The Pennsylvania State University

The Graduate School

College of the Liberal Arts

INTRAINDIVIDUAL COGNITIVE VARIABILITY IN SPORTS-RELATED CONCUSSION: IMPLICATIONS FOR MOTIVATION AND NEUROLOGICAL VULNERABILITY

A Dissertation in

Psychology

by

Amanda R. Rabinowitz

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

August 2012

The dissertation of Amanda R. Rabinowitz was reviewed and approved* by the following:

Peter A. Arnett
Associate Professor of Psychology
Dissertation Adviser
Chair of Committee

Frank G. Hillary
Associate Professor of Psychology

Richard A. Carlson
Professor of Psychology

Lisa Gatzke-Kopp
Assistant Professor of Human Development

Melvin M. Mark
Professor of Psychology
Head of the Department of Psychology

*Signatures are on file in the Graduate School

Abstract

The present thesis provides four publication-style empirical research papers that, taken as a whole, represent a study of intraindividual cross-domain cognitive variability in college athletes before and after sports-related head injury. Specifically, these papers examine the role of motivation and neurological vulnerability to injury as contributors to inconsistency in college athletes' cognitive test performance. Paper 1 establishes an evidence-based criterion for dividing athletes into two groups following concussion—those experiencing neuropsychological impairment *(impaired)* and those who are not experiencing significant neuropsychological impairment *(unimpaired)*. Paper 2 characterizes cross-domain intraindividual cognitive variability in college athletes before and after sports-related concussion. This paper examines the impact of concussion on cognitive variability, divides athletes into clusters based on cognitive variability before and after injury, and explores possible correlates of this variability. Paper 3 examines the influence of motivation on neuropsychological test performance. This study considers athletes' motivation at baseline in relationship to baseline neuropsychological test performance, as well as the likelihood of being classified as impaired post-concussion. Paper 4 evaluates cross-domain cognitive variability as an indicator of vulnerability to injury at baseline, and as an indicator of neurological impairment post-concussion. This paper uses longitudinal structural equation modeling to test a multi-stage mediation model predicting post-concussion cognitive decline. The theoretical implications of these findings are discussed.

Table of Contents

List of Tables and Figures

Acknowledgements

Firstly, it is my pleasure to thank my advisor, Dr. Peter Arnett, for his extraordinary mentorship over the past six years. Without his wisdom and support, this thesis would not be possible. Under Dr. Arnett's guidance I have grown as a scientist, as a clinician, and as a professional. My experience at Penn State has been a true joy, due in large part to Dr. Arnett's warmth and encouragement.

I also would also like to thank the other members of my thesis-committee—Dr. Richard Carlson, Dr. Lisa Gatzke-Kopp, and Dr. Frank Hillary—for their support and mentorship in a number of capacities over the course of my graduate training. Exposure to their perspectives and areas of expertise has broadened my thinking, and their examples have inspired me in my career goals.

It is my honor to acknowledge the other graduate and undergraduate students who have contributed to the Penn State Sports Concussion Lab over the years. In particular, special thanks are due to Dr. Aaron Ronesnbaum, Dr. Fiona Barwick, and Dr. Chris Bailey for making innovations in the organization and procedures of the Sports Concussion Lab, which have helped to maximize the research potential of this program. During my tenure at Penn State, there have been many undergraduate students who have made invaluable contributions to this research. In particular, I would like to thank, Andrew Lynn, Patrick Kelly, Michael Yacovelli, Kaitlyn Loghren, Alicia Evens, Shannon Hitchcock, Katherine Robinette, Madeline Martinez, Kristina Krecko, Victoria Quimpo, Kristina Rapuano, Jeremiah Robinson, and Evangelina Baez.

Furthermore, I would like to express my sincere gratitude to the athletes, coaches, athletic trainers and team physicians who participate in the Sports Concussion Program and make this research possible.

This thesis has been funded by the Research and Graduate Office Dissertation Support Award, the Research and Graduate Office Dissertation Enhancement Award, and the Benton-Meier Neuropsychology Scholarship.

Dedication

This thesis is dedicated to my mother, Vita, who has always encouraged me to be the best version of myself. I am humbled by her extraordinary pride in my accomplishments. Her aspirations on my behalf have carried me through this journey.

Chapter 1. Introduction

Proper identification and management of sports-related concussion is necessary in order to prevent the tragic acute and protracted outcomes associated with these injuries. Because cognitive tests are objective and sensitive to concussion, neuropsychological testing has emerged as a critical tool for this purpose (Echemendia & Cantu, 2003). Baseline testing—that is, taking a pre-injury assessment of athletes' functioning prior to the start of play—is becoming the gold standard in concussion management (Barth et al., 1989). An objective measure of athletes' premorbid cognitive abilities provides an ideal comparison standard for post-concussion assessment—post-injury cognitive performance is compared with baseline results, and significant declines from baseline are interpreted as injury-related deficits. However, some authors have drawn attention to issues that complicate straight-forward pre- post-injury test comparisons (Bailey, Echemendia, & Arnett, 2006; Ragan & M. Kang, 2007; Randolph, McCrea, & Barr, 2005). For example, many healthy athletes' baseline cognitive performance defies the expectation that healthy intellectual functioning is consistent—"Given reasonably normal conditions of physical and mental development, there is one performance level that best represents a person's cognitive abilities and skills, generally" (Lezak, Howieson, & Loring, 2005).

Intraindividual variability is a term that has been used to describe moment-to-moment fluctuations in state, or inconsistencies (Ram, Rabbitt, Stollery, & Nesselroade, 2005). Intraindividual variability in premorbid test performance complicates clinical interpretation—cognitive inconsistency could be related to true idiosyncratic strengths and weaknesses, fluctuations in effort due to premorbid neurological vulnerabilities, or fluctuations in effort due to sub-optimal motivation. Distinguishing between these potential sources of cognitive inconsistency is crucial for valid assessment.

The purpose of the present study is to elucidate the correlates of cognitive inconsistency. Specifically, the proposed study aims to examine two factors that may be related to intraindividual variability in cognitive performance at baseline—effort towards testing (motivation), and neurological vulnerability to injury. Both of these factors have profound clinical relevance. Sub-optimal motivation during baseline testing could lead to underestimation of athletes' true level of premorbid functioning, thus increasing the chance that a vulnerable athlete returns to play prematurely and risks further injury. However, for some athletes, intraindividual variability may not suggest sub-optimal motivation, but may rather be a sign of premorbid vulnerability. Athletes who are vulnerable to injury may require a more conservative return-to-play approach in order to decrease long-term risk of neurological dysfunction. A better understanding of how these factors influence test performance could lead to more accurate detection of sports-related concussions and safer return-to-play procedures.

Specific Aims and Related Papers

Paper 1 (Chapter 2): Determining neuropsychological impairment following sports-related concussion: The sensitivity and specificity of reliable change from baseline

The aim of Paper 1 is to develop an evidence-based criterion for dividing athletes into two groups following concussion—those experiencing neuropsychological impairment *(impaired)* and those who are not experiencing significant neuropsychological impairment *(unimpaired)*. This chapter establishes a classification criterion that will then be utilized in the following papers.

Paper 2 (Chapter 3): An exploratory analysis of cross-domain intraindividual cognitive variability pre- and post-sports related concussion

The aim of Paper 2 is to characterize cross-domain intraindividual cognitive variability in college athletes before and after sports-related concussion. Specifically, this chapter examines the impact of concussion on cognitive variability, divides athletes into clusters based on cognitive variability before and after injury, and explores possible correlates of this variability.

Paper 3 (Chapter 4): The influence of motivation on neuropsychological test performance before and after sports-related concussion: Implications for vulnerability to injury

The aim of Paper 3 is to evaluate the influence of motivation on neuropsychological test performance. This study examines athletes' motivation at baseline in relationship to baseline neuropsychological test performance, as well as the likelihood of being classified as impaired post-concussion. Cognitive performance at baseline is operationalized as mean level of performance *(overall performance)*, cross-domain cognitive variability *(performance inconsistency)*, and the discrepancy between an estimate of full-scale IQ and actual cognitive performance.

Paper 4 (Chapter 5): Cross-domain cognitive variability is an indicator of clinically meaningful states before and after sports-related concussion

Finally, the aim of Paper 4 is to evaluate cross-domain cognitive variability as an indicator of vulnerability to injury at baseline, and as an indicator of neurological impairment post-concussion. This study uses longitudinal structural equation modeling to test a multi-stage mediation model predicting post-concussion cognitive decline.

Chapter 2. Paper 1: Determining neuropsychological impairment following sports-related concussion: The sensitivity and specificity of reliable change from baseline

The Centers for Disease Control and Prevention estimate that approximately 300,000 sports-related concussions occur annually in the United States (Thunnan, Branche, & Sniezek, 1998), and it is likely that this number is an underestimate of the true incidence of concussion (McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004). The preponderance of evidence now suggests that there is the potential for serious immediate and long-term consequences of these so-called minor injuries—specifically Second Impact Syndrome (Cantu & Voy, 1995) and Chronic Traumatic Encephalopathy (McKee et al., 2009). The proper detection and management of sports-related concussion is now deemed essential.

Because athletes may be likely to minimize symptoms in order to prevent removal from play (Bailey, et al., 2006; Echemendia & Julian, 2001), objective methods of identifying concussion and tracking recovery are preferable to self-report alone in order to best manage these injuries. Research has demonstrated that cognitive tests are sensitive to the neuropsychological symptoms of sports-related concussion (Belanger & Vanderploeg, 2005). Baseline testing—that is, taking a pre-injury assessment of athletes' functioning prior to the start of play—has become the gold standard in concussion management (Barth, et al., 1989). Although some have raised questions regarding the validity and clinical utility of this approach (Randolph, et al., 2005), other research has supported the use of this model for diagnosing and managing sports-related brain injuries (Echemendia, Putukian, Mackin, Julian, & Shoss, 2001; McCrea et al., 2003).

Baseline testing is now commonly employed in many athletic programs at the high school, college, and professional level. However, questions remain regarding how to best make use of these data clinically. Specifically, guidelines for interpreting change from baseline on a given test within the context of a larger test battery may be helpful to those who make return-to-play decisions. Furthermore, individual neuropsychological tests vary in their psychometric properties and sensitivity to practice effects, and hence guidelines for incorporating this information into clinical interpretation could improve concussion management.

The present study examines reliable change from baseline to post-concussion on 12 test-indices that comprise a neuropsychological test battery designed for use in a concussion management program at a large university. The sensitivity and specificity of reliable decline on at least 1, 2, or 3 tests are evaluated in two ways—one based on each cut-point's ability to detect concussed athletes versus healthy control participants, and the other based on the ability to detect symptomatic athletes versus a non-symptomatic athletes and healthy controls.

Method

Participants

Participants in the present study are 48 college athletes participating in a concussion program at a large university, a multi-sport program that assesses participants prior to and following sports-related concussion, as well as 42 control participants (see Table 2.1 for characteristics of the sample). Control participants are college students at the same university who participate in athletic activities at the intramural level, but do not participate in the sports concussion program. This program is designed according to the Sports as a Laboratory

Assessment Model (SLAM; Barth, et al., 1989) paradigm, in order to provide objective neuropsychological test data to team physicians to inform return-to-play decisions. Eight of the athletic programs regularly participate in baseline testing: Football, Men's and Women's Lacrosse, Men's and Women's Soccer, Men's and Women's Basketball, Men's Ice Hockey, and Wrestling. Post-concussion testing is provided for any university athlete who sustains a head injury. Whenever possible, post-concussion assessment takes place within 48 hours of injury. All athletes who have undergone baseline or post-concussion assessment are included in the present study.

Measures

The test battery consists of a number of measures that assess cognitive and affective functioning, as well as a range of other symptoms. The measures include: the Hopkins Verbal Learning Test-Revised (HVLT-R; Benedict, Schretlen, Groninger, & Brandt, 1998), the Brief Visuospatial Memory Test-Revised (BVMT-R; Benedict, 1997), the Symbol-Digit Modalities Test (SDMT; Smith, 1982), the Digit Span Test (Wechsler, 1997), the PSU Cancellation Task, the Stroop Color-Word Test (SCWT; Trenerry, Crosson, DeBoe, & Leber, 1989), and the Wechsler Test of Adult Reading (WTAR; The Psychological Corporation, 2001). For athletes who underwent multiple evaluations (baseline testing and one or more post-concussion evaluations), alternate forms of the HVLT-R, BVMT-R, SDMT, and PSU Cancellation Task were used (see Benedict et al., 1998; Benedict, 1997; and Smith, 1982, for alternate form reliability information). With the exception of the WTAR, all of these tests have been shown to be sensitive to traumatic brain injury in prior work (Bailey, Echemendia, & Arnett, 2005; Bohnen et al., 1992; Bruce & Echemendia, 2003; Ponsford & Kinsella, 1992; Vanderploeg, Curtiss, & Belanger, 2005). The Immediate Post-Concussion Assessment and Cognitive Testing computerized battery (ImPACT; Lovell, Collins, Podell, Powell, & Maroon, 2000) was also used. Although complete validity data for the use of this test battery in sports related concussion have not yet been published, it assesses cognitive domains typically affected following such injury.

The ImPACT (Lovell, et al., 2000) is a computerized test battery that was designed to offer a time-effective and standardized method for collecting data to assist in concussion assessment and management. The battery consists of three main parts: demographic data, neuropsychological tests, and the Post-Concussion Symptom Scale. Six neuropsychological tests are included, designed to target attention, memory, processing speed, and reaction time. From the six primary tests, five composite scores are derived: Verbal Memory, Visual Memory, Visuomotor Speed, Reaction Time, and Impulse Control. Studies in high school and college athletes have demonstrated that the ImPACT performance is correlated with performance on similar paper-and-pencil neuropsychological tests (Iverson, Lovell, & Collins, 2005), and furthermore, ImPACT performance is sensitive to the acute effects of concussion (Schatz, Pardini, Lovell, Collins, & Podell, 2006).

In addition to the neuropsychological tests, the battery includes a self-report measure of symptoms. The Post-Concussion Symptom Scale (PCSS) is a list of symptoms that are commonly associated with concussion, including items like headache, nausea, dizziness, trouble concentrating, and feeling “in a fog”. Examinees rate the extent to which they are currently experiencing each symptom on a scale from 0-6, with 0 indicating the absence of the symptom, and 6 indicating extreme distress from that symptom. The PCSS was administered prior to cognitive tests at both baseline and post-concussion evaluations.

Procedure

Athletes: Athletes have undergone both baseline and post-concussion assessment. Initial post-concussion assessments take place approximately 48-hours after the injury. Follow-up assessments are conducted as-needed, until the athletes' performance has returned to baseline-levels. For the purpose of the present study, only the initial post-concussion evaluation is considered. Baseline and post-injury evaluations are conducted by a Ph.D.-level clinical neuropsychologist, or a graduate or undergraduate assistant who has been trailed by a Ph.D.-level clinical neuropsychologist. Testing sessions take approximately 1.5 hours per evaluation, and also require approximately 30 minutes for paperwork, debriefing, and administration of other instruments not included in the present study.

Controls: Control participants were administered the same test battery and accompanying paperwork. Participants in this group were tested at two time points one month apart.

Approach to data analysis

Reliable change indices were calculated according to the method outlined by Jacobson and Truax (Jacobson & Truax, 1991) using test-retest data from the control group. A 90% confidence interval was selected as the criterion for determining reliable decline in performance post concussion. An index of *total impaired scores* was calculated by summing the total number of tests for which an individual demonstrated reliable decline.

Results

Reliability for each test index (R_{xx}), and the standard error of the difference between test and retest scores (S_{diff}) are reported in Table 2. Post-hoc analyses were conducted to check the alternate form reliability of the HVLT-R and the BVMT-R within this sample. ANOVA revealed that, at baseline, there was a significant difference between alternate forms for the BVMT-R immediate and delayed recall ($F = 4.02$, $p < .01$; and $F = 3.65$, $p < .05$, respectively), but not the HVLT-R ($F = 1.40$, $p = .24$ for immediate; and $F = .60$, $p = .64$ for delayed).

The frequency of the number of scores that reliably declined was examined in the athlete and control groups. In the athlete group, 52% of the sample had no scores that reliably declined post-injury, 14% exhibited reliable decline on one test, 14% reliably declined on two tests, and 20% reliably declined on 3 or more tests. In the control group, 69% of the sample had no scores that reliably declined at retest, 21% reliably declined on a single test, and 10% reliably declined on exactly two tests. No participants in the control group exhibited reliable decline on more than two tests.

In order to evaluate a possible influence of days since concussion on likelihood of exhibiting cognitive decline post-concussion, athletes who were tested within 48 hours of their injury were compared with those who were tested greater than 48 hours since their injury. These groups were not significantly different in total number of scores to reliably decline post-injury ($t = -.70$, $p = .47$). Hence this variable was not controlled for in subsequent analyses.

The sensitivity and specificity of 1, 2, or 3 reliably declined scores was examined in two ways—ability to distinguish between athletes and controls, and ability to distinguish between symptomatic athletes and a group comprised of controls and non-symptomatic. These results are reported in Table 2.3. As shown, specificity is very high when three or more tests reliably declined is used as the cut point.

Discussion

The present study examined the sensitivity and specificity of a neuropsychological test battery for identifying athletes with sports-related concussion. Reliable change indices were calculated using test-retest data obtained from a control group, in order to account for practice effects and the reliability of each test-index. Cut-points of one, two, and three reliably declined scores were examined. Furthermore, the target patient group was operationalized in two ways—as concussed athletes, and as concussed athletes who were also currently reporting post-concussion symptoms.

Results suggest that, within the control group, neuropsychological tests vary widely in their test-retest reliability, with a number of tests demonstrating inadequate reliability. Only four of the 12 test indices in the battery exhibited reliability coefficients greater than .60—theses tests were the Trail Making Task Trial 1, Trail Making Task Trial 2, Symbol Digit Modalities Test, and the Stroop Color-Word test. For all of the ImPACT composite scores, reliability was below .60. It is possible that this relatively low reliability is, in part, due to the influence of practice effects, or genuinely poor alternate form reliability. Importantly, for 5 out of 8 of the test indices that had test-retest reliability below .6, alternate forms were administered at retest. This hypothesis is somewhat supported by the fact that there were significant differences between alternate forms for the BVMT-R.

