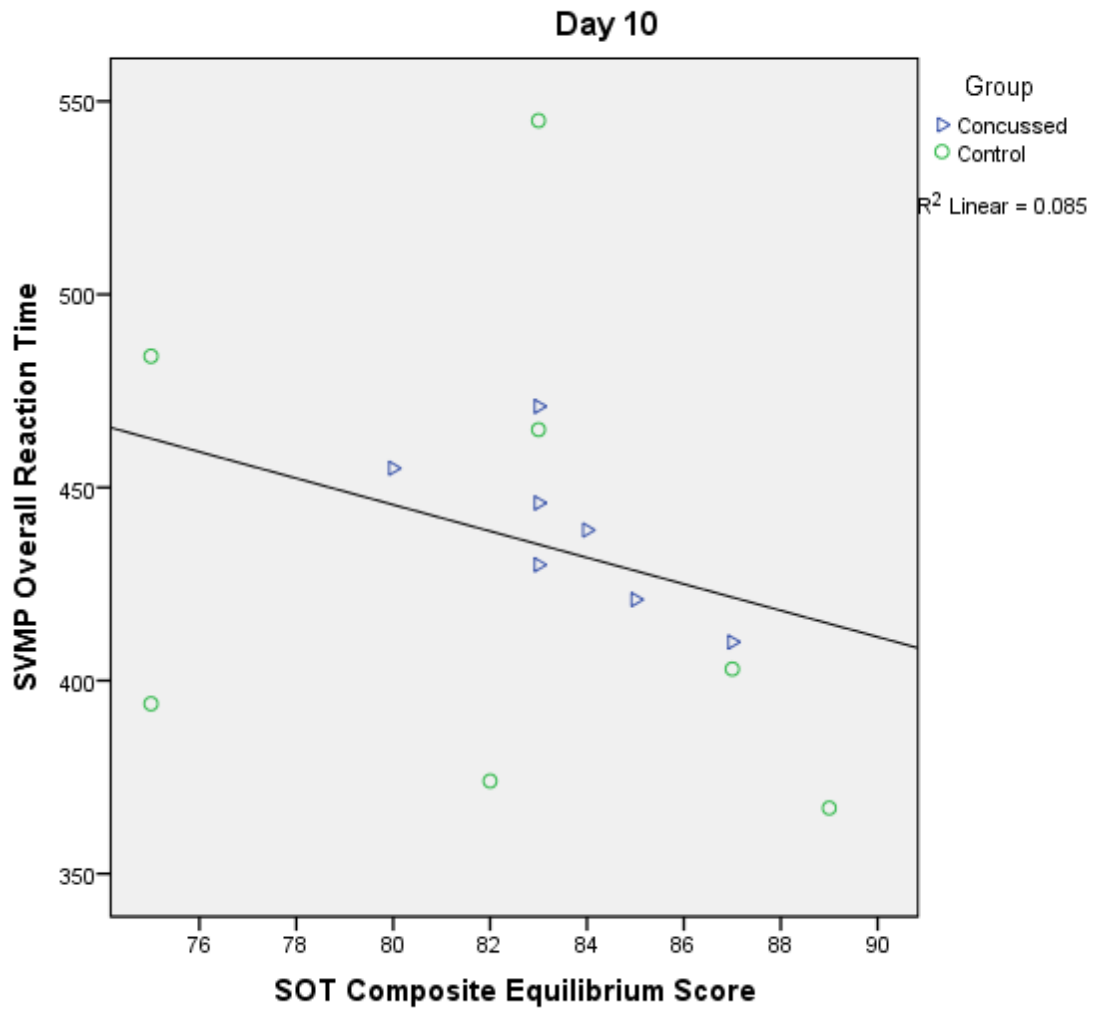


Figure 4.5 SVMP and SOT Correlation Day 10

Table 4.1 Descriptive Statistics for SVMP variables by Day and Group (mean ± SD)

SVMP Variable	Concussed (n=7)		Control (n=7)	
	Day 1	Day 10	Day 1	Day 10
Overall Reaction Time ^a	496.18±52.85*	439.01±20.62*	436.32±74.37	433.14±66.60
Reaction Time Trials 1-20 ^a	500.13±74.85	431.67±62.80	445.72±122.08	438.02±37.11
Reaction Time Trials 21-40 ^a	451.05±73.82	437.63±34.82	432.13±96.70	430.19±87.48
Reaction Time Trials 41-60 ^a	466.92±58.61	427.02±36.87	451.54±68.30	422.10±81.32
Reaction Time Trials 61-80 ^a	530.24±147.81	431.30±17.82	434.06±70.05	436.24±89.89
Reaction Time Trials 81-100 ^a	532.31±107.37*†	421.00±25.92*	422.35±80.04†	424.70±56.97
Reaction Time Trials 101-120 ^a	500.12±54.17†	484.77±43.10†	439.81±59.05†	427.76±68.77†
Reaction Time Left ^a	484.97±64.60*	429.35±34.19*	448.98±91.32	431.15±71.51
Reaction Time Right ^a	474.88±44.44*	413.76±28.79*	421.55±68.88	413.71±51.90
Reaction Time Ambiguous ^a	530.22±62.74*†	472.30±26.98*	452.58±81.13†	448.89±77.21

^aReaction Time measures in ms

*p<0.10; significant difference between days of testing

†p<0.10; significant differences between groups (concussed & control)

Table 4.2 Descriptive Statistics for SOT and mCTSIB variables

Variable	Concussed(n=7)		Control (n=7)	
	Day 1	Day 10	Day 1	Day 10
SOT Composite Equilibrium Score	73.14±5.73*	83.57±2.15*	78.71±7.74	82.00±5.39
SOT Somatosensory Ratio	1.09±0.07*†	1.03±0.04*	1.00±0.00†	1.04±0.05
SOT Visual Ratio	0.88±0.10*	0.97±0.03*†	0.88±0.10	0.93±0.04†
SOT Vestibular Ratio	0.61±0.09*†	0.80±0.05*	0.71±0.12†	0.77±0.09
SOT Preference	1.00±0.11	1.01±0.05	0.97±0.12	1.01±0.08
mCTSIB mean COG sway velocity	0.96±0.32	0.83±0.33	0.70±0.18	0.74±0.14

*p<0.10; significant difference between days of testing

†p<0.10; significant differences between groups (concussed & control)

Table 4.3 Descriptive Statistics for Visual Acuity variables

Assessment	Visual Acuity Variables	Concussed		Control (n=7)	
		Day 1(n=5) ^a	Day 10(n=7)	Day 1	Day 10
GST	Perception Time	23.33±8.17	20.00±0.00	20.00±0.00	20.00±0.00
	Static Acuity (logMAR)	-0.01±0.04*†	-0.11±0.13*	-0.15±0.13†	-0.22±0.10
	Maximum Velocity Left (deg/sec)	157.80±28.23	161.60±20.9	143.15±52.11	151.57±38.53
	Maximum Velocity Right (deg/sec)	191.40±28.19	159.60±44.3	162.00±57.04	176.14±28.67
DVA	Visual Acuity Loss Left (logMAR)	0.13±0.11	0.16±0.05	0.14±0.11	0.21±0.14
	Visual Acuity Loss Right (logMAR)	0.13±0.11	0.16±0.05	0.14±0.11	0.21±0.14

GST; Gaze Stabilization Test, DVA; Dynamic Visual Acuity Test

^aTwo subjects were unable to complete the test as it provoked symptoms

*p<0.10; significant difference between days of testing (day 1 and day 10)

†p<0.10; significant differences between groups (concussed & control)

Table 4.4 Correlation between CDP and a SVMP Task

				Pearson Correlation	p- value
Day 1	Concussed	SOT CES	SVMP Trials 101-120	-0.830	0.021
	Control	SOT CES	SVMP Trials 1-20	-0.729	0.063
Day 10	Concussed	SOT PREF	SVMP RT Left	-0.677	0.095
		SOT CES	SVMP RT Left	-0.683	0.091
	SOT VEST	SVMP Overall RT	-0.741	0.057	
	Control	SOT VEST	SVMP Trials 41-60	-0.762	0.047
		SOT SOM	SVMP RT Right	-0.696	0.082
		SOT PREF	SVMP RT Right	0.673	0.098
			SVMP Trials 41-60	-0.729	0.063
			SVMP RT Amb	-0.910	0.004