Using reliable decline from baseline, the battery exhibited excellent specificity and reasonable sensitivity to the neuropsychological effects of sports-related concussion. A cut-off of one or more reliably declined tests as the criterion for classification had the greatest sensitivity. This cut-off resulted in accurate classification of 44% of concussed athletes and 60% of symptomatic athletes. A cut-off of one or more declined scores also had reasonably good specificity, correctly classifying 69% of controls and 76% of controls plus asymptomatic athletes. Cut-offs of two or more and three or more reliably declined scores exhibited excellent specificity, resulting in correct classification of 90% and 100% of controls respectively, and 91% and 97% of those in the group of asymptomatic athletes and controls. However, these cut-offs were not particularly sensitive to concussion, classifying only 38% and 23% of symptomatic athletes, respectively.

In summary, these results support the utility of using neuropsychological tests for the diagnosis and management of sports-related concussion. Reliable decline on two or more test indices is very unusual in healthy controls; therefore, when these tests are administered to athletes post-concussion, such decline strongly suggests that an athlete is experiencing neuropsychological symptoms of concussion. A cut-off of one reliably declined score had the best combined sensitivity and specificity. This finding supports the use of this criterion for clinical and research purposes. Sixty percent of athletes who were currently reporting post-concussion symptoms were correctly identified using this criterion.

There are limitations of this study that bear noting. Firstly, the reliability of neuropsychological test indices was surprising low in some cases—specifically, for all of the ImPACT composite scores, and for the HVLT-R and BVMT-R immediate and delayed recall indices. Follow-up analyses suggested that there was poor alternate form reliability for the BVMT-R in the sample of control participants. The poor reliability of a number of tests within the control sample could be due to psychometric limitations of the aforementioned test indices, or idiosyncrasies of the present control sample. Another limitation of the present study is that all control participants were re-tested one month following their original test administration, whereas, athletes who were tested post-concussion were re-tested a mean of 457 days after their baseline test. It is quite possible that this between-group difference in interval between test sessions influenced neuropsychological test scores. Additionally, there were a number of other demographic and clinical characteristics that differed between the athlete and control groups—specifically, gender and ethnicity.

The poor reliability of a number of indices within the present sample is concerning, and further research should be done to evaluate the reliability of neuropsychological tests administered in settings analogous to a university-level sports-concussion management program. Despite this limitation, using reliable change indices, the test battery demonstrated good sensitivity and specificity to the effects of sports-related concussion, hence providing further support for the use of the SLAM paradigm for identifying and managing these injuries. Furthermore, these results suggest that reliable change scores can be used for clinical and research purposes, in order to account for psychometric influences on test-scores. Among these 12 test indices, a cut-point of one or more reliably declined scores had best combined sensitivity and specificity to sports-related concussion.

Table 2.1. Sample Characteristics

	Athlete	**Control**
% Male	79	49
% Caucasian	72	95
% ADHD	5	0
% LD	6	0
Age M(SD)	18.6(.8)	18.5(.8)

Table 2.2. Reliable Change Statistics

Test Index	**R_{xx}**	**Significant Change***
Trail Making Test 1	.80	18
Trail Making Test 2	.64	17
ImPACT Verbal Memory Composite	.35	25
ImPACT Visual Memory Composite	.58	24
ImPACT Visual Motor Speed Composite	.40	26
ImPACT Reaction Time Composite	.48	21
BVMT Delayed Recall	.38	16
BVMT Immediate Recall	.48	17
HVLT Delayed Recall	.24	23
HVLT Immediate Recall	.58	19
Symbol Digit Modalities Test	.81	14
Stroop Color-Word Time	.78	15

* Change in standard score points

Table 2.3. Sensitivity and Specificity

	Athletes vs. Controls			Symptomatic vs. Other		
	Sensitivity	Specificity	χ^2 sig	Sensitivity	Specificity	χ^2 sig
1 or more	0.44	0.69	0.18	0.60	0.76	0.00
2 or more	0.28	0.90	0.02	0.38	0.91	0.00
3 or more	0.18	1.00	0.00	0.23	0.97	0.00

Chapter 3. Paper 2: An exploratory analysis of cross-domain intraindividual cognitive variability pre- and post-sports related concussion

Clinical and research protocols designed to assess sports-related concussion and track its recovery have been implemented at the professional, collegiate, and high school level over the past 20 years. Barth and colleagues (1989) at the University of Virginia (UVA) were the first to develop the Sports as a Laboratory Assessment Model (SLAM) as an attempt to better characterize the neuropsychological impact of concussion and the trajectory of recovery. The UVA group was the first to conduct pre-concussion (baseline) neuropsychological assessment on athletes—a method that allows for the impact of the injury to be assessed directly (as change from baseline performance) rather than simply inferred based on cutoff scores or assumptions regarding premorbid functioning (Barth, et al., 1989). Today, baseline testing is becoming the gold standard in concussion management, and not surprisingly—an objective measure of athletes' premorbid cognitive abilities provides an ideal comparison standard for post-concussion assessment.

Some authors have drawn attention to issues that complicate straight-forward pre- post-injury test comparisons (Bailey, et al., 2006; Ragan & Kang, 2007; Randolph, et al., 2005). For example, pre-injury, many athletes' baseline cognitive performance defies the expectation that healthy intellectual functioning is consistent—"Given reasonably normal conditions of physical and mental development, there is one performance level that best represents a person's cognitive abilities and skills, generally" (Lezak, Howieson, & Loring, 2005). Intraindividual variability is a term that has been used to describe moment-to-moment fluctuations in state, or inconsistencies

(Ram, et al., 2005). Inconsistency in premorbid test performance complicates clinical interpretation—cognitive variability could be related to true idiosyncratic strengths and weaknesses, fluctuations in effort due to premorbid neurological vulnerabilities, or fluctuations in effort due to sub-optimal motivation. Distinguishing between these potential sources of cognitive inconsistency is crucial for valid assessment.

In the field of psychology, a science that is dominated by central-tendency, intraindividual variability has traditionally been characterized as error, instability, and noise. However, within the neuopsychological literature, a new and growing research interest in performance variability has already amassed impressive evidence suggesting that fluctuations in cognitive performance reflect more than random error and measurement unreliability, and, in fact, are often negatively correlated with mean levels of performance (Hultsch & MacDonald, 2004; Hultsch, Strauss, Hunter, & MacDonald, 2008). Research has linked increased variability with a number of clinical phenomena including aging, depression and anxiety, traumatic brain injury (TBI), attention deficit hyperactivity disorder (ADHD), and schizophrenia (see Macdonald, Li, & Backman, 2009 for review). Furthermore, there is some evidence suggesting that variability may be, in fact, more sensitive than mean level of performance in detecting cognitive decline—In a longitudinal study of cognitive aging, Lovden and colleagues (2007) found that changes in variability preceded measurable deficits in mean-level of performance (Lovden, Li, Shing, & Lindenberger, 2007).

These findings suggest that intraindividual variability is a promising indicator of disability. In order to elucidate the link between variability and disability, theoretical proposals have been put forth to explain the cognitive and neurobiological mechanisms that may lead to inconsistency in performance. At the cognitive level, variability has been attributed to lapses in attention (Bunce, Warr, & Cochrane, 1993), and failure to maintain executive control (West, Murphy, Armilio, Craik, & Stuss, 2002). At the neuroanatomical level, variability is thought to arise from inefficiencies in central nervous system (CNS) functioning. CNS inefficiencies may be related to disrupted neural connectivity (Kelly, Uddin, Biswal, Castellanos, & Milham, 2008), reduced efficacy of neurostransmitter systems (Backman, Nyberg, Lindenberger, Li, & Farde, 2006), structural damage to gray matter (Sowell et al., 2003; Stuss, Murphy, Binns, & Alexander, 2003), or loss of white-matter integrity (Anstey et al., 2007; Britton, Meyer, & Benecke, 1991; Walhovd & Fjell, 2007).

Investigators examining intraindividual inconsistencies in cognitive performance have operationalized performance variability in a number of ways. Some work has used intraindividual standard deviations taken from multiple trials within a single task (Ram, et al., 2005). Other studies have considered variability in performance on the same task on separate occasions (Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000). A few investigators have taken a cross-domain approach to intraindividual variability by examining within-person inconsistency in performance across different neuropsychological tests administered as part of a neuropsychological test-battery (Holtzer, Verghese, Wang, Hall, & Lipton, 2008; Kliegel & Sliwinski, 2000; Schretlen, Munro, Anthony, & Pearlson, 2003).

A cross-test approach to variability considers performance on a battery of neuropsychological tests, standardize these tests with reference to a common sample, and index the extent to which these scores deviate from each other using a variance parameter, like standard deviation. For example, take a neuropsychological battery that includes one test of verbal memory, one test of visual memory, one test of processing speed, and a test of attention. If a participant's scores on these tests, in standard score units, are 98, 105, 111, and 102, this participant's cross test-variability could be indexed by spread (13 standard score points), variance (30 standard score points), or standard deviation (5.48 standard score points).

A cross-test approach to intraindividual variability is appealing, because indices of cross-test variability can be derived from any neuropsychological battery. However, in order to interpret inconsistencies across a test battery as abnormal or meaningful, it must first be established that normal performance is consistent. From a theoretical perspective, there are reasons to posit that a given individual's test performance should have low variability under typical conditions, granted that an individual is non-injured, healthy, and developmentally normal. The concept of general intelligence (or Spearman's *g*) supports this assumption. Intraindividual consistency in cognitive behavior, subserved by IQ, is a foundational assumption underlying the deficit measurement paradigm in clinical neuropsychological assessment—a rubric for determining the presence of neuropsychological impairment by comparing an individual's test scores with a comparison standard. This comparison standard may be estimated based on population norms, premorbid test data, personal-historical information like academic performance or occupation, or indirectly from the current test findings and observations. The expectation that premorbid cognitive performance should be consistent justifies the use of a unitary comparison standard.

However, many have noted that environmental factors and personality differences can lead to intraindividual differences in intellectual skills. Research utilizing a cross-test variability approach has found evidence of marked performance variability in healthy adults (Schretlen, et al., 2003). Specialization of interests and activities, socialization experiences, personal expectations, educational limitations, or emotional disturbance could lead to inconsistencies in performance across cognitive domains (Halpern, 1997). Furthermore, recent research has demonstrated that, for normal healthy individuals, performance in the impaired range on at least one test index from a large neuropsychological battery is psychometrically normal (Binder, Iverson, & Brooks, 2009). This suggests that some level of cross-test variability is normative. Furthermore, there are many exceptions to the generality that cognitive behavior is consistent across situations. Few persons consistently function at their maximum potential for a variety of reasons, including factors like illness, educational deficiencies, impulsivity, test-anxiety, or disinterest (Lezak, Howieson, & Loring, 2005).

The present study aims to examine cognitive inconsistency within college athletes tested at baseline and post-concussion by examining the degree of intraindividual variability across the cognitive tests administered as part of a sports-concussion assessment battery. Because non-injured athletes are tested at baseline (before the start of team activities when they first arrive at the university) and also post-concussion, these data provide an opportunity to address the following questions: 1) How variable is cognitive performance in healthy non-injured persons; 2) what is the effect of cerebral concussion on intra-individual variability; and 3) what factors are related to cross-domain cognitive inconsistency before and after head-injury.

Method

Participants

Participants in the present study were 71 college athletes participating in the Penn State Concussion program, a multi-sport program that assesses participants prior to and following sports-related concussion (see Table 3.1 for characteristics of the sample). This program is designed according to the Sports as a Laboratory Assessment Model (SLAM; Barth, et al., 1989) paradigm, in order to provide objective neuropsychological test-data to team physicians to inform return-to-play decisions. Eight of the athletic programs at Penn State University regularly participate in baseline testing: Football, Men's and Women's Lacrosse, Men's and Women's Soccer, Men's and Women's Basketball, Men's Ice Hockey, and Wrestling. Post-concussion testing is provided for any Penn State athlete who sustains a head injury. Whenever possible, post-concussion assessment takes place within 48 hours of injury. Only athletes who had undergone both baseline and post-concussion assessment have been included in the present analyses.

Measures

The Penn State Concussion test battery consists of a number of measures that assess cognitive, physiological, and affective functioning. The measures include: the Hopkins Verbal Learning Test-Revised (HVLT-R; Benedict, et al., 1998), the Brief Visuospatial Memory Test-Revised (BVMT-R; Benedict, 1997), the Symbol-Digit Modalities Test (SDMT; Smith, 1982), the Digit Span Test (Wechsler, 1997), the PSU Cancellation Task, the Stroop Color-Word Test (SCWT; Trenerry, et al., 1989), and the Wechsler Test of Adult Reading (WTAR; The Psychological Corporation, 2001). For athletes who underwent multiple evaluations (baseline testing and one or more post-concussion evaluations), alternate forms of the HVLT-R, BVMT-R, SDMT, and PSU Cancellation Task were used (see Benedict et al., 1998; Benedict, 1997; and Smith, 1982, for alternate form reliability information). With the exception of the WTAR, all of these tests have been shown to be sensitive to traumatic brain injury in prior work (Bailey, et al., 2005; Bohnen, et al., 1992; Bruce & Echemendia, 2003; Ponsford & Kinsella, 1992; Vanderploeg, et al., 2005).

The Immediate Post-Concussion Assessment and Cognitive Testing computerized battery (ImPACT; Lovell, et al., 2000) was also used. Although complete validity data for the use of this test battery in sports related concussion have not yet been published, it assesses cognitive domains typically affected following such injury. The ImPACT (Lovell, et al., 2000) is a computerized test battery that was designed to offer a time-effective and standardized method for collecting data to assist in concussion assessment and management. The battery consists of three main parts: demographic data, neuropsychological tests, and the Post-Concussion Symptom Scale. Six neuropsychological tests are included, designed to target attention, memory, processing speed, and reaction time. From the six tests, five composite scores are derived: Verbal Memory, Visual Memory, Visuomotor Speed, Reaction Time, and Impulse Control. Studies in high school and college athletes have demonstrated that the ImPACT performance is correlated with performance on similar paper-and-pencil neuropsychological tests (Iverson, et al., 2005), and furthermore, ImPACT performance is sensitive to the acute effects of concussion (Schatz, et al., 2006).

The WTAR is a test of reading recognition that was designed for premorbid IQ estimation. The WTAR was developed and co-normed with the WAIS-III and WMS-III in both the US and the United Kingdom using the same large, representative sample of normally functioning adults. Using the normative data from the co-norming sample, WTAR scores can be converted to Full Scale IQ (FSIQ) estimates. Research has demonstrated that the WTAR has strong correlations (.70-.80) with WAIS-III Full Scale IQ scores for a wide age range of WTAR scores, and WTAR performance is relatively resistant to the effects of traumatic brain injury (The Psychological Corporation, 2001). WTAR scores are highly correlated with other accepted premorbid measures including the American National Adult Reading Test (.90), National Adult

Reading Test (.78), and the Wide Range Achievement Test – Revised Reading Test (.73). Test-retest reliability for the instrument is .92 for the 16-29 age group (The Psychological Corporation, 2001).

In addition to the neuropsychological tests, the battery includes a self-report measure of symptoms. The Post-Concussion Symptom Scale (PCSS) is a list of symptoms that are commonly associated with concussion, including items like headache, nausea, dizziness, trouble concentrating, and feeling "in a fog". Athletes rate the extent to which they are currently experiencing each symptom on a scale from 0-6, with 0 indicating the absence of the symptom, and 6 indicating extreme distress from that symptom.

Procedure

All 71 participants have undergone baseline and post-concussion testing, including the instruments described in detail above. Athletes may have been tested a number of times post-injury, depending on the course of their recovery and the team physician's referral. The majority of initial post-concussion assessments take place within one week of the head injury, and within 48 hours whenever possible. For the purpose of the present study, only the initial post-concussion evaluation is considered. Baseline and post-injury evaluations are conducted by a Ph.D.-level clinical neuropsychologist, or a graduate or undergraduate assistant who has been trailed by a Ph.D.-level clinical neuropsychologist. Testing sessions take approximately 1.5 hours per evaluation, and also require approximately 30 minutes for paperwork, debriefing, and administration of other instruments not included in the proposed study.

Approach to data analysis

Indices of overall performance and performance variability

Because the intent of the present study is to examine cross-test variability as an indicator of motivation at baseline and injury severity post-concussion, the index of variability should assess variability that is meaningful with respect to the individual, and eliminate, to the greatest extent possible, variability that is related to properties of the tests. For this purpose, a Principal Components Analysis was performed on the following test indices as assessed at baseline: Vigil-Total Omissions, Vigil-Total Comissions, Vigil-Average Delay, ImPACT Verbal Memory Composite, ImPACT Visual Memory Composite, ImPACT Visuomotor Speed Composite, ImPACT Reaction Time Composite, ImPACT Impulse Control Composite, BVMT-R Total Immediate Recall, BVMT-R Total Delayed Recall, HVLT-R Total Immediate Recall, HVLT-R Total Delayed Recall, SDMT- Total Correct, SDMT- Incidental Memory, DSF, DSB, SCWT-Stroop-W Time, SCWT-Stroop-CW Time, PSU Cancellation Test Total Correct, COWAT Total, TMT-Trial 1 Time, and TMT-Trial 2 Time. A priori, it was decided that all test-indices with component loadings on the first component greater than .4 would be retained for subsequent analysis, and Cronbach's α would be consulted to confirm the internal consistency of the retained indices at the aggregate level.

These retained indices were then used to calculate measures of *overall performance* and *performance variability*. First, all test indices were put on the same metric by converting them to standard scores (SSs). SSs have a mean of 100 and a standard deviation of 15. SS units have been chosen because this is the metric employed by many commonly used neuropsychological tests, including the Wechsler Adult Intelligence Scales Full Scale IQ score. The sample mean and sample standard deviation from the athletes tested at baseline was used to calculate SSs. Test-indices for which higher scores indicate poorer performance (i.e. Stroop-CW Time) were calculated by subtracting the observed score from the sample mean, so that for all SSs, higher scores indicate better performance.

Overall performance at baseline was calculated by taking the mean across all SS-converted retained test-indices for that individual at baseline. Similarly, o*verall performance* post-concussion was calculated by taking the mean across all SS-converted retained test-indices for that individual post-concussion. *Performance variability* at baseline was calculated by taking the standard deviation across all SS-converted retained test-indices for that individual at baseline. Similarly, *performance variability* post-concussion was calculated by taking the standard deviation across all SS-converted retained test-indices for that individual post-concussion.

Results

Thirty-one percent of athletes were evaluated within 48 hours of their concussion, 52% were tested within 72 hours, and 82% were tested within 10 days. In order to evaluate a possible influence of days since concussion on post-concussion neuropsychological test performance, athletes who were tested within 48 hours of their injury were compared with those who were tested greater than 48 hours since their injury. These groups were not significantly different in their likelihood as being classified as impaired, according to a criterion for impairment that is described elsewhere (see chapter 2 for details; $\chi^2 = .03$, $p = .86$). Hence this variable was not controlled for in subsequent analyses.

A list of the tests included and their component loadings can be found in Table 3.2. Cronbach's α was calculated using the retained indices in order to confirm consistency of these items at the aggregate level. This analysis suggested that the retained items have good internal consistency ($\alpha = 0.82$).

Based on those retained tests, indices of *overall performance* and *performance variability* were calculated as described above. Performance variability was significantly greater than 0 at baseline (M = 12.05; $t_{70} = 23.20$; $p < .001$) and post-concussion (M = 12.39; $t_{70} = 21.30$; $p < .001$). In order to examine the relationship between *performance variability* and other indices of cognitive functioning, bivariate correlations among *performance variability, overall performance,* and WTAR FSIQ estimate were examined. At baseline, *overall performance* was negatively correlated with *performance variability* ($r = -0.44$; $p < .001$). This negative relationship between *performance variability* and *overall performance* was also significant post-concussion ($r = -0.52$; $p < .001$). WTAR FSIQ estimate was significantly correlated with *overall performance*, but not *performance variability* at both time-points (see Table 3.3).

Paired sample t-tests revealed that *overall performance* and *performance variability* did not differ across time-points in the sample as a whole. For *overall performance* the mean difference between baseline and post-concussion assessments was .33 SS points in favor of the post-concussion assessment ($t_{70} = -0.30$; $p = 0.77$); similarly, for *performance variability* the mean difference between time-points was .33 SS points in favor of the post-concussion assessment ($t_{70} = -0.53$; $p = 0.60$).

Follow-up analyses: cluster analysis

Because there was no effect of concussion on overall performance or performance variability, cluster analysis was used to examine potential heterogeneity in the sample. Baseline and post-concussion *performance variability* indices were entered into a k-means cluster analysis where k was set equal to 2. Final cluster centers for cluster 1 (N = 46) were *baseline performance variability* = 10.4 SS points, and *post-concussion performance variability* = 9.6 SS points; whereas, cluster centers for cluster 2 (N = 25) were *baseline performance variability* = 15.3 SS points, and *post-concussion performance variability* = 17.6 SS points (these will be referred to subsequently as the *high variability cluster* and *low variability cluster*, respectively). A repeated measures ANOVA was conducted to examine a potential cluster by time-point interaction, which was confirmed (F = 5.77; p < 0.05). The nature of the effect is such that the *low variability cluster* demonstrated a slight decrease in *performance variability*, whereas the *high variability cluster* demonstrated an *increase* in *performance variability* post-concussion. This effect is illustrated in Figure 3.1.

In order to further examine the effect of concussion on neuropsychological performance and symptom reporting in these clusters, separate repeated measures ANOVAs were run using *overall performance* and PCSS score as dependent variables. Results indicated a significant main effect of cluster on *overall performance* (F = 21.18, p < .001), as well as a significant cluster by time-point interaction (F = 6.38; p < .05). The nature of this effect is such that the *low variability cluster* demonstrated a slight increase in *overall performance*, whereas the *high variability cluster* demonstrated a decrease in *overall performance*. With regard to PCSS score, there was no significant main effect of time-point, and no significant time-point by cluster interaction. There was a trend towards a main effect of cluster on PCSS score (F = 3.25; p = .076). These results are illustrated in Figure 3.1.

Post-hoc paired sample t-tests were conducted in order to further examine the significant cluster by time-point interactions. This analysis revealed that the *low variability cluster* exhibited a significant increase in *overall performance* post-concussion (t = -2.14, p < .05), but no significant change in *performance variability* (t = 1.12, p = .27). Whereas, the *high variability cluster* exhibited no significant change in *overall performance* post-concussion (t = 1.44, p = .16), but a trend towards a significant increase in *performance variability* (t = -1.96, p = .06).

The *high variability* and *low variability* clusters were not significantly different from each other with respect to self-reported previous head injuries (p = .97), WTAR FSIQ estimate (p = .16), or diagnosis of Attention Deficit Hyperactivity Disorder or Learning Disability (p = .14, and p = .29, respectively).

Discussion

The purpose of the present study was to examine intraindividual variability across cognitive tests in college athletes tested pre- and post-injury. These findings suggest that normative cognitive performance in college athletes is characterized by significant intraindividual variation across tests, on the order of nearly one standard deviation (12 SS points). Greater performance variability was unrelated to an estimate of intellectual functioning (WTAR FSIQ estimate), but was significantly related to lower mean-level of performance on the test battery. In the sample as a whole, there was no effect of concussion on either *performance variability* or *overall performance*. However, a cluster analysis revealed two clusters that predicted pre- and post-injury change in *overall performance* and *performance variability*.

Roughly two-thirds of the sample exhibited cognitive performance that was characterized by relatively low variability. Membership in this *low variability* cluster predicted a decrease in *performance variability* and an increase in *overall performance* post-concussion. This finding suggests that this group is most likely exhibiting a practice effect associated with prior exposure to the test battery, and this practice effect is characterized by increased *overall performance* and decreased *performance variability*. Roughly one-third of the sample exhibited cognitive performance that was characterized by relatively high variability. Membership in the *high variability* cluster predicted an increase in *performance variability* and a decrease in *overall performance* post-concussion. This finding suggests that this group is experiencing neurocognitive decline at the time of the post-concussion assessment as a result of the recent head injury—impairment that is characterized by a lower mean level of performance and greater intraindividual variability.

Taken together, these results suggest that there is a relationship between cross-test intraindividual variability and mean level of performance, such that, as performance improves cross-test variability decreases. This relationship between performance and inconsistency on a cross-domain level is consistent with previous work demonstrating a link between cross-test intraindividual variability and cognitive decline (Holtzer, et al., 2008; Kliegel & Sliwinski, 2000), as well as a larger body of research which has reported an inverse relationship between mean level of performance and intraindividual inconsistency within a single task (Hultsch & MacDonald, 2004; Hultsch, et al., 2008). The replication and extension of this finding at the cross-domain level has potential clinical relevance, because cross-test variability can be easily calculated within most typical neuropsychological batteries administered for clinical purposes.

Importantly, although *performance inconsistency* was significantly correlated with *overall performance,* it was not significantly correlated with an estimate of intellectual functioning. This suggests that the association between *performance inconsistency* and *overall performance* is independent of IQ. Furthermore, because all participants in this study were college students at the same institution, and hence, there are not gross educational discrepancies among these participants, one may further assume that the relationship between *performance inconsistency* and *overall performance* in this sample is independent of educational attainment. These observations suggest that intraindividual variability may be indexing an important cognitive process that cannot be fully explained by IQ or education. It is possible that this process is related to lapses in attention (Bunce, et al., 1993), failure to maintain executive control (West, et al., 2002), or inefficiencies CNS functioning (Holtzer, et al., 2008).

Although there was no effect of concussion on cognitive performance in the sample as a whole (neither *overall performance* nor *performance variability* changed significantly), cluster-membership based on *performance variability* was related to response to injury—with the *low variability* cluster demonstrating no signs of neurocognitive impairment in response to concussion and the *high variability* cluster demonstrating concussion-related neurocognitive impairment. There are a number of possible explanations for this finding. Intraindividual variability in the *high variability* group may indicate a level of premorbid vulnerability to injury. That is, this group may be more likely to experience neurological decline as a result of mild traumatic brain injury. The high and low variability clusters were not significantly different from each other with regard to self-report of previous head-injury, ADHD diagnosis, or LD diagnosis. These results suggest that any group differences in vulnerability to injury are not related to these particular premorbid conditions.

However, the validity of self-reported prior concussion has been called into question. Researchers have typically been unable to identify neuropsychological outcomes that are related to self-report of previous head injuries (Iverson, Brooks, Lovell, & Collins, 2006). There are a number of methodological concerns that may account for this unexpected phenomenon. Self-report of prior head injury may be an inaccurate index of true concussion history for a variety of reasons. Firstly, many athletes may fail to recognize when they have sustained a brain-injury. This could be due to inadequate information about the nature of a concussion or to an athletic culture that may minimize the significance of these injuries by referring to them as “dings” or “bell-ringers”. Furthermore, athletes participating in a sports-related concussion program may be hesitant to report previous injuries for fear that a positive concussion history may jeopardize their sports participation, or delay return-to-play if they do go on to sustain a concussion during their involvement in the program.

It is also likely that simply the number of previous concussions, no matter how accurate this number may be, is too imprecise a measure of prior brain-trauma. The number of previous head injuries fails to capture important clinical features of concussion; for example, injury severity, the amount of time between injuries, and age at the time of injury, just to name a few. It is also quite possible that chronic subconcussive blows to the head, which are difficult to quantify retrospectively, may have a cumulative impact on neurological functioning. For these reasons, history of head trauma cannot be ruled out as a possible mechanism of premorbid intraindividual variability.

Genetic factors may constitute another possible source of intraindividual variability and premorbid vulnerability to head-trauma. Observed heterogeneity in response to concussion has lead many researchers to suspect that there may be a genetic predisposition that affects metabolic activity in the brain, and hence, concussion severity. Although this area of inquiry is relatively new, investigators have begun to consider the gene that codes for the protein apolipoprotein E (ApoE), which plays an essential role in lipoprotein metabolism. The APOE gene is polymorphic with three major isoforms, ApoE2, ApoE3, and ApoE4. The ApoE-ε4 allele has been associated with Alzheimer’s disease, and is under investigation in a number of other neurodegenerative disorders. There is evidence that the ApoE-ε4 alelle is also associated with negative long-term outcomes related to chronic mild traumatic brain injury (Guskiewicz et al., 2005; Kutner, Erlanger, Tsai, Jordan, & Relkin, 2000), and recent research suggests that genetic factors related to ApoE functioning may be related to risk for concussion in college athletes (Terrell et al., 2008). The extent to which ApoE-ε4 may be related to premorbid intraindividual variability remains an empirical question, as does the extent to which this allele may confer risk for injury severity after head trauma. Both of these issues have important clinical relevance and warrant further study.

Athletes' approach to testing could be another possible explanation for the difference between clusters. It may be the case that higher levels of intraindividual variability are related to poor effort towards testing. In the high variability group, suboptimal motivation at baseline may interfere with athletes' ability to benefit from prior exposure to the battery and demonstrate a practice effect at the post-injury assessment. It is not surprising that a subset of athletes may exhibit suboptimal motivation during the baseline assessment. At baseline, athletes may undervalue the importance of putting forth adequate effort. They may fail to see the significance of baseline concussion testing, or they may regard the testing session as an imposition. It is also possible that some athletes could purposefully under-perform at baseline, in order to decrease their chances of being evaluated as impaired post-concussion. This notion has been supported by work by Bailey and colleagues demonstrating that some athletes exhibit improved cognitive performance in response to concussion (Bailey, et al., 2006).

On the other hand, the *low variability* group may be highly motivated at baseline. In this group, practice effects may mask any neurocognitive impairment related to mild and uncomplicated concussions. Prior research has demonstrated that, within a single task, intraindividual variability in reaction time decreases with repeated exposure to the task, suggesting that decreased inconsistency is a hallmark of practice (Ram, Rabbitt, Stollery, & Nesselroade, 2005). Hence, one possible explanation for the present findings is that baseline motivation moderates the impact of prior exposure to the battery on post-injury performance. It should be noted that this hypothesis does not exclude the possibility that performance inconsistency is also related to premorbid neurological vulnerability.

There are limitations of the present study that bear noting. Firstly, with 71 participants, it is possible that this study was underpowered to detect small to moderate effects—particularly with regard to group differences between the *high variability* and *low variability* clusters. Furthermore, self-report of important clinical variables like history of premorbid conditions, previous concussions, and post-concussion symptoms are subject to biases. A more objective examination of the relationship between these variables and intraindividual variability is warranted. Finally, the present study is exploratory in nature. Intrainidivual variability in cognitive performance is a relatively new area of research, and cross-domain inconsistency has not thus far been evaluated for its potential clinical and theoretical relevance in concussion.

The aim of the present study was two-fold: 1) to describe cross-test intraindividual variability in a sample of college athletes before and after sports-related head-injury; and 2) to begin to explore potential correlates of this cognitive inconsistency. Future studies evaluating some of the specific hypotheses discussed above—cognitive inconsistency as an index of genetic vulnerability, cognitive inconsistency as an index of previous head-trauma, and cognitive inconsistency as an index of suboptimal motivation—are necessary in order to determine the potential theoretical significance and clinical utility of cross-test intraindividual variability in sports-related concussion assessment.

Table 3.1. Characteristics of the sample

Clinical & Demographic Characteristics		Sport	
Age at baseline	18 (.9)	Football	38%
Female	21%	Men's Ice Hokey	14%
Caucasian American	68%	Men's Lacrosse	13%
African American	25%	Women's Soccer	10%
ADHD diagnosis	6%	Women's Lacrosse	7%
LD diagnosis	3%	Men's Basketball	3%
Previous Head Injuries		Men's Soccer	4%
Denied	51%	Wrestling	4%
1	34%	Women's Basketball	3%
2 or more	14%		

Table 3.2. Retained test indices and their component loadings.

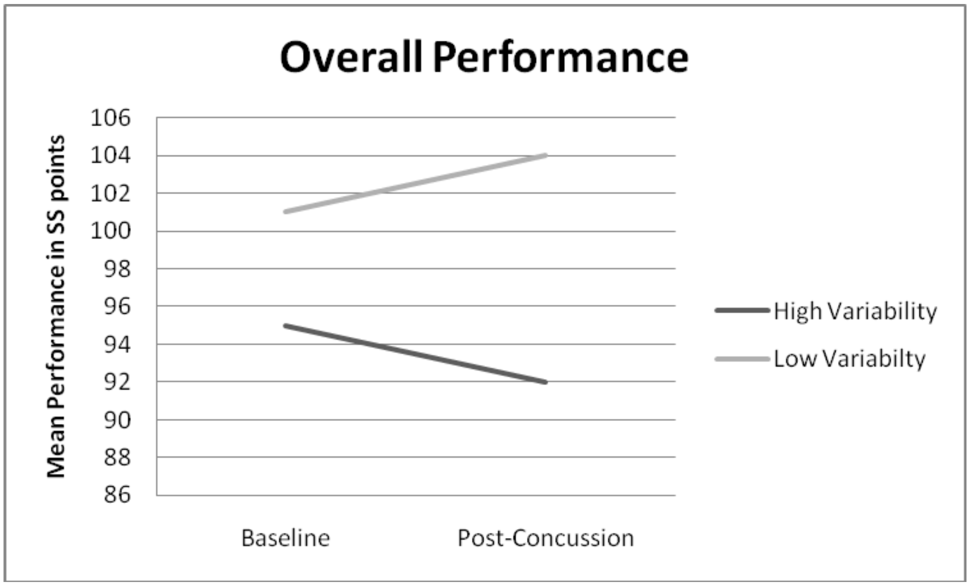
Test Index	**Component 1 loading**
Trail Making Test 1	.41
Trail Making Test 2	.57
ImPACT Verbal Memory Composite	.41
ImPACT Visual Memory Composite	.64
ImPACT Visual Motor Speed Composite	.76
ImPACT Reaction Time Composite	.67
BVMT Delayed Recall	.62
HVLT Delayed Recall	.46
Symbol Digit Modalities Test	.54
Stroop Color-Word Time	.63

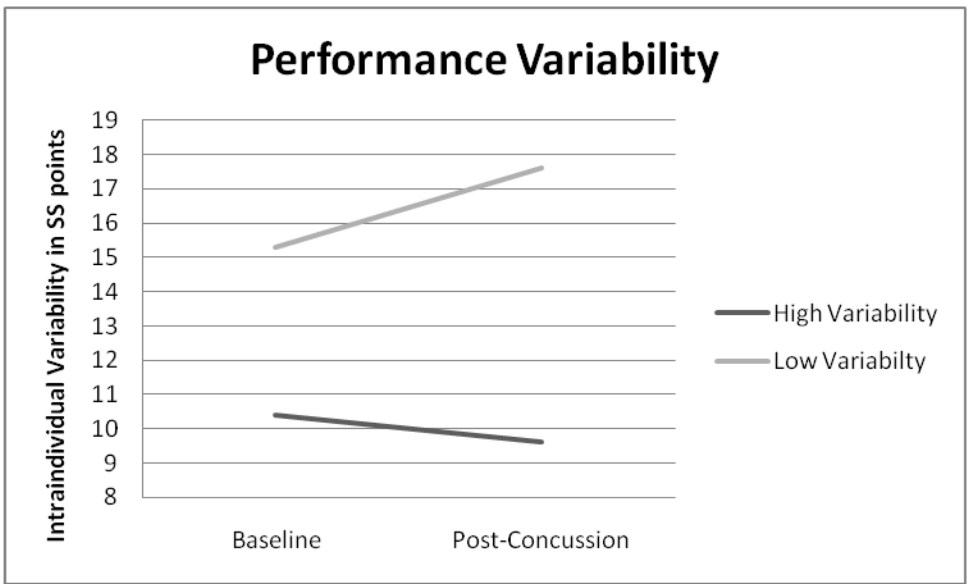
Table 3.3. Correlations.

	1	2	3	4
1. Baseline Overall Performance	--	--	--	--
2. Baseline Performance Variability	-.44**	--	--	--
3. Post-Concussion Overall Performance	.61**	-.30*	--	--
4. Post-Concussion Performance Variability	-.27	.36*	-.52**	--
5. WTAR FSIQ Estimate	.38**	-.03	.46**	-.14

**.Correlation is significant at the .01 level (2-tailed)
*.Correlation is significant at the .05 level (2-tailed)

Figure 3.1. Cluster by time point interactions.





Chapter 4. Paper 3: The influence of motivation on neuropsychological test-performance before and after sports-related concussion: Implications for neurological vulnerability to injury

Baseline testing is becoming the gold standard in return-to-play decision-making following sports-related concussion. Although there are clear advantages to having objective premorbid test data, those who work with athletes have been quick to note that an athlete's approach to testing can be dramatically different during the baseline and post-concussion assessments. Athletes post-concussion are often highly motivated to return-to-play, and eager to demonstrate to the assessor that they are functioning well. However, at baseline, it is sometimes the case that athletes are less engaged in cognitive testing. They may even view the testing session as a nuisance or an imposition. The aim of the present study is to evaluate the extent to which differences in motivation across assessments may influence athletes' test performance and complicate test interpretation.