SOT: Sensory Organization Test, CES: Composite Equilibrium Score, SOM: Somatosensory Ratio, PREF: Preference Ratio, VEST: Vestibular Ration, mCTSIB Comp Sway: Modified Clinical Test of Sensory Interaction on Balance Mean COG Sway Velocity, SVMP: Simple visuo-motor processing task, Amb: Ambiguous

Chapter 5 Visual Perturbation Alters Upright Postural Stability in Acutely Concussed Athletes

Introduction

Individuals participating in sporting activities at all levels of competition are placed at a significant risk of sustaining a concussion. Between 1.6 to 3.8 million individuals involved in athletics suffer a concussion annually.¹ With \$76.5 billion dollars annually spent in the United States on direct and indirect medical costs, the diagnosis, management and rehabilitation of concussions (or mild traumatic brain injuries) must be a top priority of all health care professionals. Considering the high rate of concussion among athletes, an effective assessment protocol to identify when a concussion has occurred and to characterize the cognitive, somatic, and behavioral impairments becomes essential. The first step in recognizing and diagnosing a concussive injury is to accurately define and describe it. While there is no standardized definition of concussion, the Concussion in Sport Group has defined a concussion as, “A complex pathophysiological process affecting the brain, induced by biomechanical forces.”^{5,113} The ability to define the injury the foremost consideration, followed by the ability to diagnose and treat concussions. Currently, assessment protocols for the evaluation of the athlete with a suspected concussion consist of self-reported symptom inventories, neuropsychological assessments, and measures of balance.⁶⁻¹²

Balance assessment following concussion traditionally include either high- or low-technology assessments.⁷ High-technology assessment include computerized dynamic posturography (CDP),²⁴ virtual reality,¹⁴⁸ and biomechanical assessments.¹⁰ The Sensory Organization Test (SOT)^{6,23,24} and modified Clinical Test of Sensory Interaction

and Balance (mCTSIB) ^{31,44} are both CDP measures which have been used extensively in the past to examine balance impairments in a variety of populations. ⁴⁸⁻⁵⁰ The cost of the CDP equipment, space requirements, and time commitment are not always clinically feasible for health care providers; however, low-technology measures such as the Balance Error Scoring System (BESS), ^{21,25} are cost effective, require minimal equipment and can be completed in a minimal amount of time. Regardless of which type of assessment is conducted, the objective of balance assessments is to determine if any post-concussive balance impairments can be identified. Researchers have reported that balance impairments occur in 30% of all concussed athletes ⁵⁴ and these impairments typically resolve within 10 days following the injury. ⁷ Balance in healthy individuals is a result of the integration of visual, vestibular, and somatosensory information. ³¹ Following a sport-related concussion, balance impairments occur as a result of a failure of these sensory systems to properly integrate information correctly. ^{24,29,31} Although the prevalence of balance impairments has been well documented, the underlying cause of balance deficits following concussion is largely unknown. The contribution of individual sensory systems, the interdependence of these systems, and the effects on balance post-injury remains unclear but warrants further investigation.

Information received by the visual system is constantly changing which requires constant attention, when participating in any sporting activity. This constant changing visual environment, which requires a continuous communication between the sensory, motor and cognitive systems, is not well understood. In athletic practice or competition, athletes are faced with a plethora of sensory stimuli, including visual stimuli, which need to be attended to in order to be successful in athletic participation. Visual stimuli during

athletics are presented in the form of moving players, tracking the trajectory of the ball, and the movement in the crowd and side-line. For successful participation, athletes must note all of these motions occurring around them, but it is equally important for athletes to be able to disregard unimportant information so they can maintain focus on the task at hand (i.e. athletic participation). Current approaches to assessing balance make no attempt to mimic this ever-changing visual environment. Challenging the visual system during upright standing and assessing how the visual system processes information in a more dynamic fashion (i.e. in the presence of visual perturbation) will assist in determining how visual processing may be affected by an acute concussive injury. Identifying this construct may ultimately lead the changes in the assessment and management of individuals who sustain a concussion.

Visual processing includes visual memory and attention, it occurs at numerous levels of the brain, has an immense representation on the cerebral cortex,⁹⁵ and is extremely important in athletics because it provides a visual representation of the athlete's surroundings and how the athlete can effectively navigate through those surroundings. Additionally, visual processing allows an individual to judge the speed and distance of objects and/or people in order to successfully interact successfully with them. Both focal and diffuse damage to either the visual processing pathways (i.e. the ventral or dorsal pathways) or the vision areas of the brain (i.e. the visual cortex and primary visual cortex) could result in impaired visual acuity, smooth motor pursuits, and proprioception.⁵⁷ The visual processing tracks in the brain are susceptible to injury following concussion³⁰ based upon the mechanism of injury and the ensuing widespread and focal physiologic alterations that occur following concussion.⁵⁵ A concussion results

in both shearing and stretching injuries at the cellular level of the brain and causes “an abrupt neuronal depolarization, release of excitatory neurotransmitters, ionic shifts, changes in glucose metabolism, altered cerebral blood flow, and impaired axonal function.”⁵⁵ Focal damage in the brain may occur in the visual processing centers of the brain located in the occipital, and frontal lobes.⁶⁰ Diffuse axonal injury (DAI) following a concussion results from the strain placed on the axons during the rotational and linear acceleration/deceleration forces at the time of injury.⁵⁶ DAI results in delayed information processing at the axonal level,⁵⁶ and includes delayed visual information processing.¹⁴⁹ Due to the speed at which visual processing needs to occur and the complexity of the visual pathways, even a minor delay in neuronal processing would cause a significant decrease in the ability of an individual to adapt to changing visual environments. The visual processing areas of the brain which are vulnerable to damage are also partially responsible for initiation and planning of coordinated movement, postural stability, and visually guided actions;^{106,107} these functions are extremely important components of sporting activities. The clinical assessment of these functional areas are often overlooked by the athletic trainer and team physician, even though visual processing deficits have been reported in the literature following concussion.³⁰ The impact of visual processing deficits following sport-related concussions and how these deficits may have an effect on balance has not been previously investigated.

Sports medicine personnel must have an understanding of the extent to which disruption of normal visual information processing impacts an athlete’s balance. This is important for clinicians because it highlights a key component of the initial evaluation and serial monitoring of the concussed athlete. If an athlete demonstrates imbalance

while in the presence of visual perturbations it may suggest that either: 1) a concussion has occurred and has affected the visual processing centers or pathways to the brain, or 2) full recovery, upon follow-up assessment, is not complete. Visual perturbation is defined as a stimulus which causes activation of visual areas of the brain. Once activated, the visual areas of the brain identify and describe the stimuli and finally identify and track the trajectory of the stimuli. The ability of an individual to disregard visual perturbations that provide incorrect movement information, such as motion occurring in an opposite direction or occurring when no movement is occurring, is important for the successful athletic participation. However, the impact that visual perturbation has on upright postural stability in a concussed athletic sample has not been systematically investigated. The purpose of this study, therefore, was to characterize the influence that visual perturbation stimuli have on upright balance among acutely concussed athletes. We hypothesized that while healthy, non-concussed athletes are able to successfully disregard visual perturbation stimuli and show no deficits in postural stability, acutely concussed athletes will not be able to disregard visual perturbation stimuli presented during balance assessments and will, as a result, demonstrate impaired postural stability compared to a balance assessment approach where no visual perturbations or visual perturbation stimuli are presented.

Methods

Design

A 2 x 2 x 2 cohort, repeated measures design was used. The independent variables included test condition (with 2 levels: visual distraction and no visual distraction) and day of testing (24 to 48 hours, and 10 days following concussion). The dependent variables

collected and analyzed included: (a) data derived from the SOT, to include the composite equilibrium score and sensory analysis scores (i.e. the preferred sensory system used to maintain balance), and (b) data derived from the mCTSIB, to include the mean center of gravity sway velocity. The primary endpoint was the composite equilibrium score on the SOT with the remaining variables being secondary endpoints.