There are a number of known deleterious outcomes related to misdiagnosis and mismanagement of sports related concussion. The most serious of these conditions is second-impact syndrome (SIS)—diffuse cerebral swelling caused by incurring a second head injury before an initial injury has completely resolved. SIS, although rare, has a mortality rate approaching 100%, and so, this possible outcome is taken very seriously. In fact, many return-to-play guidelines have been developed precisely to avoid catastrophic outcomes like SIS. More is being discovered regarding possible long-term negative outcomes associated with sports-related concussion. Chronic traumatic encephalopathy (CTE) is a neurodegenerative disorder that, until recently, was thought to only afflict boxers. Symptoms of CTE can include profound cognitive, motor, emotional, and personality disturbance. Recent research has uncovered evidence of this condition in professional football and hockey players (Cantu, 2007; Schwarz, 2011; Schwarz & Klien, 2011). Newly identified CTE cases are reported by the popular press with increasing frequency. Recently, a University of Pennsylvania college football player tragically committed suicide, likely as a result of mood changes secondary to sports-related head injuries (Schwarz, 2010). These findings have drawn attention to the seriousness of these so-called “minor” injuries.

Baseline cognitive testing provides clinical neuropsychologists with a coveted opportunity for test-interpretation; the advantages of using an athlete’s baseline assessment results as the point of comparison for determining injury impact are clear. However, some authors have drawn attention to issues that complicate straight-forward pre- post-injury test comparisons (Bailey, et al., 2006; Ragan & Kang, 2007; Randolph, et al., 2005). For example, as mentioned previously, differential motivation during baseline testing and post-concussion assessments may complicate test interpretation. Sub-optimal motivation during baseline testing could lead to invalid conclusions regarding the athlete’s true level of premorbid functioning (Bailey, et al., 2006). In fact, data presented by Bailey and colleagues demonstrates that there are some athletes who exhibit improved performance post-concussion relative to their baseline scores, strongly suggesting that, for some athletes, the baseline assessment under-represents their true premorbid abilities.

It is not surprising that athletes may experience changes in motivation across pre- and post-injury testing. Post-injury, athletes are aware that their neuropsychological test-data will be used to inform return-to-play decisions, and many athletes may be highly motivated to return to play as soon as possible. There are both social and personal implications of taking time out from sports participation. Athletes may be concerned that sitting out games due to injury will be viewed by teammates or coaches as a disappointment. Time away from participation could have implications for an individual's athletic career, social status, or identity as an athlete. Furthermore, the potential vulnerability of neurocognitive functioning can be difficult for anyone to accept, perhaps young healthy individuals in particular. Hence, there are many reasons to suspect that the desire to avoid news of cognitive decline may influence athletes' approach to testing.

A high level of motivation during neuropsychological assessment is, of course, desirable. In fact, the ability to attribute deficits in performance to injury rests on the assumption that subjects are adequately motivated during testing. Clearly, a highly motivated approach to post-concussion testing is not inherently problematic. However, concern arises because the factors that increase motivation post-injury are not present at the time of baseline assessment. At baseline, athletes may undervalue the importance of putting forth adequate effort. They may fail to see the significance of baseline concussion testing, or they may regard the testing session as an imposition. It is also possible that some athletes could purposefully under-perform at baseline, in order to decrease their chances of being evaluated as impaired post-concussion.

Although it is likely that motivation-related-differences between baseline and post-concussion contexts influence all athletes to some extent, it may be the case that there are important individual differences in the extent to which athletes are sensitive to this change. For example, it is likely that many athletes exhibit adequate motivation at baseline, and hence, their test results provide a valid estimate of their premorbid ability. However, there may be a subset of athletes who exhibit suboptimal motivation at baseline. For these athletes, a comparison of pre- and post-concussion test performance may be invalid, because baseline test-performance could underestimate true premorbid functioning. If this were indeed the case, distinguishing between athletes who are adequately and sub-optimally motivated would have important implications for valid assessment. Underestimation of an athlete's true pre-injury abilities undermines the assessor's ability to detect true decline, thus increasing the chance that a vulnerable athlete returns to play prematurely, risking further injury.

There is an extensive body of literature on the influence of poor effort towards testing on neurocognitive test performance in the context of external incentives, like financial compensation (Iverson & Binder, 2000). However, suboptimal motivation may be a qualitatively different phenomenon from malingering. In the case of frank malingering, an examinee deliberately fakes poor performance for some secondary gain. It is certainly possible that some athletes may malinger at baseline in order to increase their chances of quickly returning to play should they later sustain a concussion. It is probably more common, however, for athletes to exhibit suboptimal effort towards testing in spite of approaching the assessment in an honest and straightforward way. It is likely that these distinct processes—malingering versus inadequate motivation—may have a quantitatively and qualitatively different influence on neuropsychological test performance.

Motivation may be conceptualized as the intentional antecedent that modulates attentional effort. Attentional effort has been defined as a cognitive incentive on attentional performance (Berridge & Robinson, 2003). Dependent on level of motivation, an individual will increase attentional effort in response to detrimental mechanisms or events in order to optimize goal-directed behavior and cognitive processes (Sarter, Gehring, & Kozak, 2006). Detrimental mechanisms are likely to be encountered during any cognitive test battery, and can include events and experiences such as distractors, fatigue, or simply prolonged time-on-task. Sarter and colleagues propose that attentional effort is modulated by a top-down supervisory system (Sarter, et al., 2006). This supervisory system could be thought of as a central executive control (Baddeley, 1986) or the anterior attention network (Posner, 1994; Posner & Dehaene, 1994).

The results of a recent study suggest that motivation thusly defined could influence performance on tests of intellectual ability (Duckworth, Quinn, Lynam, Loeber, & Stouthamer-Loeber, 2011). The present study aims to examine the impact of motivation on athletes' cognitive test performance at baseline. Examiners' rating of effort toward testing will be used to predict athletes' overall level of performance, performance inconsistency (cross-test intraindividual variability), and discrepancy between overall level of performance and an estimate of premorbid IQ. Furthermore, the impact of suboptimal motivation on post-injury clinical decision-making will also be examined. Baseline motivation will be used to predict the likelihood of demonstrating post-concussion neurocognitive impairment, operationalized as significant reliable decrements relative to baseline performance. If suboptimal motivation at baseline leads to an underestimation of athletes' true premorbid abilities, one would expect that suboptimally motivated athletes would be less likely to exhibit concussion-related neurocognitive impairment, relative to their baseline.

Method

Participants

Participants in the present study are 638 college athletes participating in the Penn State Concussion program, a multi-sport program that assesses participants prior to and following sports-related concussion, as well as 42 control participants (see Table 4.1 for characteristics of the sample). Control participants are Penn State students who participate in athletic activities at the intramural level, but do not participate in the Sports Concussion program. This program is designed according to the Sports as a Laboratory Assessment Model (SLAM; Barth, et al., 1989) paradigm, in order to provide objective neuropsychological test-data to team physicians to inform return-to-play decisions. Eight of the athletic programs at Penn State University regularly participate in baseline testing: Football, Men's and Women's Lacrosse, Men's and Women's Soccer, Men's and Women's Basketball, Men's Ice Hockey, and Wrestling. Post-concussion testing is provided for any Penn State athlete who sustains a head injury. Whenever possible, post-concussion assessment takes place within 48 hours of injury. All athletes who have undergone baseline or post-concussion assessment are included in the present study.

Measures

The Penn State Concussion test battery consists of a number of measures that assess cognitive, physiological, and affective functioning. The measures include: the Hopkins Verbal Learning Test-Revised (HVLT-R; Benedict, et al., 1998), the Brief Visuospatial Memory Test-Revised (BVMT-R; Benedict, 1997), the Symbol-Digit Modalities Test (SDMT; Smith, 1982), the Digit Span Test (Wechsler, 1997), the PSU Cancellation Task, and the Stroop Color-Word Test (SCWT; Trenerry, et al., 1989), and the Wechsler Test of Adult Reading (WTAR; The Psychological Corporation, 2001). For athletes who underwent multiple evaluations (baseline testing and one or more post-concussion evaluations), alternate forms of the HVLT-R, BVMT-R, SDMT, and PSU Cancellation Task were used (see Benedict et al., 1998; Benedict, 1997; and Smith, 1982, for alternate form reliability information). With the exception of the WTAR, all of these tests have been shown to be sensitive to traumatic brain injury in prior work (Bailey, et al., 2005; Bohnen, et al., 1992; Bruce & Echemendia, 2003; Ponsford & Kinsella, 1992; Vanderploeg, et al., 2005). The Immediate Post-Concussion Assessment and Cognitive Testing computerized battery (ImPACT; Lovell, et al., 2000) was also used. Although complete validity data for the use of this test battery in sports related concussion have not yet been published, it assesses cognitive domains typically affected following such injury.

The ImPACT (Lovell, et al., 2000) is a computerized test battery that was designed to offer a time-effective and standardized method for collecting data to assist in concussion assessment and management. The battery consists of three main parts: demographic data, neuropsychological tests, and the Post-Concussion Symptom Scale. Six neuropsychological tests are included, designed to target attention, memory, processing speed, and reaction time. From the six tests, five composite scores are derived: Verbal Memory, Visual Memory, Visuomotor Speed, Reaction Time, and Impulse Control. Studies in high school and college athletes have demonstrated that the ImPACT performance is correlated with performance on similar paper-and-pencil neuropsychological tests (Iverson, et al., 2005), and furthermore, ImPACT performance is sensitive to the acute effects of concussion (Schatz, et al., 2006).

The WTAR is a test of reading recognition that was designed for premorbid IQ estimation. The WTAR was developed and co-normed with the WAIS-III and WMS-III in both the US and the United Kingdom using the same large, representative sample of normally functioning adults. Using the normative data from the co-norming sample, WTAR scores can be converted to Full Scale IQ (FSIQ) estimates. Research has demonstrated that the WTAR has strong correlations (.70-.80) with WAIS-III Full Scale IQ scores for a wide age range of WTAR scores, and WTAR performance is relatively resistant to the effects of traumatic brain injury (The Psychological Corporation, 2001). WTAR scores are highly correlated with other accepted premorbid measures including the American National Adult Reading Test (.90), National Adult Reading Test (.78), and the Wide Range Achievement Test – Revised Reading Test (.73). Test-retest reliability for the instrument is .92 for the 16-29 age group (The Psychological Corporation, 2001).

In addition to the neuropsychological tests, the battery includes a self-report measure of symptoms. The Post-Concussion Symptom Scale (PCSS) is a list of symptoms that are commonly associated with concussion, including items like headache, nausea, dizziness, trouble concentrating, and feeling “in a fog”. Athletes rate the extent to which they are currently experiencing each symptom on a scale from 0-6, with 0 indicating the absence of the symptom, and 6 indicating extreme distress from that symptom. At the end of the test session, examiners rate the level of motivation exhibited by the athlete on a 1-7 scale, with 1 indicating that the athlete was “not trying at all”, and 7 indicating that the athlete was “trying as hard as they can”. Examiners’ were instructed to rate effort towards testing as dissociable from actual test performance. All raters were blind to the hypotheses under investigation.

Procedure

Athletes: Six-hundred and thirteen athletes have undergone baseline testing, including the instruments described in detail above. Participants in the post-concussion group (N=48) have all undergone baseline assessment. These participants may have been tested a number of times post-injury, depending on the course of their recovery and the team physician’s referral. The majority of initial post-concussion assessments take place within one week of the head injury, and within 48 hours whenever possible. In this sample, 36% of participants were tested within 48 hours, and 74% were tested within one week. For the purpose of the present study, only the initial post-concussion evaluation is considered. Baseline and post-injury evaluations are conducted by a Ph.D.-level clinical neuropsychologist, or a graduate or undergraduate assistant who has been trailed by a Ph.D.-level clinical neuropsychologist. Testing sessions take approximately 1.5 hours per evaluation, and also require approximately 30 minutes for paperwork, debriefing, and administration of other instruments not included in the proposed study.

Controls: Control participants were administered the same test battery and accompanying paperwork. Participants in this group were tested at two time points one month apart. See Table 4.1 for characteristics of this sample.

Approach to data analysis

Indices of overall performance and performance inconsistency

Baseline test-performance was examined with regard to both overall level of performance and performance inconsistency. In order to obtain a meaningful summary index, a Principal Components Analysis was performed on the following test indices as assessed at baseline: Vigil- Total Omissions, Vigil- Total Comissions, Vigil- Average Delay, ImPACT Verbal Memory Composite, ImPACT Visual Memory Composite, ImPACT Visuomotor Speed Composite, ImPACT Reaction Time Composite, ImPACT Impulse Control Composite, BVMT- Total Immediate Recall, BVMT- Total Delayed Recall, HVLT- Total Immediate Recall, HVLT- total Delayed Recall, SDMT- Total Correct, SDMT- Incidental Memory, DSF, DSB, SCWT- Stroop-W Time, SCWT- Stroop-CW Time, PSU Cancellation Test Total Correct, COWAT Total, TMT- Trial 1 Time, and TMT- Trial 2 Time. A priori, it was decided that all test-indices with component loadings on the first component greater than .4 would be retained for subsequent analyses and Cronbach's α would be consulted to confirm the internal consistency of the retained indices at the aggregate level.

These retained indices were then used to calculate measures of *overall performance* and *performance variability*. First, all test indices were put on the same metric by converting them to standard scores (SSs). SSs have a mean of 100 and a standard deviation of 15. SS units have been chosen because this is the metric employed by many commonly used neuropsychological tests, including the Wechsler Adult Intelligence Scales Full Scale IQ score. The sample mean and sample standard deviation from the athletes tested at baseline was used to calculate SSs. Test-indices for which higher scores indicate poorer performance (i.e. Stroop-CW Time) were calculated by subtracting the observed score from the sample mean, so that for all SSs, higher scores indicate better performance.

Overall performance at baseline was calculated by taking the mean across all SS-converted retained test-indices for that individual at baseline. *Performance variability* at baseline was calculated by taking the standard deviation across all SS-converted retained test-indices for that individual at baseline. *IQ-performance discrepancy* was calculated by subtracting the *overall performance* index from the WTAR FSIQ estimate. This index summarizes the average discrepancy between a participant's WTAR FISQ estimate and their actual premorbid neuropsychological test performance at baseline.

Post-Concussion Impairment

In order to operationalize impairment post-concussion, reliable change indices were calculated. Reliability statistics were calculated based on the control group. A 90% confidence interval was selected as the criterion for determining reliable decline in performance post concussion. An index of *total impaired scores* was calculated by summing the total number of tests for which an individual demonstrated reliable decline. Frequency statistics for *total* *impaired scores* in athletes and controls were consulted in order to determine a reasonable threshold for dividing athletes into two groups—those evidencing post-concussion neurocognitive decline *(impaired)*, and those whose scores do not indicate neurocognitive decline *(unimpaired)*.

Results

Baseline Analyses

A list of the tests included and their component loadings can be found in Table 4.2. Cronbach's α was calculated using the retained indices in order to confirm consistency of these items at the aggregate level. This analysis suggested that the retained items have good internal consistency ($\alpha = 0.82$).

Athletes at baseline were divided into three groups based on examiners' ratings of motivation on a seven point scale: motivation rating less than or equal to four (*low motivation*, $n = 67$), motivation rating five or six (*adequate motivation*, $n = 381$), and motivation rating equal to seven (*high motivation,* $n = 165$). MANOVA results revealed that there was a significant multivariate effect of motivation group on the three dependent variables: *overall performance, performance inconsistency,* and *IQ-performance discrepancy* (Pilai's Trace $F = 6.7$, $p < .001$). The tests of between subjects effects revealed a significant between univariate group effect of motivation rating on *overall performance* ($F = 18.7$, $p < .001$, Cohen's $d = .50$), *performance inconsistency* ($F = 4.0$, $p < .05$, Cohen's $d = .23$), and *IQ-performance discrepancy* ($F = 8.1$, $p < .001$, Cohen's $d = .34$).

Custom hypothesis tests using a difference contrast were consulted to further examine the nature of these effects, and results indicated that there were significant differences between the *adequate* and the *high motivation groups* with regard to *overall performance* (a difference of 4.6 SS points, $p < .001$), *performance inconsistency* (a difference of 1.4 SS points, $p < .05$), and *IQ-performance discrepancy* (a difference of 3.6 SS points, $p < .005$). These effects were such that the *high motivation group,* relative to the *adequate motivation group* demonstrated higher scores on the *overall performance* index, they had lower scores on the *performance inconsistency* index, and they exhibited less discrepancy between their actual premorbid neuropsychological test performance and their WTAR FSIQ-estimate.

Furthermore, there were significant differences between the *adequate motivation group* and the *low motivation group* with regard to *overall performance* (a difference of 5.2 SS points, $p < .001$), *performance inconsistency* (a difference of 0.9 SS points, $p < .05$), and *IQ-performance discrepancy* (a difference of 3.3 SS points, $p < .001$). That is, the *adequate motivation group* had higher scores on the *overall performance* index, lower scores on the *performance inconsistency* index, and they exhibited less discrepancy between their premorbid neuropsychological test performance and their WTAR FSIQ-estimate.

In attempt to minimize the influence of examiners' impressions of test-performance on their motivation ratings, follow-up analyses were conducted using computer tests for which the examiners had no access to athletes' performance. Multivariate analysis of variance was conducted using only the ImPACT composite scores as dependent variables—the Verbal Memory Composite, the Visual Memory Composite, the Visual Motor Speed Composite, and the Reaction Time Composite. Results revealed that there was a multivariate effect of *motivation group* on ImPACT performance (Pillai's Trace $F = 6.6$, $p < .001$). Post-hoc tests revealed that for each composite score, there was a significant difference among the three motivation groups (F = 14.6, 10.2, 12.5, and 8.2 respectively; p < .001 for all ANOVA tests). For all indices the *high motivation group* exhibited the highest composite scores (ranging from a mean of 102 SS points on the Visual Motor Speed Composite to a mean 105 SS points on the Verbal Memory Composite) and the *low motivation group* exhibited the lowest composite scores (ranging from a mean of 91 SS points on the Visual Motor Speed Composite to a mean of 94 SS points on the Reaction Time Composite). See Table 4.3 for the complete results of Tukey post-hoc multiple comparisons.

Post-concussion Analyses

In order to evaluate the influence of return-to-play incentive on motivation, a repeated measures ANOVA predicting examiner motivation ratings was constructed using group (athletes versus controls) as a between subjects factor and time (baseline versus post-concussion for athletes; and test versus retest for controls) as a within subjects factor. These results revealed no significant main effects for group (F = 0.0, p = .94) or time (F = 1.2, p = .29). However, there was a significant group by time interaction (F = 4.9, p < .05). This effect was such that athletes exhibited an increase in motivation rating at the second time point (post-concussion; t = 2.2, p < .05), whereas, controls exhibited no significant change in motivation ratings across time points (t = -1.1, p = .27).

A cut-point of one or more reliably declined scores was selected as the criterion for dividing athletes post-concussion into *impaired* and *unimpaired* groups (see Chapter 1).

In order to evaluate a possible influence of days since concussion on likelihood of being classified as impaired, athletes who were tested within 48 hours of their injury were compared with those who were tested greater than 48 hours since their injury. These groups were not significantly different in their likelihood as being classified as impaired (χ^2 = .03, p = .86). Hence this variable was not controlled for in subsequent analyses.

A logistic regression model predicting post-concussion impairment was constructed in order to examine the impact of baseline motivation on the detection of concussion-related cognitive deficits post-injury. As described above, post-concussion impairment was operationalized as exhibiting reliable decline on one or more test indices. Of the 52 athletes who were tested both at baseline and post-concussion, 25 athletes met these criteria for impairment. Presence of post-concussion symptoms was entered into the first block of the regression model. This block significantly improved model fit above and beyond the null model ($\chi^2(1) = 11.8$; $p < .005$), and accounted for approximately 28% of the variance in classification (Nagelkerke R^2 = .28).

In order to test whether indicators of motivation would improve prediction, baseline *motivation group* was entered into the model. For the purpose of this model, the *adequate* and *high motivation* groups were collapsed into one group, as it was hypothesized that inadequate motivation specifically would influence the ability to detect post-concussion impairment. The second regression block significantly improved model fit over the null-model ($\chi^2(2) = 16.1$; $p < .001$), and the restricted model ($\chi^2(1) = 4.3$; $p < .05$), and accounted for approximately 36% of the variance in classification (Nagelkerke R^2 = .36). These effects were such that, reporting post-concussive symptoms increased the odds of being classified as impaired post-concussion (odds ratio, *OR* = 22, Wald = 7.9, $p < .01$) and being rated as adequately or highly motivated decreased the odds of being classified as impaired post-concussion (*OR* = .1, Wald = 3.2, $p < .1$).

Discussion

The aim of the present study was to examine the influence of suboptimal motivation on neuropsychological test-performance within the context of a collegiate sports-concussion management program. Examiners' ratings of athletes' motivation during the baseline assessment were considered in relation to neuropsychological test-performance cross-sectionally, and also in relation to post-injury decrements in test performance.

The present findings suggest that athletes experience a change in motivation across assessments, and motivation significantly impacts performance on neurocognitive tests at baseline. The cross-sectional analysis revealed that examiners' ratings of motivation were significantly related to concurrent *overall performance* (Cohen's d = .50) and *performance inconsistency* (Cohen's d = .23) on the test-battery, with those who were given the highest motivation rating exhibiting the highest mean-level of performance and the least variable performance, and those receiving lower motivation ratings exhibiting relatively worse and more variable test performance. Examiners' ratings of motivation were also modestly related to the discrepancy between athletes' mean-level of performance and the WTAR-FSIQ estimate (Cohen's d = .34), with those in *high motivation* group exhibiting the least discrepancy between WTAR-FSIQ estimate and neuropsychological test performance, and those in the *low motivation* group exhibiting the greatest discrepancy. Taken together, these results reveal a small to moderate association between observation-based ratings of motivation and concurrent neurocognitive test performance. These cross-sectional findings suggest that, for those athletes who are rated as sub-optimally motivated at baseline, baseline test-results represent an underestimate of true premorbid abilities.

Although the post-injury results support the notion that baseline motivation is related to post-injury cognitive decline, this effect was not in the predicted direction. Examiners' baseline motivation ratings significantly improved prediction of neuropsychological decline post-concussion. It was hypothesized that individuals exhibiting suboptimal motivation at baseline would be less likely to be classified as impaired post-concussion, for the reason that their baseline performance would be an underestimate of their true premorbid abilities. Contrary to this hypothesis, the logistic regression results suggest that membership in the *low motivation* group at baseline actually *increased* the odds that individuals would be classified as impaired post-concussion. This suggests that suboptimal motivation at baseline did not interfere with the test battery's ability to detect neurocognitive impairment post-concussion. Rather, these results indicate that poor motivation at baseline may reflect an underlying risk factor for concussion related impairment.

Taken together, the present findings reveal a complex relationship between motivational factors and performance on neuropsychological tests. The results of the baseline analyses suggest that athletes' level of motivation is associated with performance on neurocognitive tests. Those who were rated as sub-optimally motivated exhibited a cognitive profile indicating that baseline test results underestimate their true premorbid abilities. However, the results of the post-concussion analyses indicate that these individuals were actually *more likely* to exhibit performance decrements post-injury. Consideration of the attentional effort definition of motivation may shed light on this seemingly counterintuitive finding.

As discussed previously, one way of understanding a relationship between motivation and neuropsychological test performance is by considering a top-down regulatory system, i.e. the central executive control system (AD Baddeley, 1986), that modulates attentional effort in order to achieve some goal-directed behavior. Dependent on level of motivation, an individual will increase attentional effort in response to detrimental mechanisms or events, such as distraction, fatigue, or boredom (Sarter, et al., 2006). In the course of a two-hour test battery, it is likely that all individuals will experience mechanisms and events that threaten to interfere with optimal neurocognitive performance.

It is possible that behavioral manifestations of motivation are related to individual differences in the functioning of this top-down regulatory system. On the whole, individuals who are rated as highly motivated by the examiner may have a superior executive control system, which in turn allows them to sustain attentional effort consistently throughout a two-hour test battery. In contrast, individuals who appear suboptimally motivated may be relatively less effective in their executive control functioning. Hence, in this group, attentional effort waxes and wanes over the course of the two-hour test battery, resulting in poorer performance that is less consistent.

Importantly, the results of the post-concussion analyses suggest that, rather than acting as confounding factor, these individual differences in apparent motivation at baseline may confer important clinical information about premorbid risk and resilience. Those individuals who were rated as highly motivated at baseline were less likely to exhibit decrements in neurocognitive test performance post-concussion. These individuals may possess some quality that protects them against neurocognitive consequences of sports-related head injury.

Cognitive reserve is a plausible protective mechanism that may account for this finding. Cognitive reserve theory has been proposed as a way of accounting for inconsistencies in the relationship between quantifiable brain pathology and functional impairment. According to this theory, individuals differ with regard to "cognitive reserve capacity"—that is, the amount of pathology that an individual can sustain before clinical deficits are observable. Active models of cognitive reserve go on to speculate that brain activity actively compensates for brain damage (Stern, 2003). Stern has suggested that these active reserve mechanisms are also employed by healthy non-injured individuals in order to optimize performance when coping with task demands.

This theoretical claim has been supported by work in neuroimaging. In his synthesis of the literature on imaging studies of working memory, Hillary argues that the extant evidence suggests that, for healthy adults as well as many clinical populations, a general mechanism in prefrontal cortex (PFC) provides transient support during periods of challenge (Hillary, 2008). In healthy adults, challenge may be related to task difficulty or detrimental mechanisms that threaten to interfere with performance, whereas in injured individuals, challenge is the direct result of an insult to the central nervous system. Individuals with greater reserve capacity would be expected to better cope with detrimental mechanisms premorbidly, and also to be able to maintain effective functioning in the face of brain injury (Stern, 2003). In other words, one explanation for the present findings is that the same mechanism that allows an individual to maintain optimal cognitive performance at baseline also allows that individual to resist cognitive decline post-concussion.

There are important limitations of the present study that warrant noting. Firstly, examiners were not blind to athlete or control group status in the current study, and this information may have influenced the examiners' motivation rating. Furthermore, examiners' motivation ratings were assessed after the participant had completed the test battery, but before tests were scored. For some of the tests in the battery, good performance may be readily apparent to the examiner without scoring the test (for example, the HVLT-R). Whereas, for other tests (all of the ImPACT tests) it is improbable that the examiner could reasonably gauge the participants' performance without consulting the score report. Examiners were blind to the hypotheses under study, and were instructed to rate how hard the participant was trying, and not how well they thought the participant performed. However, it is possible that motivation ratings were influenced by the examiners' impressions of participants' performance on the battery. However, when performance on only the computer tests was considered in follow-up analyses, results revealed that there was still a significant and comparable relationship between motivation rating and test-performance. This finding suggests that the relationship between motivation rating and performance generalized to tests for which performance was not readily apparent to the examiner.

Although the results of the present study provide some support for the validity of the 7-point motivation rating scale, there are psychometric limitations with single-item measurements; specifically, such measures are presumed to have unacceptably low reliability (Wanous, Reichers, & Hudy, 1997). In a few areas of study there is a precedent for using single-item measures to assess constructs that may be sufficiently narrow or unambiguous, e.g. expectancy (Ilgen, Nebeker, & Pritchard, 1981) or job satisfaction (Wanous, et al., 1997). The reliability of the single-item measure of motivation used in the present study was not assessed, but it is possible that insufficient reliability may have diluted potentially important relationships between true motivation and neuropsychological test performance. This issue may have contributed to the relatively small effect of motivation on *performance inconsistency* and *IQ-performance discrepancy.* Future work should be done evaluating the inter-rater reliability of single-item and multi-item motivation rating scales.

Another limitation of the present study is the relatively small sample size of the post-concussion group. In this sample, there was a low base-rate of athletes who were rated as suboptimally motivated, and so, of the 48 athletes assessed post-concussion, just seven of these were rated as putting forth low motivation of baseline. Future studies with a larger sample of athletes with pre- and post-concussion assessments are necessary to replicate these findings. Finally, the sample of college athletes used in the present study was mostly male, and roughly a third of the participants in the present study were football players. These sample characteristics may have implications for motivation and neurocognitive test performance, and so these results should be generalized to other populations with caution.

These limitations notwithstanding, these findings may have important implications for the assessment of sports-related concussion. These results corroborate the notion that athletes may have a less-motivated approach to testing at baseline, when a powerful return-to-play incentive is absent. However, although motivation may have a significant influence on neurocognitive test performance, these findings suggest that suspect motivation at baseline dose not undermine the assessor's ability to detect post-concussion cognitive decline. In this respect, these results support the utility of baseline testing for sports-concussion management, even in the face of possible differences in motivation across time-points. Furthermore, these findings highlight the importance of behavioral observations; specifically, this study suggests that observations regarding approach to testing at baseline may convey important clinical information related to risk and resilience following injury.

Baseline testing is a potentially powerful tool for neuropsychological assessment. However the influence of contextual differences between baseline and post-injury assessments may raise concerns about the validity of pre-post injury comparisons. The present study endeavored to explore one such contextual factor—motivation. These results suggest that low motivation at baseline did not interfere with the ability to detect post-concussion cognitive decline, but rather, appeared to indicate risk for post-concussion impairment. Future studies should continue to evaluate factors that may complicate pre-post injury comparisons in sports-concussion assessment. These results also suggest future avenues for illuminating possible risk and resilience factors related to concussion severity. Such research promises to improve the diagnosis and management of this serious and pervasive injury.

Table 4.1. Characteristics of the sample

	Athlete	Control
% Male	79	49
% Caucasian	72	95
% ADHD	5	0
% LD	6	0
Age M(SD)	18.6(.8)	18.5(.8)

Table 4.2. Retained test indices and their component loadings

Test Index	Component 1 loading
Trail Making Test 1	.41
Trail Making Test 2	.57
ImPACT Verbal Memory Composite	.41
ImPACT Visual Memory Composite	.64
ImPACT Visual Motor Speed Composite	.76
ImPACT Reaction Time Composite	.67
BVMT Delayed Recall	.62
HVLT Delayed Recall	.46
Symbol Digit Modalities Test	.54
Stroop Color-Word Time	.63

Table 4.3. Tukey post-hoc test results for ImPACT composite scores by motivation group. All values in standard score units.

	Comparison *i*	*j*	**Mean difference** ***(i - j)***	**p-value**
Verbal Memory	low vs.	adequate	-5.3	< .05
		high	-10.9	< .001
	adequate vs.	high	-5.7	< .05
Visual Memory	low vs.	adequate	-7.4	< .005
		high	-9.9	< .001
	adequate vs.	high	-2.5	0.18
Visual Motor Speed	low vs.	adequate	-9.2	< .001
		high	-10.6	< .001
	adequate vs.	high	-1.4	0.59
Reaction Time	low vs.	adequate	-6.0	< .05
		high	-9.1	< .001
	adequate vs.	high	-3.1	0.08

Chapter 5. Paper 4: Cross-domain cognitive variability is an indicator of clinically meaningful states before and after sports-related concussion

The neuropsychological response to sports-related concussion is heterogeneous, and the nature of concussion-related cognitive decline is often transient and subtle. However, there is a growing awareness of the potential seriousness of these injuries within both the scientific community and the general public. It is now clear that there can be long-term cumulative effects of sports-related concussions, which in some cases may result in tragic cognitive and mood disturbance later in life. Research on neuropsychological performance in sports-related concussion suggests that although the majority of adult athletes fully recover from their injuries within ten days (McCrea, et al., 2003), a significant proportion of cases demonstrate a more protracted recovery time-line (Iverson, 2007). Additionally, it is yet unclear which athletes are at greatest risk for the deleterious long-term outcomes associated with these injuries—i.e. chronic traumatic encephalopathy (CTE; McCrory, 2011). In light of this observed inter-individual variability, it is clinically and theoretically important to identify and characterize pre- and post-injury factors that may be related to concussion severity.

Work in the cognitive aging literature has demonstrated that *intra*individual variability in cognitive performance is a promising index of neurological vulnerability and cognitive decline. In light of these findings, the present paper aims to examine intraindividual variability as a potential indicator of clinically meaningful states before and after sports-related concussion. Specifically, pre-injury cognitive variability may be a reflection of neurological vulnerability to injury, whereas post-injury variability may reflect the neurocognitive consequences of concussion and injury severity.

Traumatic brain injury (TBI) and the aging process are very different mechanisms by which central nervous system (CNS) functioning may be disturbed. However, similarities among cognitive profiles in the aging and TBI populations have been noted (Bashore & Ridderinkhof, 2002), and this is not surprising given parallels in functional changes related to these conditions. Some neurological disorders are characterized by relatively focal CNS disturbance—for example in disorders like Aphasia or Spatial Neglect a relatively localized region incurs damage. In turn, this focal damage results in a neuropsychological profile indicating the selective impairment of that area's corresponding function. Conversely, CNS disruption related to aging or head injury tends to be diffuse and marked by disturbances that are distributed across the CNS—e.g. axonal sheering in concussion (Gaetz, 2004), or widespread white matter changes related to cognitive aging (Peters, 2002). Hence, cognitive changes related to these conditions may be subtle, non-specific, and transient or variable in nature.

Indeed, common deficits across both conditions include impairments in working memory, attention, and information-processing speed—all cognitive functions that are subserved by multiple brain regions and rely on the efficiency of neural networks. The similarities between cognitive deficits following TBI and cognitive aging has lead some investigators to suggest that the two processes may influence common neural mechanisms (Hicks & Birren, 1970; Miller, 1970; Stokx & Gaillard, 1986)—a claim which has been somewhat supported by neuroinmaging work (Hillary, Genova, Chiaravalloti, Rypma, & DeLuca, 2006). For these reasons, there is potential utility in consulting the relatively more extensive literature on cognitive aging in order to inform future directions in the study of sports-related concussion.

In the aging literature, recent work has been published linking intraindividual variability with meaningful interindividual differences in current cognitive functioning and risk for future dementia (Holtzer, et al., 2008; Hultsch & MacDonald, 2004; Hultsch, et al., 2008; Kliegel & Sliwinski, 2000; Salthouse, 2007). Investigators examining intraindividual inconsistencies in cognitive performance have operationalized performance variability in a number of ways. Some work has used intraindividual standard deviations taken from multiple trials within a single task (Ram, et al., 2005). Other studies have considered variability in performance on the same task on separate occasions (Hultsch, et al., 2000). Others still have taken a cross-domain approach to intraindividual variability by examining within-person variability in performance across different neuropsychological tests administered as part of a neuropsychological test-battery (Holtzer, et al., 2008; Kliegel & Sliwinski, 2000; Schretlen, et al., 2003).

A cross-test approach to variability would consider performance on a battery of neuropsychological tests, standardize these tests with reference to a common sample, and index the extent to which these scores deviate from each other using a variance parameter, like standard deviation. For example, take a neuropsychological battery that includes one test of verbal memory, one test of visual memory, one test of processing speed, and a test of attention. If an examinee's scores on these tests, in standard score units, are 98, 105, 111, and 102, the cross test-variability could be indexed by spread (13 standard score points), variance (30 standard score points), or standard deviation (5.48 standard score points). Variability across cognitive domains has been conceptualized as "a signature of decline in cerebral integrity" (p. 827, Holtzer et al., 2008). Research utilizing a cross-test variability approach has found evidence of performance variability even in healthy adults (Schretlen, et al., 2003). In older individuals, cross-domain cognitive variability has been associated with impending cognitive decline and dementia (Holtzer, et al., 2008; Kliegel & Sliwinski, 2000).

With these considerations in mind, the purpose of the present study is to explore cross-domain intraindividual cognitive variability as a reflection of concussion-vulnerability and concussion-related cognitive decline in a sample of college athletes participating in a sports-concussion management program. Specifically, baseline cross-domain cognitive variability will be examined as an indicator of neurological vulnerability to injury, and post-concussion variability will be evaluated as a mechanism of cognitive decline within a longitudinal structural equation model (SEM). The proposed path-model is a two-staged mediation model: 1) post-concussive symptoms will be examined as a mediator of the relationship between baseline cognitive variability and post-concussion cognitive variability; and 2) post-concussion cognitive variability will be examined as a mediator of the relationship between post-concussion symptoms and post-concussion cognitive decline. In this model, post-concussion symptoms are presumed to be an epiphenomenon of CNS disruption related to concussive injury. These symptoms are easily assessable by self-report, and prior research has demonstrated a strong relationship between post-concussion symptoms and electrophysiological brain abnormalities (Dupuis, Johnston, Lavoie, Lepore, & Lassonde, 2000). Thus, regarding path model 2 above, post-concussion symptoms are thought to reflect CNS dysfunction; this, in turn, leads to post-concussion cognitive variability, which then results in cognitive decline.

Method

Participants

Participants in the present study were 71 college athletes participating in the Penn State Concussion program, a multi-sport program that assesses participants prior to and following sports-related concussion (see Table 5.1 for characteristics of the sample). This program is designed according to the Sports as a Laboratory Assessment Model (SLAM; Barth, et al., 1989) paradigm, in order to provide objective neuropsychological test-data to team physicians to inform return-to-play decisions. Eight of the athletic programs at Penn State University regularly participate in baseline testing: Football, Men's and Women's Lacrosse, Men's and Women's Soccer, Men's and Women's Basketball, Men's Ice Hockey, and Wrestling. Post-concussion testing is provided for any Penn State athlete who sustains a head injury. Whenever possible, post-concussion assessment takes place within 48 hours of injury. Only athletes who had undergone both baseline and post-concussion assessment have been included in the present analyses.