Subjects

The target number of subjects necessary based on an exploratory power analysis using postural stability data derived from Guskiewicz et al. (2001)⁷, using an *a priori* level of $P < .10$, was a minimum of 12 subjects per group. An alpha level of 0.10 was chosen because the research question was exploratory in nature and the testing procedures (i.e. visual distraction task) had not been used previously in the selected population or with the same outcomes.

Seven acutely concussed subjects [age (17.1 ± 3.0 years), height (174.0 ± 74.2 cm), weight (73.3 ± 23.8 kg)] participated in the study. Inclusion criteria for the concussed group included participation in an intercollegiate, interscholastic, or club sport and a diagnosis of concussion made by a certified athletic trainer or physician which was sustained within the previous 48 hours. Seven control subjects [age (17.3 ± 3.1 years), height (178.8 ± 11.6 cm), weight (77.9 ± 23.4 kg)] with similar age, sport, and gender participated. Control subjects had no self-reported history of a concussion within the previous year. Exclusion criteria for all subjects included any medications that may affect balance (e.g. NSAIDs, antidepressants, anticonvulsants, vestibular suppressants, neurostimulants, antimetics)¹³² taken within 2 hours of the scheduled testing, or vision (less than 20/20) as measured during the static visual acuity testing using the

NeuroCom® InVision program (see Testing Procedures below). All subjects were volunteers whom signed a written informed consent or assent form. Human subject's approval was obtained from the Office of Research Integrity at the University of Kentucky (IRB#12-0509) prior to beginning the study.

Instrumentation

The NeuroCom SMART Balance System (NeuroCom® International, Inc; Clackamas, OR) was used for all balance and visual acuity assessments. The Sensory Organization Test (SOT) was performed on the NeuroCom® Smart Balance System forceplate following the standard SOT protocol. Subjects performed the modified Clinical Test of Sensory Interaction on Balance (mCTSIB) on the longforce plate of the NeuroCom. Both testing procedures (SOT and mCTSIB) are valid and reliable techniques for balance testing^{48,145} In addition to the standard protocols subjects, were tested on the SOT and mCTSIB while in the presence of a visual perturbation [the 'forever' stars screensaver, Opanoid.com: London, UK] which represented a radical optical flow pattern. Visual acuity testing was conducted with the NeuroCom® InVision software. The hardware included a head- mounted tracking device that determines head rotation angle, distance, and velocity of head motion.

Procedures

Subjects reported to the research laboratory on two separate occasions (24 to 48 hours, and 10 days following concussion). These testing time points were chosen based upon previous published research demonstrating recovery of postural stability comparable to control subjects, which occurs within 3-10 days in the majority of athletes

following a concussion.^{24,26-28} Control subjects were assessed at the same time intervals but not necessarily on the same day as their matched concussed subjects. All subjects were screened using a self-reported medical screening in regards to their health and medical history. Demographic information (height, weight, age, gender, and sport) was collected using standard techniques and entered into the NeuroCom® Smart Balance System data files. All subjects underwent balance testing in a random order. Two protocols for assessing balance were administered at each time interval: the SOT and the mCTSIB.

The SOT⁷ is designed to systematically disrupt the sensory selection processing by altering available visual, vestibular, and somatosensory information. The SOT test protocol consists of 18 total trials (20 seconds per each trial) in each of 6 conditions. Subjects were barefoot for all of the testing procedures and each subject's stance position was standardized according to the NeuroCom® protocol based upon their own height. All subjects were fitted with a safety harness prior to the start of the SOT and secured to the overhead frame to ensure their safety during testing. During the mCTSIB were supervised by the investigator at all times to deter a fall from occurring. Subjects were presented with different visual conditions (eyes closed, eyes open, sway reference surround) and different somatosensory conditions (fixed, sway referenced) comprising the 6 different testing conditions. 'Sway- referencing' refers to the tilting of the support surface (force platform) or visual surround, or both.²⁸ During each of the conditions, subjects were asked to stand as motionless as possible. **Figure 5.1** depicts each of the SOT conditions. Outcome measures from the SOT included: equilibrium score, and sensory analysis ratio (visual, vestibular, somatosensory, preference).

The mCTSIB⁴⁵ is a simplified test derived from the CTSIB⁴⁶ that attempts to replicate clinical balance assessment, the Balance Error Scoring System (BESS)⁴³. The mCTSIB is a measure of the patient's functional balance control. The mCTSIB consists of two visual conditions (eyes open, eyes closed) and two surface conditions (foam, firm) performed on the NeuroCom long forceplate. Twelve total trials (10 second trials) were conducted for each of the four testing conditions (eyes open/foam, eyes open/firm, eyes closed/foam, eyes closed/firm). During each of the testing conditions, subjects are asked to remain as motionless as possible. Outcome measures for the mCTSIB included: mean center of gravity (COG) sway velocity (deg/sec), composite score, and COG alignment.

Subjects completed each of the trials for both the SOT and mCTSIB tests with no instruction given on where to focus their visual gaze during testing. Subjects also completed the assessments a second time while being presented with a radial optical flow stimulus (i.e. visual perturbation) on a 14 inch computer screen placed 24 inches in front of them and were instructed to focus their gaze on the center of the computer screen. Optical flow^{150,151} is a type of complex motion information that assists with visual pattern perception as an individual navigates through the environment. Optical flow is dependent on the type of stimuli presented and can be either lamellar or radial stimuli.¹⁵² Lamellar and radial optical flow patterns are different types of optical flow and stimulate different regions in the fovea, causing stimuli to be perceived differently.¹⁵² Radial optic flow stimuli simulate the subject moving forward through space.³⁰ For example, computer-generated white stars on a black background move in a radial pattern at random speeds and distances. Subjects were instructed to remain as motionless as possible during the balance testing while still maintaining gaze towards the screen. The eyes closed

conditions of the mCTSIB and SOT were not conducted during the visual perturbation testing.

All subjects underwent standardized visual acuity testing using the NeuroCom *InVision* system to determine static and dynamic visual acuity. Subjects sat 10 feet (3 meters) away from a computer monitor adjusted to eye level. To determine static visual acuity, subjects completed the Static Visual Acuity (SVA) and Perception Time Test (PTT) in which subjects were asked to correctly identify the orientation of an optotype (capital letter 'E'); the direction of the optotype could be up, down, left or right. During the PTT (the shortest presentation time that the optotype can be accurately determined by the subject)⁷¹ the length of presentation of the optotype automatically decreased incrementally from 240 ms to 20 ms until either the subjects' final speed (20 ms) is achieved or the subject failed to identify the orientation of the optotype at a faster speed. SVA was determined by reducing the size of the optotype (measured as the Snellen fraction and expressed as a logMAR score) until the subject was unable to correctly identify its orientation in 3 out of 5 trials.

Dynamic visual acuity was measured on two assessments: the Dynamic Visual Acuity (DVA) test and the Gaze Stabilization Test (GST). For both tests the beginning size of the optotype (capital letter 'E') was 0.2 logMAR greater than what was determined on the SVA test. The DVA test is a measure of the subject's ability to correctly identify orientation of the optotype while the head is actively moving; this test assesses the functional integrity of the vestibular ocular reflex (VOR).⁷¹ During the DVA test, subjects were fitted with a head mounted sensor (**Figure 5.2**) which tracks velocity and degree of the subject's head movement. Subjects were asked to move their head in a side-

to-side motion 20° in each direction in a horizontal plane at 85 degrees/second while maintaining their visual gaze on the computer screen positioned 10 feet (3 m) in front of them. Subjects were required to correctly identify the orientation of the optotype when presented. When a subject failed to correctly identify 3 out of 5 successive orientations, the test was automatically stopped.

In contrast to the DVA, the GST measured the subject's ability to maintain an acceptable level of visual acuity while moving the head at higher speeds. The same head mounted sensor was placed on the head of the seated subject. Subjects then rotate their head 20° in each direction in a horizontal plane at varying speeds ranging from 10 to $150^\circ/\text{sec}$ until they failed to correctly identify three out of five orientations. The initial head rotation velocity is automatically set for $70^\circ/\text{sec}$ per the GST protocol; the required head velocity is then either sped up (as a result of the subject providing a correct response to the stimulus) or slowed down (as a result of an incorrect response) depending if the subject was able to accurately visualize the orientation of the optotype. Practice trials for the PTT, GST, and DVA were administered prior to all testing to ensure subjects understood the task and to account for potential practice effects.