Measures

The Penn State Concussion test battery consists of a number of measures that assess cognitive and affective functioning. The measures include: the Hopkins Verbal Learning Test-Revised (HVLT-R; Benedict, et al., 1998), the Brief Visuospatial Memory Test-Revised (BVMT-R; Benedict, 1997), the Symbol-Digit Modalities Test (SDMT; Smith, 1982), the Digit Span Test (Wechsler, 1997), the PSU Cancellation Task, the Stroop Color-Word Test (SCWT; Trenerry, et al., 1989), and the Wechsler Test of Adult Reading (WTAR; The Psychological Corporation, 2001). For athletes who underwent multiple evaluations (baseline testing and one or more post-concussion evaluations), alternate forms of the HVLT-R, BVMT-R, SDMT, and PSU Cancellation Task were used (see Benedict et al., 1998; Benedict, 1997; and Smith, 1982, for alternate form reliability information). With the exception of the WTAR, all of these tests have been shown to be sensitive to traumatic brain injury in prior work (Bailey, et al., 2005; Bohnen, et al., 1992; Bruce & Echemendia, 2003; Ponsford & Kinsella, 1992; Vanderploeg, et al., 2005).

The Immediate Post-Concussion Assessment and Cognitive Testing computerized battery (ImPACT; Lovell, et al., 2000) was also used. Although complete validity data for the use of this test battery in sports related concussion have not yet been published, it assesses cognitive domains typically affected following such injury. The ImPACT (Lovell, et al., 2000) is a computerized test battery that was designed to offer a time-effective and standardized method for collecting data to assist in concussion assessment and management. The battery consists of three main parts: demographic data, neuropsychological tests, and the Post-Concussion Symptom Scale. Six neuropsychological tests are included, designed to target attention, memory, processing speed, and reaction time. From the six tests, five composite scores are derived: Verbal Memory, Visual Memory, Visuomotor Speed, Reaction Time, and Impulse Control. Studies in high school and college athletes have demonstrated that the ImPACT performance is correlated with performance on similar paper-and-pencil neuropsychological tests (Iverson, Lovell, & Collins, 2005; Iverson, et al., 2005), and furthermore, ImPACT performance is sensitive to the acute effects of concussion (Schatz, et al., 2006).

In addition to the neuropsychological tests, the battery includes a self-report measure of symptoms. The Post-Concussion Symptom Scale (PCSS) is a list of symptoms that are commonly associated with concussion, including items like headache, nausea, dizziness, trouble concentrating, and feeling “in a fog”. Athletes rate the extent to which they are currently experiencing each symptom on a scale from 0-6, with 0 indicating the absence of the symptom, and 6 indicating extreme distress from that symptom. The PCSS was administered prior to cognitive tests at both baseline and post-concussion evaluations.

Procedure

All 71 participants have undergone baseline and post-concussion testing, including the instruments described in detail above. Athletes may have been tested a number of times post-injury, depending on the course of their recovery and the team physician's referral. The majority of initial post-concussion assessments take place within one week of the head injury, and within 48 hours whenever possible. For the purpose of the present study, only the initial post-concussion evaluation is considered. Baseline and post-injury evaluations are conducted by a Ph.D.-level clinical neuropsychologist, or a graduate or undergraduate assistant who has been trailed by a Ph.D.-level clinical neuropsychologist. Testing sessions take approximately 1.5 hours per evaluation, and also require approximately 30 minutes for paperwork, debriefing, and administration of other instruments not included in the proposed study.

Approach to data analysis

Indices of overall performance and performance variability

Baseline test-performance was examined with regard to both overall level of performance and performance inconsistency. In order to obtain a meaningful summary index, a Principal Components Analysis was performed on the following test indices as assessed at baseline: Vigil-Total Omissions, Vigil-Total Commissions, Vigil-Average Delay, ImPACT Verbal Memory Composite, ImPACT Visual Memory Composite, ImPACT Visuomotor Speed Composite, ImPACT Reaction Time Composite, ImPACT Impulse Control Composite, BVMT-R Total Immediate Recall, BVMT-R Total Delayed Recall, HVLT-R Total Immediate Recall, HVLT-R Total Delayed Recall, SDMT- Total Correct, SDMT- Incidental Memory, DSF, DSB, SCWT-Stroop-W Time, SCWT-Stroop-CW Time, PSU Cancellation Test Total Correct, COWAT Total, TMT-Trial 1 Time, and TMT-Trial 2 Time. A priori, it was decided that all test-indices with component loadings on the first component greater than .4 would be retained for subsequent analyses, and Cronbach's α would be consulted to confirm the internal consistency of the retained indices at the aggregate level.

These retained indices were then used to calculate measures of *overall performance* and *performance variability*. First, all test indices were put on the same metric by converting them to standard scores (SSs). SSs have a mean of 100 and a standard deviation of 15. SS units have been chosen because this is the metric employed by many commonly used neuropsychological tests, including the Wechsler Adult Intelligence Scales' Full Scale IQ score. The sample mean and sample standard deviation from the athletes tested at baseline was used to calculate SSs. Test-indices for which higher scores indicate poorer performance (i.e. Stroop-CW Time) were calculated by subtracting the observed score from the sample mean, so that for all SSs, higher scores indicate better performance.

Overall performance at baseline was calculated by taking the mean across all SS-converted retained test-indices for that individual at baseline. *Performance variability* at baseline was calculated by taking the standard deviation across all SS-converted retained test-indices for that individual at baseline. Similarly, *performance variability* post-concussion was calculated by taking the standard deviation across all SS-converted retained test-indices for that individual post-concussion.

Post-concussion decline

In order to operationalize impairment post-concussion, reliable change indices (RCIs) were calculated (Jacobson & Truax, 1991), based on the control group (see Chapter 1). A 90% confidence interval was selected as the criterion for determining reliable decline in performance post concussion. An index of *post-concussion decline* was calculated by summing the total number of tests for which an individual demonstrated reliable decline.

Longitudinal structural model

The purpose of the study is to evaluate intraindividual variability as a vulnerability factor at baseline and as the mechanism of post-concussion impairment after injury within the context of a longitudinal structural model. Central to the proposed model are two mediating relationships. A mediation is a relationship between some independent variable (X) and some dependent variable (Y), that is fully or partially explained by an intervening variable (also called a mediator; M). The proposed mediating paths in the present analysis are a path from *baseline variability* (X) to *post-concussion variability* (Y) via *post-concussion symptoms* (M), and a path from *post-concussion symptoms* (X) to *post-concussion decline* (Y) via *post-concussion variability* (M).

A given variable or process serves as a mediator when: 1. the independent variable, X, has a direct and significant effect on the dependent variable, Y; 2. the mediator, M, has a direct and significant effect on Y when controlling for X; and 3. the direct effect of X on Y is reduced or negated when allowing an indirect effect of X on Y via M, that is, when M mediates the relationship between X and Y (Baron & Kenny, 1986; Cole & Maxwell, 2003; Kenny, Kashy, & Bolger, 1998). A negation of the direct effect of X on Y is a full mediation, whereas a significant reduction is a partial mediation. However, Cole and Maxwell (2003) note that additional concern must be given to the temporal nature of the data. Mediators are assumed to be mechanisms by which X exerts its effect on Y. Therefore, X must cause M, and M, in turn, must cause Y. In order to satisfy these causal requirements, X must precede M, and M must precede Y in time (Cole & Maxwell, 2003; Holland, 1986).

The proposed longitudinal model is a two-stage mediation, whereby the mediating variable from stage 1 then acts as an independent variable at stage 2 (*post-concussion symptoms*). Because structural equation modeling (SEM) allows the same variable to serve as both an independent variable and a dependent variable, a multi-stage SEM path analyses was employed to test the two-stage mediation. *Baseline overall performance* and *baseline symptoms* were entered as covariates during model-construction. Path analyses were conducted using the sixth edition of Mplus (Muthén & Muthén, 2009). All analyses were carried out using maximum likelihood (ML) estimation.

Results

Preliminary analyses

A list of the tests included and their component loadings can be found in Table 5.2. Cronbach's α was calculated using the retained indices in order to confirm consistency of these items at the aggregate level. This analysis suggested that the retained items have good internal consistency ($\alpha = 0.82$).

The frequency of the number of scores that reliably declined was examined. In the athlete group, 52% of the sample had no scores that reliably declined post-injury, 14% exhibited reliable decline on one test, 14% reliably declined on two tests, and 20% reliably declined on 3 or more tests. In the control group, 69% of the sample had no scores that reliably declined at retest, 21%

reliably declined on a single test, and 10% reliably declined on exactly two tests. No participants in the control group exhibited reliable decline on more than two tests.

Longitudinal two-stage mediation model

Mediation 1: Post-concussion symptoms as a mediator

Step 1: Post-concussion Variability (Y) *on Baseline Variability* (X). A path model was first constructed wherein *post-concussion variability* was regressed on *baseline variability*, controlling for *baseline overall performance.* Model results revealed a significant effect of *baseline variability* on *post-concussion variability* (B = 0.31, $\beta = 0.31$, SE = 0.12, t = 2.63, d = 0.44), but not a significant effect of *overall performance* on *post-concussion variability* (B =-0.11, $\beta = 0.21$, SE = 0.06, t = -1.7, d = -0.29). This model explained 20% of the variance in *post-concussion variability* (R^2 = .20).

Step 2: Post-concussion Symptoms (M) *on Baseline Variability* (X). Next, a path model was constructed regressing *baseline variability on post-concussion symptoms.* Model results revealed a significant effect of *baseline variability* on *post-concussion symptoms* (B =0.52, β = 0.33, SE = 0.18, t = 2.94, d = 0.49). This model explained 11% of the variance in *post-concussion symptoms* (R^2 = .11).

Step 3: Stage 1 Mediation. Finally, a mediation model was constructed such that, in addition to the paths reported for steps 1 and 2, a path regressing *post-concussion variability* (Y) and *post-concussion symptoms* (M) was added. This model provided excellent fit to the data, $\chi^2(1) = 0.02$, p = 0.89, *RMSEA* < .001. The regression path for *post-concussion variability* (Y) on *post-concussion symptoms* (M) was significant (B =0.18, $\beta = 0.28$, SE = 0.07, t = 2.63, d = 0.44). Once this path was added to the model, the path between *baseline variability* (X) and *post-*

concussion variability (Y) was no longer significant (*B* =0.21*, β = 0.22, SE* = 0.12, *t* = 1.83, *d* = 0.31). The standardized β was reduced from .31 in the initial model to .21 in the mediation model. *Baseline variability* significantly predicted *post-concussion symptoms* (*B* =0.52*, β = 0.33, SE* = 0.18, *t* = 2.9, *d* = 0.49). This model accounted for 11% of the variance in *post-concussion symptoms* and 27% of the variance in *post-concussion variability* (R^2 = .11 and R^2 = .20, respectively). Figure 5.1 depicts the path models for steps 1, 2, and 3.

Mediation 2: Post-concussion Variability as a mediator

Step 1: Post-concussion Decline (Y) *on Post-concussion Symptoms* (X). Next, the same steps were taken to evaluate the second proposed mediation. First, a path model was constructed wherein *post-concussion decline* was regressed on *post-concussion symptoms*, controlling for *baseline overall performance.* Model results revealed a significant effect of *post-concussion symptoms* on *post-concussion decline* (*B* = 1.19*, β = 0.34, SE* = 0.39, *t* = 3.04, *d* = 0.51), but not a significant effect of *baseline overall performance* on *post-concussion decline* (*B* =-0.28*, β = 0.10, SE* = 0.32, *t* = -0.86, *d* = -0.14). This model explained 13% of the variance in *post-concussion decline* (R^2 = .13).

Step 2: Post-concussion Variability (M) *on Post-concussion Symptoms* (X). Next, a path model was constructed regressing *post-concussion variability* on *post-concussion symptoms,* controlling for *baseline overall performance.* Model results revealed a significant effect of *post-concussion symptoms* on *post-concussion variability* (*B* =0.22*, β = 0.34, SE* = 0.07, *t* = 3.27, *d* = 0.55), and a significant effect of *baseline overall performance* on *post-concussion variability* (*B* =-0.16*, β = 0.30, SE* = 0.05, *t* = -2.89, *d* = -0.49). This model explained 24% of the variance in *post-concussion variability* (R^2 = .24).

Step 3: Stage 2 Mediation. Finally, a mediation model was constructed such that, in addition to the paths reported for steps 1 and 2, a path regressing *post-concussion decline* (Y) on *post-concussion variability* (M) was added. Because this model is saturated, model-fit cannot be assessed. The regression path for *post-concussion decline* (Y) on *post-concussion variability* (M) was significant (B =2.9, $\beta = 0.52$, SE = 0.62, t = 4.72, d = 0.49). Once this path was added to the model, the path between *post-concussion symptoms* (X) and *post-concussion decline* (Y) was no longer significant (B =0.57, $\beta = 0.16$, SE = 0.37, t = 1.54, d = 0.26). The standardized β was reduced from .34 in the initial model to .16 in the mediation model. *Post-concussion symptoms* significantly predicted *post-concussion variability* (B =0.22, $\beta = 0.34$, SE = 0.07, t = 3.2, d = 0.49). *Baseline overall performance* also significantly predicted *post-concussion variability* in this model (B = -0.16, $\beta = -0.30$, SE = 0.05, t = -2.9, d = -0.48). This model accounted for 24% of the variance in *post-concussion variability* and 34% of the variance in *post-concussion decline* (R^2 = .24 and R^2 = .34, respectively). Figure 5.2 depicts the path models for steps 1, 2, and 3.

Full Longitudinal Model

Finally the two mediation models from stage 1 and stage 2 were combined to form the complete longitudinal two-stage mediation model. This model provided excellent fit to the data, $\chi^2(6) = 3.5$, p = 0.75, *RMSEA* < .001. Complete model statistics are provided in Table 5.3, and the full model is depicted in Figure 5.3.

Follow-up analyses

In order to further examine possible mechanisms of cognitive variability at baseline, an independent samples t-test was conducted comparing athletes with a self-reported history of previous head-injuries (n = 34) with those denying prior concussion (n = 37). These groups were not different with regard to *baseline variability* ($t = .62$, $p = .54$). Furthermore, the correlation between WTAR FSIQ estimate and *baseline variability* was examined, and these variables were not significantly correlated ($r = -.02$; $p = .91$).

Discussion

The present findings support a two-stage mediation model explaining the relationship between baseline cognitive variability and post-concussion cognitive decline. The proposed model supports the hypothesis that post-concussion symptoms mediate the relationship between baseline variability and post-concussion cognitive variability; and furthermore, that post-concussion cognitive variability mediates the relationship between post-concussion symptoms and post-concussion cognitive decline. Taken together, this model suggests that cross-domain cognitive variability is related to clinically meaningful states pre- and post-concussive injury—specifically, baseline cognitive variability is related to post-concussion severity and may indicate neurological vulnerability to injury, whereas post-concussion cognitive variability may be a mechanism by which athletes manifest neuropsychological impairment post-concussion. Mean-level of cognitive performance at baseline and pre-injury self-report of symptoms were controlled for during analyses, and hence the aforementioned effects are independent of premorbid overall cognitive performance and symptom reporting.

The first stage of the mediation model proposes that baseline cognitive variability is related to post-concussion cognitive variability via its effect on post-concussion symptoms; post-concussion symptoms fully mediated this relationship between cognitive variability pre- and post-injury. Athletes with relatively greater cognitive variability at baseline were more likely to report post-concussive symptoms in response to concussion; and symptom reporting, in turn, was related to greater cognitive variability post-concussion. Prior research has demonstrated a strong relationship between post-concussion symptoms and electrophysiological brain abnormalities (Dupuis, et al., 2000). Furthermore, work has demonstrated that symptomatic athletes manifest greater impairment on neuropsychological tests (Collie, Makdissi, Maruff, Bennell, & McCrory, 2006). These findings suggest that post-concussion symptoms may be a reasonable indication of the pathophysiological impact of concussive injury. Given the aforementioned literature, one explanation for the present findings is that cognitive variability at baseline leads to greater neurological disturbance in response to head-injury—which is characterized by increased cognitive variability post-concussion.

History of previous head-injuries is one explanation for the relationship between baseline cognitive variability and post-concussion symptoms. Previous research has suggested that prior concussions may contribute to injury severity and recovery time (Guskiewicz et al., 2003), although other investigators have failed to replicate this finding (Iverson, 2007). It is possible that a history of previous head-injuries causes increased cognitive variability at baseline and confers risk for greater neurological disturbance following subsequent head-injuries. In the present sample, there was no relationship between self-report of previous concussion and baseline cognitive variability. However, it remains possible that prior trauma could increase cognitive variability at baseline. For example, some investigators have suggested that sub-concussive impacts may increase neurological vulnerability to future injury (Belanger & Vanderploeg, 2005). Furthermore, self-report of previous concussions may be inaccurate for a number of reasons. Many athletes may fail to recognize when they have sustained a brain-injury, or they may be hesitant to report previous injuries for fear that a positive concussion history may jeopardize their sports participation or delay return-to-play.

The second stage of the longitudinal mediation model supports the hypothesis that post-concussion cognitive variability mediates the relationship between post-concussion symptoms and concussion-related cognitive decline. This finding suggests that the mechanism of cognitive impairment post-concussion may be increased intraindividual variability in cognitive performance, rather than depressed cognitive performance generally. Other work that has operationalized intraindividual variability in this way—across a variety of cognitive domains—has suggested that this type of cognitive variability may indicate a decline in cerebral integrity (Holtzer, et al., 2008). Cerebral integrity has been operationalized using a number of different biomarkers, including gray matter thickness, intergryal and sulcal spans, fractional anisotropy (FA), and volume of T2-hyperintense white matter (Kochunov et al., 2008).

Research has linked concussion with at least one of these indices of cerebral integrity—specifically FA. Higher levels of FA are thought to reflect disruption of white-matter tracts. Using diffusion tensor imaging (DTI), investigators have found increased FA in recently concussed adolescents as compared with age-matched controls. Furthermore, increased FA was associated with the severity of post-concussion symptoms in that group (Wilde et al., 2008). Another study examining DTI indices across a range of TBI severity found FA differences between healthy controls and those with TBI, with greater levels of FA in those with more severe injuries. In this sample, global FA was also related to performance on neuropsychological tests, with the strongest correlations between FA and measures of executive functioning and memory—functions that rely on widespread cortical and subcortical networks (Kraus et al., 2007).