Data Reduction

All data were summarized automatically by the NeuroCom software and were exported into an Excel datasheet for data processing. In order to calculate the final outcome of both the mCTSIB and SOT while in the presence of visual distraction, eyes closed condition information was taken from the standard assessment protocol and substituted into the calculation. Data derived from the DVA test (i.e. DVA loss, DVA loss symmetry, average velocity achieved, number trials, number of errors and number of

incorrect velocities) and GST (average velocity achieved, velocity symmetry, number of trials, and number of incorrect responses) test were expressed as a log of the minimal angle of resolution (LogMAR) score. LogMAR scores represent a measure of visual acuity loss and was used for primary analysis; LogMAR scores were later converted to a Snellen fraction for interpretation.¹³⁴

Statistical Analysis

Descriptive statistics, measures of central tendency and variability were calculated to summarize the demographic characteristics of the sample. A repeated measure two-way ANOVA with Bonferroni correction was conducted to identify any significant differences between testing conditions (visual perturbation and no visual perturbation) and days of testing. All statistical analyses were performed with SPSS software (PASW Statistics 18.0, SPSS Inc., Chicago, IL). An *a priori* alpha level of $P \leq .10$ was applied to all data to determine significant differences; because this was an exploratory study, the level of significance was less stringent than the traditional *a priori* alpha level of $P \leq .05$.

Results

Descriptive statistics for CDP measures (SOT, mCTSIB) and visual acuity testing (GST and DVA) are presented in **Tables 5.1** and **5.3** respectively.

SOT Composite Equilibrium Score

Results of the repeated measures ANOVA revealed a significant condition by group interaction ($F_{1,7}=4.74$, Wilk's $\lambda=0.717$, $p=0.05$, $\omega^2=0.283$, $1-\beta=0.658$) for the SOT composite equilibrium score (**Figure 5.3**). Pairwise post-hoc testing determined there were significant differences for concussed athletes on day 1 between visual testing conditions (CES no distraction= 73.14 ± 5.73 , distraction = 76.97 ± 4.38 , $p<0.001$)

(**Figure 5.4**). Additionally, post-hoc testing revealed a significant impairment in the CES among the concussed group; during the no visual distraction testing conditions. There was a significant difference in CES between days 1 and day 10 (CES day 1 = 73.14 ± 5.73 , day 10 = 83.57 ± 2.15 , $p=0.020$). No other significant differences were found for SOT CES as shown in **Figure 5.5**.

SOT Somatosensory Ratio

Results of the repeated measures ANOVA revealed a significant condition by group interaction ($F_{1,7}=5.14$, Wilk's $\lambda=0.700$, $p=0.043$, $\omega^2=0.30$, $1-\beta=0.689$) for SOT SOM ratio. Pairwise post-hoc testing demonstrate a significant difference between the groups during no visual distraction testing conditions on either day of testing (SOM day 1 concussed = 1.09 ± 0.07 , control = 1.00 ± 0.01 , $p=0.009$ and day 10 concussed = 1.03 ± 0.04 , control = 1.04 ± 0.05 , $p=0.069$). Significant differences were also observed between the visual conditions (distraction, no distraction) among the concussed group on days 1 and 10 (SOM day 1 no distraction = 1.09 ± 0.07 , distraction = 1.08 ± 0.10 , $p=0.044$ and day 10 no distraction = 1.03 ± 0.04 , distraction = 1.02 ± 0.02 , $p=0.094$ respectively).

SOT Visual Ratio

No significant interactions were observed for the SOT VIS ratio however, a significant main effect was found for condition. Post-hoc testing revealed differences between the groups during visual distraction condition on day 1 of testing (VIS concussed = 0.91 ± 0.07 , control = 0.87 ± 0.12 , $p=0.046$), as well as group differences during visual distraction condition on day 10 of testing (VIS concussed = 0.96 ± 0.03 , control = 0.92 ± 0.03 , $p=0.028$). Additional significant differences were also noted

between the visual conditions among the concussed group on day 1 (no distraction = 0.88 ± 0.10 , distraction = 0.91 ± 0.07 , $p=0.038$). No other significant differences were found for the SOT VIS ratio.

SOT Vestibular Ratio

The repeated measures ANOVA revealed a significant condition by group interaction ($F_{1,7}=9.54$, Wilk's $\lambda= 0.557$, $p=0.009$, $\omega^2=0.443$, $1-\beta=0.897$) for the SOT vestibular ratio. Pairwise post-hoc analysis demonstrated significant differences for a number of outcomes including: (1) day 1, no visual distraction condition, between groups (concussed= 0.61 ± 0.09 , control = 0.71 ± 0.12 , $p=0.095$), (2) day 10, no visual distraction condition, between groups (concussed= 0.80 ± 0.05 , control= 0.77 ± 0.09 , $p=0.095$), (3) among the concussed subjects on day 1 of testing between visual distraction conditions (no distraction= 0.61 ± 0.09 , distraction= 0.62 ± 0.08 , $p=0.000$), and (4) among the concussed subjects on day 10 between the visual testing conditions (no distraction= 0.80 ± 0.05 , distraction= 0.81 ± 0.06 , $p=0.000$). No other significant differences were noted for the SOT vestibular ratio.

SOT Preference Ratio

Results of the repeated measures ANOVA revealed significant day by condition ($F_{1,7}=7.59$, $p=0.017$) and day by group interactions ($F_{1,7}=6.09$, Wilk's $\lambda= 0.613$, $p=0.030$, $\omega^2= 0.387$, $1-\beta=0.829$). Pairwise post-hoc analysis revealed multiple significant differences: (1) within the concussed group during the no visual distraction condition, there was a difference between days of testing (day 1 = 1.00 ± 0.11 , day 10 = 1.01 ± 0.05 , $p=0.000$); (2) within the control group during the no visual distraction condition there was a difference between days of testing (day 1= 0.97 ± 0.12 , day 10 = 1.01 ± 0.08 ,

p=0.019); (3) Additional differences were found on day 10 of testing during no distraction conditions between the concussed and control group (concussed = 1.01 ± 0.05 , control = 1.01 ± 0.08 , p=0.031). Finally concussed subjects on day 10 of testing showed a significant difference between distraction and no distraction conditions (no distraction = 1.01 ± 0.05 , distraction = 1.03 ± 0.10 , p=0.008). No other significant differences were observed for SOT PREF ratio.

mCTSIB Mean COG Sway Velocity

No significant interactions or main effects were noted for the mCTSIB mean COG sway velocity.

Visual Acuity

The results of the repeated measures ANOVA demonstrated no significant interactions for any of the visual acuity outcomes. Significant main effects on the variable for group determined on day 1 of testing concussed athletes were significantly different than control subjects on static acuity (concussed= -0.01 ± 0.04 , control= -0.15 ± 0.13). Significant main effects were noted for the concussed group on static acuity between day of testing (day 1= -0.01 ± 0.04 , day 10= -0.11 ± 0.13 , p=0.058) indicating that concussed athletes demonstrated poorer visual acuity when compared to control subjects. No other significant interaction or main effects were noted between day or group (see **Table 5.3**).

Discussion

In this pilot research study we investigated the influence of visual perturbation on upright postural stability among acutely concussed athletes. The study employed two measures of CDP to measure postural stability in acutely concussed athletes: the SOT and mCTSIB. The overall results suggest that in the immediate (24-48 hours) post-concussion

phase injured athletes experience balance deficits as measured by the SOT, which is consistent with previous research.^{7,43} The results also demonstrate that acutely concussed athletes will show improvements in their postural stability while in the presence of visual perturbation. This study is the first to document the relationship between increased postural stability and the presence of a visual perturbation. The ability of an individual to maintain postural stability is most often a subconscious process that typically doesn't require cognitive thought;²⁹ however, it has been suggested that following a concussion the process of maintaining balance moves to a more conscious process.²² Our results suggest that even in the presence of visual perturbation, healthy individuals are able to maintain balance. When balance changes from an unconscious to a more conscious process, the ability to multi-task becomes impaired in concussed individuals.^{22,153} The dual-task literature demonstrates impairments in both balance and gait following a concussion while the individual is simultaneously performing a cognitive task (serial sevens, verbal memory recall, etc.).^{22,154-157} The visual perturbation stimuli was not a true cognitive task, athletes were told to focus gaze on the middle of the computer screen depicting the visual perturbation stimuli requiring them to use their cognitive attention to maintain gaze. By using cognitive attention, concussed athletes directed more conscious processes to the cognitive task which ultimately affected balance.

Consistent with previous research was the noted recovery of balance between days 1 and 10 post-concussion.⁷ Most concussed individuals will recover their balance back to baseline levels or compared to normative data within ten days following the initial injury.^{7,43} Contrary to the hypothesis, no significant differences were found between the concussed and control group for the composite equilibrium score. One

possible explanation for the lack of a significant difference in CES between the groups may be from the data reduction method used. During the SOT, the CES and sensory ratios (SOM, VIS, VEST, and PREF) require that all 6 conditions on the SOT are completed. During the visual perturbation testing, conditions 2 and 5 of the SOT (both with the subject's eyes closed during testing) were not completed. In order to impute the final outcomes of the SOT, data from conditions 2 and 5 were input from no distraction testing. To ensure the above results were accurate, post-hoc repeated measures ANOVA were conducted on conditions 1, 3, 4 and 6 of the SOT. Descriptive statistics for these outcomes are reported in **Table 5.2**. Condition 1 (eyes open, fixed surround and support) demonstrated no differences between day, group, or condition. A significant main effect for day was observed for SOT condition 3 (eyes open, sway referenced surround). Pairwise comparisons revealed a significant difference in the concussed group on day 1 of testing between the distraction and no distraction condition (visual distraction = 89.81 ± 4.70 , no visual distraction = 92.24 ± 3.36 , $p=0.085$). Additionally, the concussed group demonstrated a significant improvement between day 1 and day 10 in the no visual distraction test condition (day 1 = 89.81 ± 4.70 , day 10 = 92.00 ± 2.27 $p = 0.033$). There were significant main effect differences for the mean of condition 4 on the SOT. Concussed athletes showed significant differences in the no distraction testing between group on day 1 (concussed = 82.29 ± 9.13 , control = 91.95 ± 2.24 , $p=0.008$). Results of the ANOVA for condition 6 of the SOT revealed significant improvement in the concussed group between day (day 1 = 52.90 ± 16.24 , day 10 = 73.48 ± 8.05 , $p=0.004$) and testing condition (no distraction = 52.90 ± 16.24 , distraction = 67.19 ± 9.44 , $p=0.004$). Condition 4 and condition 6 of the SOT are both incorporating inaccurate somatosensory information

by have subjects stand on a sway referenced support surface. Researchers conducting balance assessments on concussed athletes initially believed that balance deficits were a result of changes at the brainstem level, more specifically a failure of the somatosensory system to send information beyond the level of the brainstem.¹⁵⁸ A more widely accepted explanation of balance impairments following concussion relates to the inability of the sensory systems to properly integrate information.^{24,29,31} The results of the current study indicate that the impairments commonly noted following the concussion may in fact be a result of the deficits in the integration of the visual-vestibular integration. Future research should focus on establishing assessment protocols which independently examine the visual and vestibular systems to identify if one or both of the systems are impaired. Secondly, future research should begin to establish training protocols for the visual and vestibular sensory systems to potentially assist with recovery following a concussion. Another possible explanation for the results may be that concussed athletes are using information from their visual system to help maintain balance. If an athlete is able to use external stimuli to maintain or improve their balance, then the testing environment becomes an essential consideration when assessing an individual for a concussion. Future research should consider examining balance in a variety of environments (laboratory, side-line, locker room) to determine if environment may have an influence on balance.

This study was the first to examine the possible influence of visual perturbation stimuli on postural stability in acutely concussed athletes with the goal of developing a better understanding of how the visual processing system contributes to the maintenance of upright balance. Visual processing includes components of working visual memory, visual attention, and visually guided tasks,¹³⁹ and when information from each of these

components is combined with vestibular and somatosensory information, upright balance ensues. Following a concussion, visual processes are impaired³⁰ which may offer an explanation, at least in part, for why balance is affected in the initial days following the injury. Additionally, visual perception and action have been linked to visual processing via the ventral and dorsal pathways of the brain.¹⁰¹ Perception and action have a strong influence on how an individual responds to external visual perturbations which ultimately impacts the fluidity of movement and balance. The results of the current study suggest that visual perturbations do have an impact on upright balance which provides support that both the ventral and dorsal pathways are impacted following a concussion. Future research should identify the extent of the impact that concussion on the dorsal and ventral pathways separately, with the intent of developing better assessment tools.

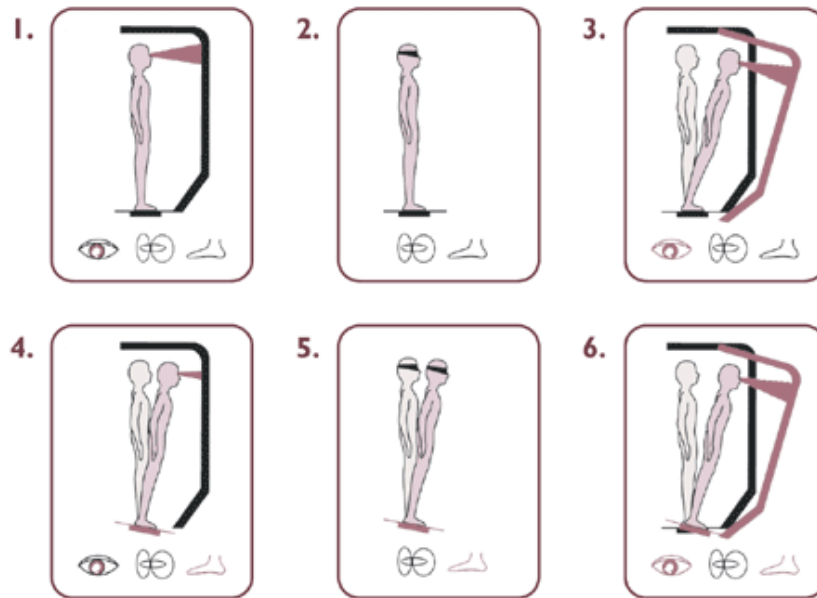
The balance assessments conducted in the current study (i.e. the SOT and mCTSIB) have been investigated extensively among acutely concussed athletes and demonstrate good to moderate test-retest reliability.^{37,46,159-161} The reliability of the SOT and mCTSIB, however, has not been examined while in the presence of a visual perturbation (such as the visual stimulus presentation used in the current study) and warrants further investigation. Additionally, we hypothesized that individuals suffering from a concussion may exhibit different balance responses to the visual perturbation for a variety of reasons, including: (1) an impaired ability to properly integrate sensory information, (2) slowed neuronal processing resulting from wide-spread physiologic disruption, and (3) damage to the terminal visual processing centers caused from concussive focal injury.^{43,46,49,162} Concussed athletes demonstrate impairments in information processing in the immediate post-injury period.⁵⁸ These impairments may place the concussed athlete at risk for re-

injury because the amount of visual information that must be processed by the visual system during sporting activities is extremely high.

The generalizability of the results is limited to individuals aged 13 to 20 years and can only be generalized to concussed athletes tested within the first 48 hours following the injury. The type of visual perturbation stimuli used in the study has been previously investigated in children³⁰ (under the age of 16 years) in which visual processing deficits were noted to occur at higher levels of the brain function following a mild traumatic brain injury. When visual processing deficits are observed, it is recommended that children should be withheld from any demanding physical activity until such time as visual processing deficits resolve.¹⁶²

Conclusion

Acutely concussed athletes demonstrate an improvement in upright balance during assessments with a visual perturbation stimuli present. An athlete's ability to disregard visual perturbation stimuli is imperative for successful and safe participation in athletics. Healthy, control subjects are able to successfully disregard visual perturbations in order to maintain balance; concussed athletes however, demonstrate changes in balance impairments when faced with a visual perturbation task. Balance performance was improved under the visual perturbation testing suggesting that when concussed athletes are given a task to focus on balance supersedes the visual task resulting in improved overall balance.