These DTI studies suggest that disruption in cerebral integrity—specifically, white matter integrity—may be a pathophysiological mechanism underlying the cognitive and somatic symptoms of concussions. Transient changes in white matter integrity may, in part, explain the mediation relationship between post-concussion symptoms and post-concussion cognitive decline, via cognitive variability. White matter disruptions may underlie somatic concussion symptoms as well as increases in cognitive variability. Cognitive variability, in turn, could account for overall decrements in cognitive performance. Within this framework, the present findings suggest that cross-domain cognitive variability could be a manifestation of concussion-related neuropathology.

In summary, the data from the longitudinal structural model in this study support the potential theoretical and clinical relevance of cross-domain cognitive variability in sports-related concussion. An interpretation of the present findings is that pre-injury cognitive variability is an index of risk for self-reported symptoms and cognitive sequelae following sports-related concussion, and that post-concussion cognitive variability is a manifestation of concussion-related neuropsychological impairment. Intraindividual variability is a relatively new area of inquiry in neuropsychology, and cross-domain cognitive variability has only been examined in a handful of other investigations (Holtzer, et al., 2008; Kliegel & Sliwinski, 2000; Schretlen, et al., 2003). Within-person cross-domain variability may be derived from any commonly used neuropsychological test battery. For this reason such an index is amenable to standard clinical neuropsychological procedures, and hence has pragmatic appeal. Although the neuroanatomical and theoretical bases for this type of variability remain speculative, there are now a few empirical investigations suggesting that cross-domain variability is related to important clinical outcomes (Holtzer, et al., 2008; Kliegel & Sliwinski, 2000). The present data add to this growing literature, and suggest that the study of cross-domain variability in the study of sports-related concussion is a promising direction for future research.

There are some limitations and methodological considerations related to the present study that warrant discussion. Firstly, cross-domain intraindividual variability as a potential construct is highly dependent on the test-indices and measures selected for inclusion in the variability index. The measures included in the present analyses were selected from a battery that was designed to evaluate cognitive domains that have been empirically linked with sports-related concussion in prior work. Specifically, the focus of this battery is attention, processing speed, memory, and executive functioning. Furthermore, an attempt was made to make the measures included in the variability index more homogeneous by employing principal components analysis to select tests that loaded highly on the first component. The result of this process was a collection of test indices that was highly internally consistent at an aggregate level (Cronbach's $\alpha = .82$). Hence, cognitive variability in this study is, precisely speaking, variability on a subset of neuropsychological tests that were highly interrelated in the present sample. This choice was made as an attempt to decrease variability attributable to properties of the tests themselves, and increase variability that might speak to meaningful individual differences. However, this was an initial attempt at constructing a meaningful within person variability index, and the potential utility of using a different set of tests remains an empirical question.

The primary purpose of the present study was to explore two mediation relationships. As discussed previously, statistical evidence of mediation is not sufficient to demonstrate that some variable M, mediates the relationship between an independent variable (X) and a dependent variable (Y). Additional concern must be given to the temporal nature of the data, in order for causal claims to be plausible. Hence, X must precede M, and M must precede Y in time (Cole &

Maxwell, 2003; Holland, 1986). In the first proposed mediation described above, baseline variability clearly precedes the proposed mediator, post-concussion symptoms. Post-concussion symptoms were assessed prior to the administration of the test battery, and so report of symptoms does precede the post-injury neuropsychological outcomes. However, it could also be argued that post-concussion symptoms and neuropsychological outcomes are epiphenomenal.

The issue of temporal precedence becomes more problematic with regard to the second stage of the model—the index of cognitive variability and the index of cognitive decline are derived from the same battery of tests. For this reason, the direction of the relationship—i.e. the designation of which variable is a mediator and which is the outcome—is arbitrary with regard to temporal constraints. For theoretical reasons discussed above, the present analyses consider cognitive variability a potential index of cerebral integrity. For this reason, the variable is evaluated as a *mechanism* of cognitive decline, and hence was designated as a mediator. However, it should be noted that causal claims are strictly speculative due to the aforementioned methodological limitations.

Despite these limitations, the present findings suggest that cross-domain variability is a promising index of concussion vulnerability and concussion severity. Should this claim be corroborated by future research, indices of intraindividual cognitive variability could have important clinical relevance. Although the literature is mixed, a number of studies have now demonstrated that history of previous head injury confers risk for greater concussion severity and a protracted recovery period. Other work has demonstrated neuropsychological and electrophysiological differences between symptomatic and asymptomatic athletes after injury. However, athletes' self-report of these factors is subject to bias; return to play may act as a powerful incentive for some athletes to minimize symptoms or deny previous concussions. For this reason, effective concussion management depends on the identification of objective performance-based indicators of clinically meaningful information. The present study suggests that intraindividual cognitive variability is a promising indicator of neurological vulnerability to injury and current neurophysiological disturbance.

Table 5.1. Characteristics of the sample

Clinical & Demographic		Sport	
Age at baseline	18 (.9)	Football	38%
Female	21%	Men's Ice Hockey	14%
Caucasian American	68%	Men's Lacrosse	13%
African American	25%	Women's Soccer	10%
ADHD diagnosis	6%	Women's Lacrosse	7%
LD diagnosis	3%	Men's Basketball	3%
Previous Head Injuries		Men's Soccer	4%
Denied	51%	Wrestling	4%
1	34%	Women's Basketball	3%
2 or more	14%		

Table 5.2. Retained test indices and component loadings.

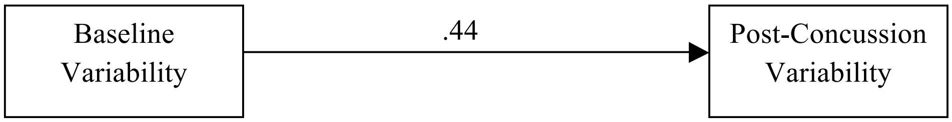
Test Index	Component 1 loading
Trail Making Test 1	.41
Trail Making Test 2	.57
ImPACT Verbal Memory Composite	.41
ImPACT Visual Memory Composite	.64
ImPACT Visual Motor Speed Composite	.76
ImPACT Reaction Time Composite	.67
BVMT Delayed Recall	.62
HVLT Delayed Recall	.46
Symbol Digit Modalities Test	.54
Stroop Color-Word Time	.63

Table 5.3. Complete results for the final path model. Results reported as regression paths (B) for each Y on X. Effect size is reported as Cohen's d.

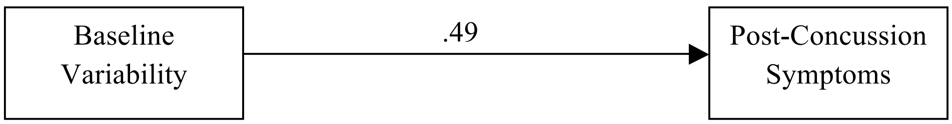
	Estimate (B)	Standardized Estimate (β)	T	Effect size
Declined Scores on				
Post-Concussion Variability	3.14	0.56	5.7	0.96
Post-Concussion Variability on				
Post-Concussion Symptoms	0.18	0.28	2.6	0.44
Baseline Overall Performance	-0.11	-0.21	-1.9	-0.32
Baseline Variability	0.21	0.22	1.8	0.30
Post-Concussion Symptoms on				
Baseline Variability	0.51	0.33	2.9	0.49
Baseline Symptoms	0.03	0.03	0.2	0.03

Figure 5.1. First stage mediation . Paths represented as effect sizes (Cohen's d).

Step 1: Y (Post-Concussion Variability) on X (Baseline Variability)



Step 2: M (PC Symptoms) on X (Baseline Variability)



Step 3: Mediation

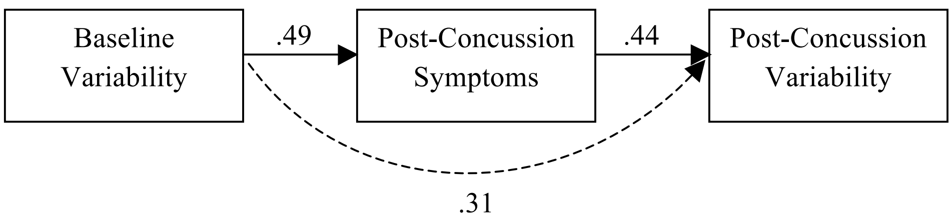
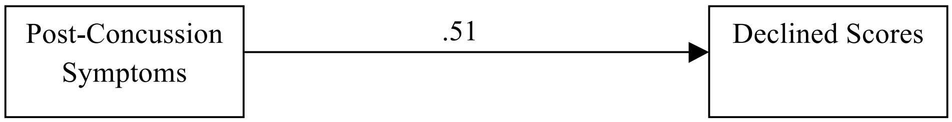
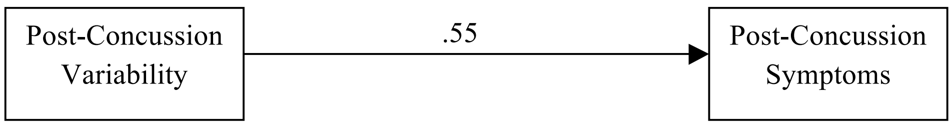


Figure 5.2. Second stage mediation. Paths represented as effect sizes (Cohen’s d).

Step 1: Y (Declined Scores) on X (Post-Concussion Symptoms)



Step 2: M (PC Variability) on X (PC Symptoms)



Step 3: Mediation

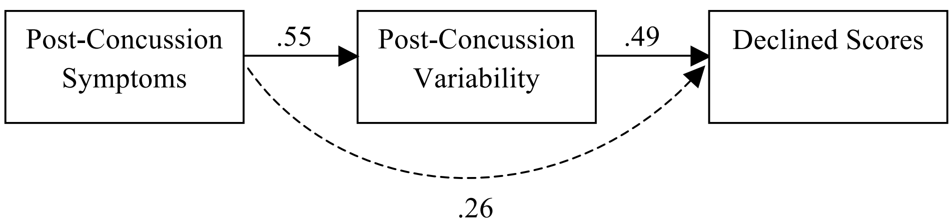
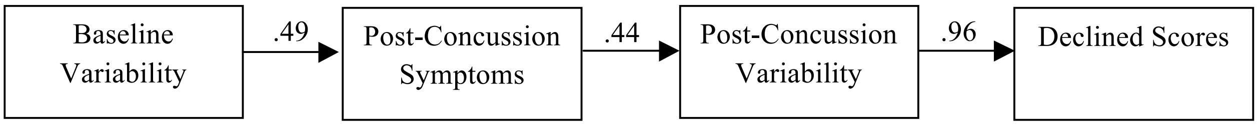


Figure 5.3. Final longitudinal model. Significant paths only. Paths represented as effect sizes (Cohen's d).



Chapter 6. General Discussion

The present thesis provides four publication-style empirical research papers that, taken as a whole, represent a study of intraindividual cross-domain cognitive variability in college athletes before and after sports-related head injury. A priori, it was hypothesized that cognitive variability at baseline would be related to sub-optimal effort towards testing, whereas cognitive variability post-concussion would be related to concussion severity. These a priori hypotheses were somewhat supported by the present findings. The findings from Paper 3 (see Chapter 4) suggest that there is a small effect of examiners' motivation rating on intraindividual cognitive variability. Findings from Paper 4 (See Chapter 5) support the hypothesis that intraindividual cognitive variability is related to both post-concussion symptoms and cognitive decline. Although these hypotheses were somewhat supported, the results of these studies suggest a more complicated relationship between motivation, cognitive variability, and post-concussion severity. Specifically, these results indicate that behavioral manifestations of suspect motivation and baseline cognitive variability may also be indicators of CNS vulnerability to concussive injury. Theoretical models of the relationships among vulnerability (conceptualized herein as CNS integrity), motivation, injury severity, and cognitive variability are depicted in Figures 6.1 and 6.2.

Paper 2

The purpose of Paper 2 (Chapter 3) was to provide an exploratory examination of intraindividual variability across cognitive tests in college athletes tested pre- and post-injury. The results suggest that normative cognitive performance in college athletes is characterized by significant intraindividual variation across tests. Greater performance variability was unrelated to an estimate of intellectual functioning, but was significantly related to lower mean-level of performance on the test battery. In the sample as a whole, there was no effect of concussion on either *performance variability* or *overall performance*. However, a cluster analysis revealed two clusters that predicted response to injury. Those athletes whose cognitive performance was characterized by a high level of cognitive variability exhibited a post-concussion cognitive profile indicative of impaired neuropsychological functioning, whereas those athletes exhibiting relatively consistent cognitive performance demonstrated an improvement in their overall performance post-concussion. This finding suggests that cognitive variability could be an indicator of vulnerability to injury.

Paper 3

The results of Paper 3 (Chapter 4) suggest that athletes experience a change in motivation across assessments, and motivation significantly impacts cognitive performance. The cross-sectional analysis revealed that examiners' ratings of motivation were significantly related to concurrent *overall performance* and *performance inconsistency* across the test-battery, with those who were given the highest motivation rating exhibiting the highest mean-level of performance and the least variable performance, and those receiving lower motivation ratings exhibiting relatively worse and more variable test performance. Taken together, these results reveal a small to moderate association between observation-based ratings of motivation and concurrent neurocognitive test performance. This suggests that, for those athletes who are rated as sub-optimally motivated at baseline, baseline test-results represent an underestimate of true premorbid abilities.

With all this said, the results of the post-injury analysis suggested a counter-intuitive relationship between baseline motivation and neuropsychological test performance post-concussion. Membership in the *low motivation* group at baseline actually *increased* the odds that individuals would be classified as impaired post-concussion. This finding suggests that, contrary to the a priori hypothesis, suboptimal motivation at baseline did not interfere with the test battery's ability to detect neurocognitive impairment post-concussion. Rather, these results indicate that poor motivation at baseline may reflect an underlying risk factor for concussion related impairment.

Paper 4

Paper 4 (Chapter 5) examined cognitive variability both pre- and post-injury within the context of a longitudinal structural model. This study used mediation analyses as an attempt to elucidate possible mechanistic relationships among these constructs—cognitive vulnerability, injury severity, and post-injury cognitive decline. The results of this study support a two-stage mediation model explaining the relationship between baseline cognitive variability and post-concussion cognitive decline. This model suggests that cross-domain cognitive variability is related to clinically meaningful states pre- and post-concussive injury; specifically, baseline cognitive variability is related to post-concussion severity and may indicate neurological vulnerability to injury, whereas post-concussion cognitive variability may be a mechanism by which athletes manifest neuropsychological impairment post-concussion.

Prior work has conceptualized cognitive variability as an indicator of cerebral integrity (Holtzer, et al., 2008) or CNS inefficiencies (Anstey, et al., 2007; Britton, et al., 1991; Kelly, Uddin, Biswal, Castellanos, & Milham, 2008; Walhovd & Fjell, 2007). The results of the present studies suggest that intraindividual variability was related to pre-morbid behavioral manifestations of motivation, vulnerability to concussive injury, and injury severity. Cognitive variability and behavioral manifestations of motivation may be reflections of CNS integrity, which could be conceptualized as cognitive reserve. Active models of cognitive reserve speculate that brain activity actively compensates for brain damage (Stern, 2003). These active reserve mechanisms may also be employed by healthy non-injured individuals in order to optimize performance when coping with task demands. Individuals with greater reserve capacity would be expected to better sustain motivated and consistent performance throughout a long test battery, and also to better maintain effective functioning in the face of brain injury (Stern, 2003).

In summary, Papers 2 and 4 suggest that cross-domain cognitive variability is a promising index of concussion vulnerability and concussion severity. Furthermore, the findings from Paper 3 highlight the importance of behavioral observations of motivation, as these may convey important clinical information related to risk and resilience following injury. Baseline testing is a potentially powerful tool for neuropsychological assessment. However, there may be contributors to baseline neuropsychological performance that have not been fully elucidated. The data presented here support the notion that motivation and premorbid vulnerability to injury may contribute to an athlete's performance on neuropsychological tests. Furthermore, these results suggest that cross-domain cognitive variability is a promising indicator of both of these constructs, particularly premorbid vulnerability to injury. Fully elucidating the contributors to neuropsychological performance in college athletes, as well as uncovering performance-based indicators of these factors, promises to improve assessment and management of these potentially devastating injuries.

Figure 6.1. Theoretical model of contributors to premorbid cognitive variability

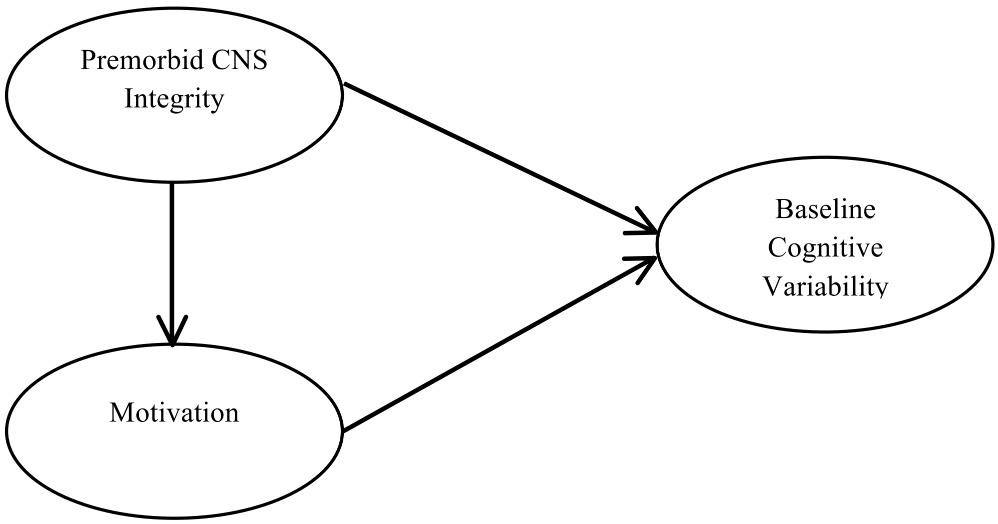
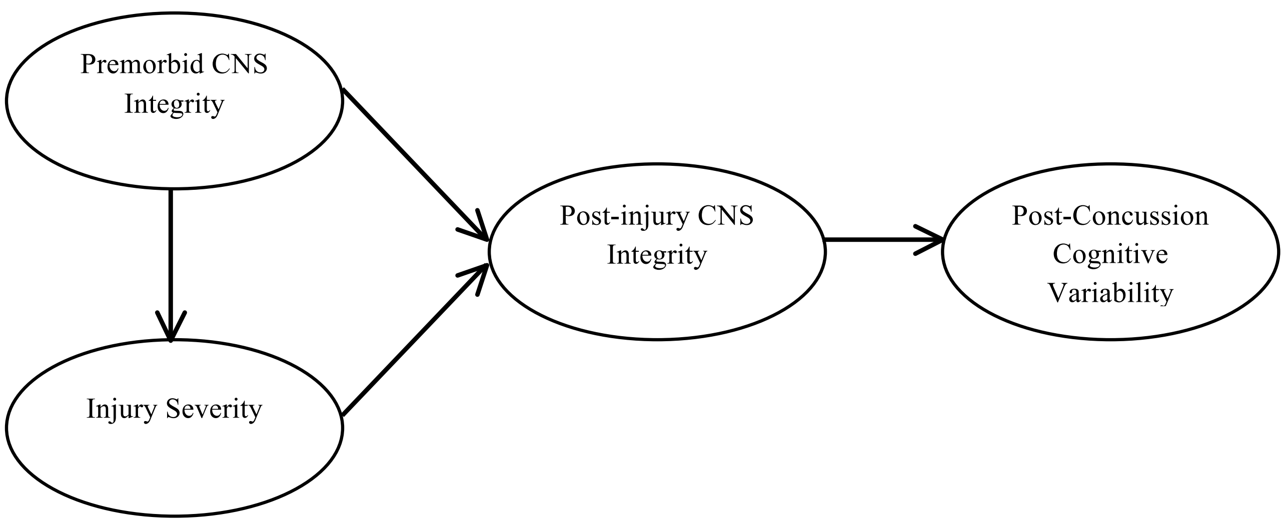


Figure 6.2. Theoretical model of contributors to post-injury cognitive vulnerability



References

Anstey, K. J., Mack, H. A., Christensen, H., Li, S. C., Reglade-Meslin, C., Maller, J., . . . Sachdev, P. (2007). Corpus callosum size, reaction time speed and variability in mild cognitive disorders and in a normative sample. *Neuropsychologia, 45*(8), 1911-1920.