Sensory Organization Test

Figure 5.1The Sensory Organization Test (SOT) test conditions. Used with permission

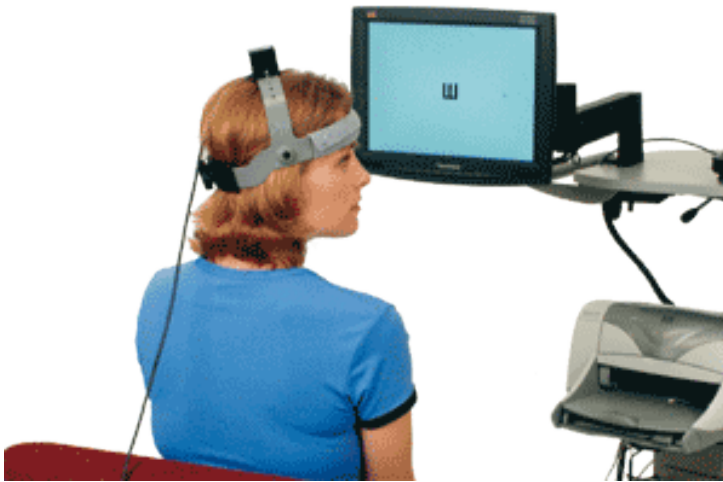


Figure 5.2 Example of the head mounted tracker and optotype stimulus. Used with permission

Table 5.1 Descriptive Statistics for CDP Variables

			Concussed		Control	
			Day 1	Day 10	Day 1	Day 10
SOT	CES	No	73.14±5.73†		78.71±7.7	
		Distraction	‡	83.57±2.15†	4	82.00±5.39
	SOM	Distraction	76.97±4.38‡	83.07±3.06	3	78.49±6.01
		No			1.00±0.01	
	VIS	Distraction	1.09±0.07*‡	1.03±0.04*‡	*	1.04±0.05*
		No	1.08±0.10‡	1.02±0.02‡	1.00±0.01	1.02±0.02
	VES	Distraction	0.88±0.10‡	0.97±0.03	0.88±0.10	0.92±0.04
		No			0.87±0.12	
	T	Distraction	0.91±0.07*‡	0.96±0.03*	*	0.92±0.03*
		No			0.71±0.12	
	PREF	Distraction	0.61±0.09*‡	0.80±0.05*‡	*	0.77±0.09*
		No	0.62±0.08‡	0.81±0.06‡	0.71±0.11	0.77±0.08
mCTSIB	Mean Sway	No		1.01±0.05*†	0.97±0.12	1.01±0.08*
		Distraction	1.00±0.11†	‡	†	†
		Distraction	1.14±0.06	1.03±0.10‡	1.03±0.11	1.01±0.03
		Distraction	0.96±0.32	0.83±0.33	0.70±0.18	0.74±0.14
		Distraction	0.92±0.33	0.76±0.29	0.66±0.15	0.73±0.19

CES: composite equilibrium score on Sensory Organization Test (SOT), VIS: visual ratio, VEST: vestibular ratio, SOM: somatosensory ratio, PREF: sensory system preference, Mean Sway: mean center of gravity sway velocity on modified Clinical Test of Sensory Interaction on Balance (mCTSIB)

*p>0.10; differences between group (concussed and control)

† p>0.10; differences between day (day 1 and day 10)

‡ p>0.10; differences between condition (distraction and no distraction)

Table 5.2 Descriptive Statistics for Mean Score SOT Eyes Open Conditions Variables

		Concussed		Control	
		Day 1	Day 10	Day 1	Day 10
Conditio n 1	No				
	Distraction	93.48±2.79	92.52±0.88	93.95±1.60	93.52±3.31
Conditio n 3	No		92.00±2.27		
	Distraction	92.24±3.11	91.57±4.20	93.33±1.28	92.57±2.69
Conditio n 4	No			91.67±2.51	91.38±3.36
	Distraction	89.81±4.70†‡	†	92.38±2.34	91.95±2.24
Conditio n 6	No	92.24±3.36‡	92.67±2.46	91.95±2.24†*	86.67±3.51
	Distraction	82.29±9.13*‡	89.43±2.19	‡	‡
Conditio n 6	No	83.62±6.35‡	88.14±1.79	80.90±11.36‡	85.29±4.44
	Distraction	52.90±16.24†	73.48±8.05		72.33±13.9
Conditio n 6	No			64.67±20.15	5
	Distraction	‡	†		
			72.62±12.1		
		67.19±9.44‡	0	71.52±16.31	72.71±8.92

*p>0.10; differences between group

† p>0.10; differences between day

‡ p>0.10; differences between condition

Table 5.3 Descriptive Statistics for Visual Acuity Variables

Assessment	Visual Acuity Variables	Concussed		Control (n=7)	
		Day 1(n=5) ^a	Day 10(n=7)	Day 1	Day 10
GST	Perception Time	23.33±8.17	20.00±0.00	20.00±0.00	20.00±0.00
	Static Acuity (logMAR)	-0.01±0.04*†	-0.11±0.13*	-0.15±0.13†	-0.22±0.10
	Maximum Velocity Left (deg/sec)	157.80±28.2	161.60±20.9	143.15±52.1	151.57±38.3
	Maximum Velocity Right (deg/sec)	191.40±28.1	159.60±44.3	162.00±57.0	176.14±28.6
		3	1	1	53
		9	0	4	67
DVA	Visual Acuity Loss Left (logMAR)	0.13±0.11	0.16±0.05	0.14±0.11	0.21±0.14
	Visual Acuity Loss Right (logMAR)	0.13±0.11	0.16±0.05	0.14±0.11	0.21±0.14

GST; Gaze Stabilization Test, DVA; Dynamic Visual Acuity Test

^a Two subjects were unable to complete the test as it provoked symptoms

*p<0.10; significant difference between days of testing (day 1 and day 10)

†p<0.10; significant differences between groups (concussed & control)

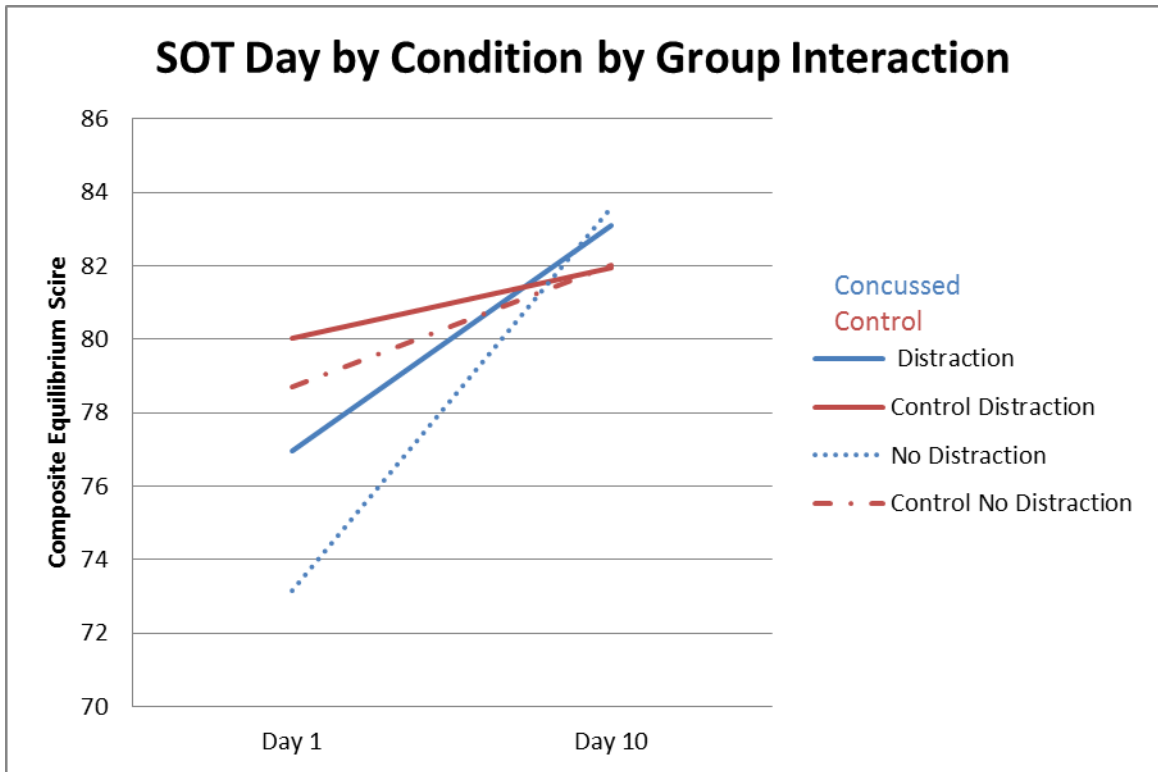


Figure 5.3 SOT Composite Equilibrium Score Interaction

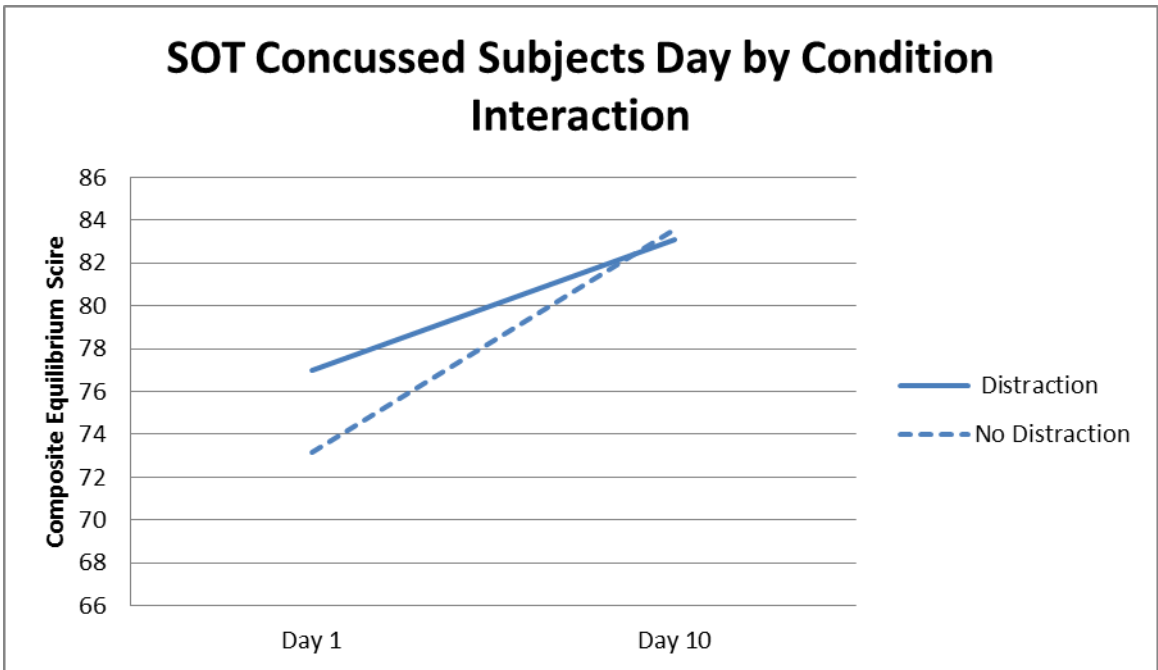


Figure 5.4 Concussed Day by Condition Interaction

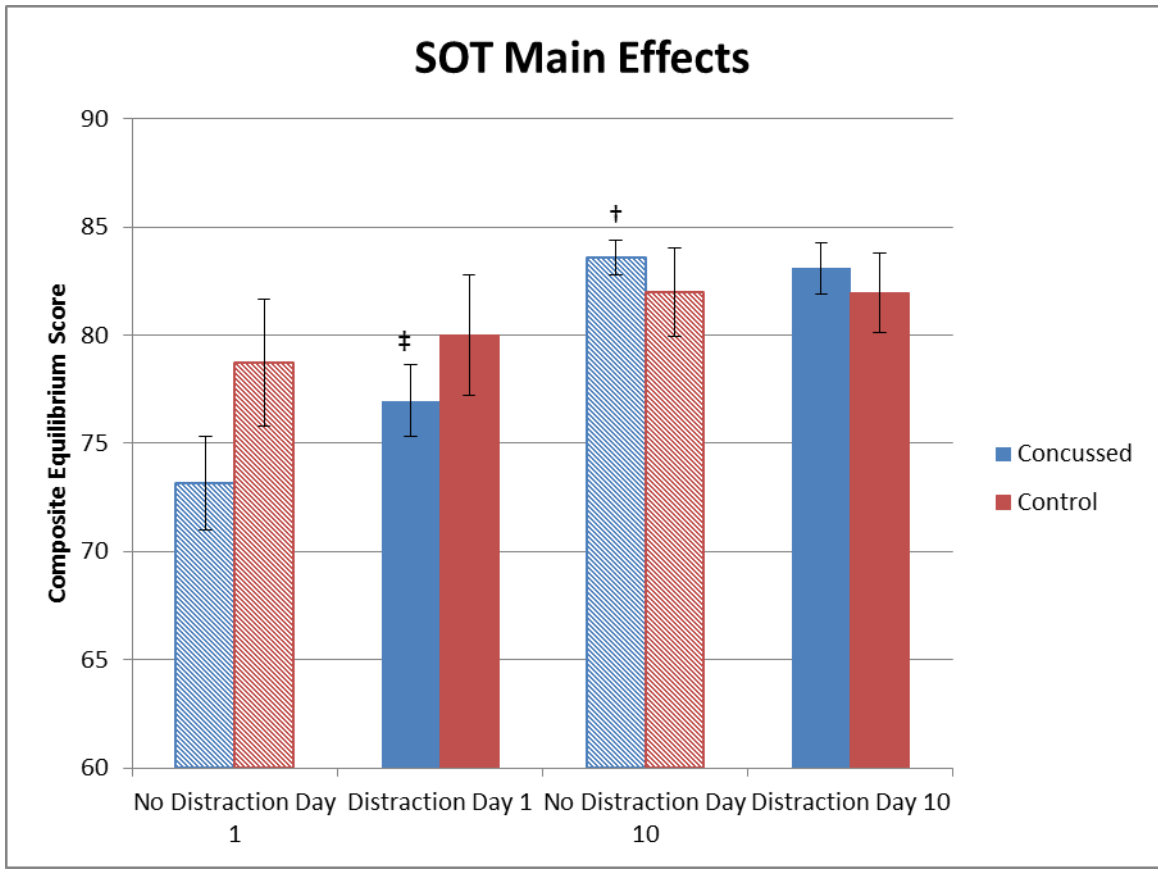


Figure 5.5 SOT Composite Equilibrium Score Main Effects

† $p > 0.10$; differences between day

‡ $p > 0.10$; differences between condition

Chapter 6 Summary

The overall purpose of this dissertation was to determine the relationship between visual processing deficits and balance impairments following concussion in athletes. The individual purposes of the three research studies were: (1) to identify the nature and extent of visuo-motor processing impairments; (2) to establish the relationship between altered visuo-motor processing and upright balance; and (3) to establish the influence of a visual perturbation stimulus has on upright balance among acutely concussed athletes. To summarize the findings, the hypotheses from Chapter 1 are revisited.

Hypothesis for Specific Aim 1: Concussed athlete will have increased reaction time, decreased accuracy, and an increased number of errors during a visuo-motor processing task compared to healthy control subjects.

Outcome: Acutely concussed athletes demonstrated increased reaction time on the simple visuo-motor process (SVMP) task. Accuracy and number of errors were not significantly different on either day of testing from the control group. A secondary aim of the research study was to determine the test-retest reliability of the SVMP task. While the majority of the SVMP outcomes demonstrated moderate to excellent reliability, three outcomes (reaction time trials 1-20, reaction time ambiguous stimuli, and number incorrect right) did demonstrate poor reliability which may be explained by the relatively small sample size and small variability. Further testing with a larger sample size would assist with validating these results. Finally, minimal detectable changes values were reported for the SVMP outcomes which will assist health care providers in interpreting changes on the test over time or among concussed subjects.

Hypothesis for Specific Aim 2: Acutely concussed athletes whom perform poorly on a visuo-motor processing task will demonstrate a negative correlation with postural stability compared to non-concussed athletes.

Outcome: This hypothesis was not confirmed; a statistically significant relationship between measures of computerized dynamic posturography (CDP) and SVMP task were observed on day 10 of testing, but were not confirmed on day 1 of testing.

Hypothesis for Specific Aim 3: The inclusion of a visual perturbation stimuli during standardized balance testing will result in a decreased of upright dynamic and static balance (i.e. impaired balance) among acutely concussed subjects compared to healthy subjects.

Outcome: This hypothesis was not confirmed. While balance impairments were noted immediately following a concussion on the SOT CES no visual perturbation conditions, adding the visual perturbation stimuli to the SOT testing sequence resulted in better balance in the concussed athletes on day 1 of testing. The results suggest that the demands to maintain balance superseded the influence of visual perturbation. Control subjects were not affected by visual perturbation which resulted in no change in upright balance. Balance impairments in the concussed group were most pronounced on day 1 of testing and improved by day 10. Results of the mCTSIB did not reveal a difference between group, day, or condition.

Synthesis and Application of Results

The overall purpose of this dissertation was to determine the relationship between visual processing deficits and balance impairments following concussion in athletes.

From the investigation, several recommendations for clinical application to athletes following a concussion can be made.

1. Athletes can expect to experience functional impairments in balance, and reaction time in response to a visual stimulus, immediately following a sports-related concussion. Functional impairments seem to recover by ten days following the injury.
2. SVMP testing should be considered as an additional measure of post-concussion function. SVMP measures the integrity of the dorsal visual pathways of the brain. The dorsal visual pathways are concerned with 'where' motion is occurring in an individual's visual field, which has direct implications on the athletes' ability to make a visual representation of the environment. Additionally, the dorsal visual pathways are directly linked to motion centers (located in the frontal cortex) and identifying impairments in this pathway may justify restrictions from sports participation until recovery has occurred. The SVMP task provides unique information about visuo-motor processing which may not be related to visual processing during balance. Visuo-motor processing may help to identify injured athletes who may not demonstrate impairments in balance.
3. Both a simple visuo-motor processing task and a measure of balance should be included in the post-concussion assessments because they are measuring two different underlying constructs. SVMP task measures the ability of the athletes to process information in the dorsal visual pathways. Balance assessments measure the integrity of the sensory systems as well as their ability to integrate information together to maintain upright postural control. SVMP and CDP assessments each provide unique

information following concussion and should be included in the clinical assessment protocol.

4. Balance testing with presentation of a visual perturbation provides justification that when an additional task is introduced to the assessment protocol, balance supersedes any additional task and ultimately improves balance. Balance performance was better when a visual perturbation stimulus was presented during the balance testing protocol, suggesting that (1) when athletes are given a specific task to perform during balance assessment (e.g. “focus your attention on the center of the computer screen”), less conscious attention is given to maintaining balance resulting in improvements in balance performance, and (3) concussed athletes are able to disregard a visual perturbation stimulus (as with conditions 3 of the SOT) and still maintain their standing balance.

Future Research

Different assessment techniques were used in this dissertation research to determine if visual processing is affected by a sport-related concussion and how visual processing may impact an athlete's balance performance. Future research should examine the relationship between visual processing impairments and balance following concussion among different age groups and different testing conditions. The research included in this dissertation focused on acutely concussed athletes between the ages of 13-24 years; although significant differences were noted in reaction time and balance, the results cannot be generalized to athletes outside this age range. Different outcomes may arise when conducting similar research procedures using middle-school athletes (12-15

years), high-school (15-17 years) or young adult (18-24 years) populations. Identifying balance deficits and visuo-motor processing impairments in these populations may reveal information that would allow health care providers to better understand the effects of concussion on the population of athletes they are working with.

The current research did not show any relationship between SVMP and CDP balance measures; the potential for a relationship between balance under visual perturbation conditions and SVMP testing has not been established and warrants further investigation. Another area that requires further investigation is research focusing on either the ventral or dorsal visual pathways to determine if one or both of these systems is affected following a concussion. The information gained from research on the visual pathways will lead to greater understanding of why visual processing is affected following a concussion. Additionally, identifying deficits in these visual pathways may suggest possible visual training protocols which could be used to enhance recovery, particularly among subjects who may not demonstrate the typical recovery time course following concussion.

The SVMP task used in the two of the present research studies used a simple one-jump motion to evaluate visual processing. Research in the elderly population using similar stimuli revealed impairments while using the simple visual stimuli and an even greater impairment while in the presence of a more challenging two jump motion analysis.⁶³ Research utilizing a two jump motion analysis may provide further evidence and support for SVMP testing following a concussion in athletes. Regardless of which stimulus is used to assess visuo-motor processing, identifying the feasibility of conducting the assessment while on the side-line or in a clinical environment will help to

transform the current laboratory-based research outcomes with a clinically meaningful assessment tool.

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Vita

Andrea E. Cripps ATC

General Information

Birth place and date: Sault Ste. Marie, ON, Canada

Certificate or Specialty Board Licensure:

National Athletic Trainers Association Board of Certification #110702021

I. Education

- 2010 – Present The University of Kentucky, College of Health Sciences,
Doctor of Philosophy, Rehabilitation Sciences
Expected Completion: August 2013
Dissertation: Alterations in Visual Processing and its Impact on
Upright Postural Stability following Sport-Related Concussion
- 2007-2010 Central Michigan University, College of Health Professions,
Master of Arts, Physical Education and Sport,
Concentration in Exercise Science
- 2003-2007 Lake Superior State University, College of Nursing, Recreation
Studies, and Exercise Science, Bachelor of Science, Athletic
Training

II. Professional Experiences

- 2010 – Present Research Assistant
Advisor: Scott C. Livingston, PhD, PT, ATC, SCS
Division of Physical Therapy
Department of Rehabilitation Sciences
University of Kentucky, Lexington, KY
- August 2007 – June 2009 Graduate Assistant Athletic Trainer
Central Michigan University
Mount Pleasant, MI

III. Teaching Activity

University of Kentucky

- 2012-2013 KHP340: Introduction to Athletic Training
Primary Instructor
- Summer 2012 PT672: Specialty Elective in Athletic Taping

Primary Instructor
Summer 2011 PT672: Specialty Elective in Athletic Taping
Teaching Assistant

IV. Honors

2012 College of Health Science Academic Excellence Scholarship, University of Kentucky

V. Speaking Engagements/Presentations

Invited

2012 3rd Annual Concussion Summit, Lexington, KY
Implementing ImpACT at your high/middle school

Peer-Reviewed

2013 National Conference on Undergraduate Research, La Crosse, WI
Establishment of Normative Data for Motor Evoked Potentials Among Healthy Young Adults (Poster)

201 2 American Physical Therapy Association Combined Sections Meeting, Chicago, IL
The Head Shake Sensory Organization Test (HS-SOT): Normative Data and Correlation with Dynamic Visual Acuity Testing

Center for Clinical and Translational Science Spring Conference, Lexington, KY
Visual Distraction Does Not Alter Static or Dynamic Upright Postural Stability in Healthy Subjects

National Athletic Trainer Association Annual Meeting, St. Louis, MO
Visual Distraction Does Not Alter Static or Dynamic Upright Postural Stability in Healthy Subjects

VI. Research Creative Productivity

Publications: Peer Reviewed Journals

Cripps, AE., Livingston, SC. The Values of Balance-Assessment Measurements in Identifying and Monitoring Acute Postural Instability Among Concussed Athletes. *Journal of Sport Rehabilitation*. 2013;11(1):68-71.

Cripps, AE., Livingston, SC. Visual Distraction Does Not Alter Static or Dynamic Upright Postural Stability in Healthy Subjects. *J of Athletic Training*. 2012. 47 (Supplement 1): 150