Backman, L., Nyberg, L., Lindenberger, U., Li, S. C., & Farde, L. (2006). The correlative triad among aging, dopamine, and cognition: current status and future prospects. *Neuroscience & Biobehavioral Reviews, 30*(6), 791-807.

Baddeley, A. (1986). Working Memory. Oxford, UK: Oxford University Press.

Bailey, C. M., Echemendia, R. J., & Arnett, P. A. (2005). *Visual memory predicts concussion status independent of verbal memory and post-mild traumatic brain injury symptoms in college athletes.* Paper presented at the 33rd annual meeting of the International Neuropsychological Society, St. Louis, MO.

Bailey, C. M., Echemendia, R. J., & Arnett, P. A. (2006). The impact of motivation on neuropsychological performance in sports-related mild traumatic brain injury. *Journal of the International Neuropsychological Society, 12*(04), 475-484.

Baron, R. M., & Kenny, D. A. (1986). The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology, 51*(6), 1173.

Barth, J. T., Alves, W. M., Ryan, T. V., Macciocchi, S. N., Rimel, R. W., Jane, J. A., & Nelson, W. E. (1989). Mild head injury in sports: Neuropsychological sequelae and recovery of function. In H. S. Levin, H. M. Eisenberg & A. L. Benton (Eds.), *Mild Head Injury* (pp. 257-275). New York: Oxford University Press.

Bashore, T. R., & Ridderinkhof, K. R. (2002). Older age, traumatic brain injury, and cognitive slowing: Some convergent and divergent findings. *Psychological Bulletin, 128*(1), 151.

Belanger, H. G., & Vanderploeg, R. D. (2005). The neuropsychological impact of sports-related concussion: a meta-analysis. *Journal of the International Neuropsychological Society, 11*(04), 345-357.

Benedict, R. H. B. (1997). *Brief Visuospatial Memory Test - Revised: Professional Manual*. Odessa, Florida: Psychological Assessment Resources.

Benedict, R. H. B., Schretlen, D., Groninger, L., & Brandt, J. (1998). Hopkins Verbal Learning TestñRevised: Normative data and analysis of inter-form and test-retest reliability. *The Clinical Neuropsychologist, 12*(1), 43-55.

Berridge, K. C., & Robinson, T. E. (2003). Parsing reward. *TRENDS in Neurosciences, 26*(9), 507-513.

Binder, L. M., Iverson, G. L., & Brooks, B. L. (2009). To Err is human:" Abnormal" neuropsychological scores and variability are common in healthy adults. *Archives of Clinical Neuropsychology, 24*(1), 31.

Bohnen, N., Twijnstra, A., Jolles, J., Moller, J. T., Cluitmans, P., Rasmussen, L. S., . . . Metsemakers, J. F. M. (1992). Performance in the Stroop color word test in relationship to the persistence of symptoms following mild head injury. *Acta. Neuro.] Scancl, 85*, 116-121.

Britton, T. C., Meyer, B. U., & Benecke, R. (1991). Variability of cortically evoked motor responses in multiple sclerosis. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 81*(3), 186-194.

Bruce, J. M., & Echemendia, R. J. (2003). Delayed-Onset Deficits in Verbal Encoding Strategies Among Patients With Mild Traumatic Brain Injury. *Neuropsychology, 17*(4), 622-629.

Bunce, D. J., Warr, P. B., & Cochrane, T. (1993). Blocks in choice responding as a function of age and physical fitness. *Psychology and Aging, 8*(1), 26-33.

Cantu, R. C. (2007). Chronic traumatic encephalopathy in the National Football League. *Neurosurgery, 61*(2), 223.

Cantu, R. C., & Voy, R. (1995). Second impact syndrome—a risk in any contact sport. *Physician and Sportsmedicine, 23*(6), 27-35.

Cole, D. A., & Maxwell, S. E. (2003). Testing mediational models with longitudinal data: Questions and tips in the use of structural equation modeling. *Journal of Abnormal Psychology, 112*(4), 558.

Collie, A., Makdissi, M., Maruff, P., Bennell, K., & McCrory, P. (2006). Cognition in the days following concussion: comparison of symptomatic versus asymptomatic athletes. *Journal of Neurology, Neurosurgery & Psychiatry, 77*(2), 241.

Duckworth, A. L., Quinn, P. D., Lynam, D. R., Loeber, R., & Stouthamer-Loeber, M. (2011). Role of test motivation in intelligence testing. *Proceedings of the National Academy of Sciences*.

Dupuis, F., Johnston, K. M., Lavoie, M., Lepore, F., & Lassonde, M. (2000). Concussions in athletes produce brain dysfunction as revealed by event-related potentials. *Neuroreport, 11*(18), 4087.

Echemendia, R. J., & Cantu, R. C. (2003). Return to play following sports-related mild traumatic brain injury: the role for neuropsychology. *Applied Neuropsychology, 10*(1), 48-55.

Echemendia, R. J., & Julian, L. J. (2001). Mild traumatic brain injury in sports: neuropsychology's contribution to a developing field. *Neuropsychology Review, 11*(2), 69-88.

Echemendia, R. J., Putukian, M., Mackin, R. S., Julian, L., & Shoss, N. (2001). Neuropsychological test performance prior to and following sports-related mild traumatic brain injury. *Clinical Journal of Sport Medicine, 11*(1), 23.

Gaetz, M. (2004). The neurophysiology of brain injury. *Clinical Neurophysiology, 115*(1), 4-18.

Guskiewicz, K. M., Marshall, S. W., Bailes, J., McCrea, M., Cantu, R. C., Randolph, C., & Jordan, B. D. (2005). Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery, 57*(4), 719.

Guskiewicz, K. M., McCrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., . . . Kelly, J. P. (2003). Cumulative effects associated with recurrent concussion in collegiate football players. *The Journal of the American Medical Association, 290*(19), 2549.

Halpern, D. F. (1997). Sex differences in intelligence: Implications for education. *American Psychologist, 52*(10), 1091-1102.

Hicks, L. H., & Birren, J. E. (1970). Aging, brain damage, and psychomotor slowing. *Psychological Bulletin, 74*(6), 377.

Hillary, F. G. (2008). Neuroimaging of working memory dysfunction and the dilemma with brain reorganization hypotheses. *Journal of the International Neuropsychological Society, 14*(04), 526-534.

Hillary, F. G., Genova, H. M., Chiaravalloti, N. D., Rypma, B., & DeLuca, J. (2006). Prefrontal modulation of working memory performance in brain injury and disease. *Human Brain Mapping, 27*(11), 837-847.

Holland, P. W. (1986). Statistics and causal inference. *Journal of the American Statistical Association, 81*(396), 945-960.

Holtzer, R., Verghese, J., Wang, C., Hall, C. B., & Lipton, R. B. (2008). Within-person across-neuropsychological test variability and incident dementia. *The Journal of the American Medical Association, 300*(7), 823.

Hultsch, D. F., & MacDonald, S. W. S. (2004). Intraindividual variability in performance as a theoretical window onto cognitive aging. In R. A. Dizon, L. Bäckman, & L. -G. Nilsson (Eds.), *New Frontiers in Cognitive Aging*, (pp. 65-88). Oxford, UK: Oxford University Press.

Hultsch, D. F., MacDonald, S. W. S., Hunter, M. A., Levy-Bencheton, J., & Strauss, E. (2000). Intraindividual variability in cognitive performance in older adults: Comparison of adults with mild dementia, adults with arthritis, and healthy adults. *Neuropsychology, 14*(4), 588-598.

Hultsch, D. F., Strauss, E., Hunter, M. A., & MacDonald, S. W. S. (2008). Intraindividual variability, cognition, and aging. *The Handbook of Aging and Cognition, 3*, 491-556.

Ilgen, D. R., Nebeker, D. M., & Pritchard, R. D. (1981). Expectancy theory measures: An empirical comparison in an experimental simulation. *Organizational Behavior and Human Performance, 28*(2), 189-223.

Iverson, G. L., Lovell, M., & Collins, M. (2005). Validity of ImPACT for measuring processing speed following sports-related concussion. *Journal of Clinical and Experimental Neuropsychology, 27*(6), 683-689.

Iverson, G. L. (2007). Predicting slow recovery from sport-related concussion: the new simple-complex distinction. *Clinical Journal of Sport Medicine, 17*(1), 31.

Iverson, G. L., & Binder, L. M. (2000). Detecting exaggeration and malingering in neuropsychological assessment. *The Journal of Head Trauma Rehabilitation, 15*(2), 829.

Iverson, G. L., Brooks, B. L., Lovell, M. R., & Collins, M. W. (2006). No cumulative effects for one or two previous concussions. *British Journal of Sports Medicine, 40*(1), 72.

Iverson, G. L., Lovell, M. R., & Collins, M. W. (2005). Validity of ImPACT for measuring processing speed following sports-related concussion. *Journal of Clinical and Experimental Neuropsychology, 27*(6), 683-689.

Jacobson, N. S., & Truax, P. (1991). Clinical significance: A statistical approach to defining meaningful change in psychotherapy research. *Journal of Consulting and Clinical Psychology, 59*(1), 12.

Kelly, A. M., Uddin, L. Q., Biswal, B. B., Castellanos, F. X., & Milham, M. P. (2008). Competition between functional brain networks mediates behavioral variability. *Neuroimage, 39*(1), 527-537.

Kenny, D. A., Kashy, D. A., & Bolger, N. (1998). *Data analysis in social psychology* (4th ed. Vol. 1). New York: McGraw-Hill.

Kliegel, M., & Sliwinski, M. (2000). MMSE cross-domain variability predicts cognitive decline in centenarians. *Gerontology, 50*(1), 39-43.

Kochunov, P., Thompson, P. M., Coyle, T. R., Lancaster, J. L., Kochunov, V., Royall, D., . . . Fox, P. T. (2008). Relationship among neuroimaging indices of cerebral health during normal aging. *Human Brain Mapping, 29*(1), 36-45.

Kraus, M. F., Susmaras, T., Caughlin, B. P., Walker, C. J., Sweeney, J. A., & Little, D. M. (2007). White matter integrity and cognition in chronic traumatic brain injury: a diffusion tensor imaging study. *Brain, 130*(10), 2508.

Kutner, K. C., Erlanger, D. M., Tsai, J., Jordan, B., & Relkin, N. R. (2000). Lower cognitive performance of older football players possessing Apolipoprotein E ε4. *Neurosurgery, 47*(3), 651.

Lezak, M. D., Howieson, D. B., & Loring, D. W. (2005). *Neuropsychological Assessment, 4th Edition* (4th ed.). New York: Oxford University Press.

Lovden, M., Li, S. C., Shing, Y. L., & Lindenberger, U. (2007). Within-person trial-to-trial variability precedes and predicts cognitive decline in old and very old age: Longitudinal data from the Berlin Aging Study. *Neuropsychologia, 45*(12), 2827-2838.

Lovell, M. R., Collins, M. W., Podell, K., Powell, J., & Maroon, J. (2000). ImPACT: Immediate post-concussion assessment and cognitive testing. *Computer software. Pittsburgh, PA: NeuroHealth Systems, LLC.*

Macdonald, S. W. S., Li, S. C., & Backman, L. (2009). Intraindividual Variability and Aging. *Psychology and Aging, 24*(4), 792-808.

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., . . . Kelly, J. P. (2003). Acute effects and recovery time following concussion in collegiate football players. *The Journal of the American Medical Association, 290*(19), 2556.

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: implications for prevention. *Clinical Journal of Sport Medicine, 14*(1), 13.

McCrory, P. (2011). Sports concussion and the risk of chronic neurological impairment. *Clinical Journal of Sport Medicine, 21*(1), 6.

McKee, A. C., Cantu, R. C., Nowinski, C. J., Hedley-Whyte, E. T., Gavett, B. E., Budson, A. E., . . . Stern, R. A. (2009). Chronic traumatic encephalopathy in athletes: progressive tauopathy following repetitive head injury. *Journal of Neuropathology and Experimental Neurology, 68*(7), 709.

Miller, E. (1970). Simple and choice reaction time following severe head injury. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior, 6*(1), 121-127.

Muthén, L., & Muthén, B. (2009). Mplus statistical modeling software (Version Version 5.21). Los Angeles.

Peters, A. (2002). The effects of normal aging on myelin and nerve fibers: a review. *Journal of Neurocytology, 31*(8), 581-593.

Ponsford, J., & Kinsella, G. (1992). Attentional deficits following closed-head injury. *Journal of Clinical and Experimental Neuropsychology, 14*(5), 822-838.

Posner, M. I. (1994). Attention: the mechanisms of consciousness. *Proceedings of the National Academy of Sciences of the United States of America, 91*(16), 7398.

Posner, M. I., & Dehaene, S. (1994). Attentional networks. *Trends in Neurosciences, 17*(2), 75-79.

Ragan, B. G., & Kang, M. (2007). Measurement Issues in Concussion Testing. *Athletic Therapy Today, 12*, 2-6.

Ram, N., Rabbitt, P., Stollery, B., & Nesselroade, J. R. (2005). Cognitive performance inconsistency: Intraindividual change and variability. *Psychology and aging, 20*(4), 623-633.

Randolph, C., McCrea, M., & Barr, W. B. (2005). Is neuropsychological testing useful in the management of sport-related concussion? *Journal of Athletic Training, 40*(3), 139.

Salthouse, T. A. (2007). Implications of within-person variability in cognitive and neuropsychological functioning for the interpretation of change. *Neuropsychology, 21*(4), 401.

Sarter, M., Gehring, W. J., & Kozak, R. (2006). More attention must be paid: the neurobiology of attentional effort. *Brain Research Reviews, 51*(2), 145-160.

Schatz, P., Pardini, J. E., Lovell, M. R., Collins, M. W., & Podell, K. (2006). Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Archives of Clinical Neuropsychology, 21*(1), 91-99.

Schretlen, D. J., Munro, C. A., Anthony, J. C., & Pearlson, G. D. (2003). Examining the range of normal intraindividual variability in neuropsychological test performance. *Journal of the International Neuropsychological Society, 9*(06), 864-870.

Schwarz, A. (2010). Penn fotball player had signs of disease seen in N.F.L., *The New York Times*.

Schwarz, A. (2011). Duerson's brain trauma diagnosed, *The New York Times*.

Schwarz, A., & Klien, J. Z. (2011). Hockey brawler paid price, with brain trauma, *The New York Times*.

Smith, A. (1982). *Symbol Digit Modalities Test (SDMT) Manual (Revised)*. Los Angeles: Western Psychological Services.

Sowell, E. R., Peterson, B. S., Thompson, P. M., Welcome, S. E., Henkenius, A. L., & Toga, A. W. (2003). Mapping cortical change across the human life span. *Nature Neuroscience, 6*(3), 309-315.

Stern, Y. (2003). The concept of cognitive reserve: a catalyst for research. *Journal of Clinical and Experimental Neuropsychology, 25*(5), 589-593.

Stokx, L. C., & Gaillard, A. W. K. (1986). Task and driving performance of patients with a severe concussion of the brain. *Journal of Clinical and Experimental Neuropsychology, 8*(4), 421-436.

Stuss, D. T., Murphy, K. J., Binns, M. A., & Alexander, M. P. (2003). Staying on the job: the frontal lobes control individual performance variability. *Brain, 126*(11), 2363.

Terrell, T. R., Bostick, R. M., Abramson, R., Xie, D., Barfield, W., Cantu, R., . . . Ewing, T. (2008). APOE, APOE promoter, and Tau genotypes and risk for concussion in college athletes. *Clinical Journal of Sport Medicine, 18*(1), 10.

The Psychological Corporation. (2001). *The Wechsler Test of Adult Reading (WTAR):Test Manual*. San Antonio, TX: The Psychological Corporation.

Thunnan, D. J., Branche, C. M., & Sniezek, J. E. (1998). The epidemiology of sports-related traumatic brain injuries in the United States: recent developments. *The Journal of Head Trauma Rehabilitation, 13*(2), 1.

Trenerry, M. R., Crosson, B., DeBoe, J., & Leber, W. R. (1989). Stroop neuropsychological screening test. *Odessa, FL: Psychological Assessment Resources*.

Vanderploeg, R. D., Curtiss, G., & Belanger, H. G. (2005). Long-term neuropsychological outcomes following mild traumatic brain injury. *Journal of the International Neuropsychological Society, 11*(03), 228-236.

Walhovd, K. B., & Fjell, A. M. (2007). White matter volume predicts reaction time instability. *Neuropsychologia, 45*(10), 2277-2284.

Wanous, J. P., Reichers, A. E., & Hudy, M. J. (1997). Overall job satisfaction: How good are single-item measures? *Journal of applied Psychology, 82*(2), 247.

Wechsler, D. (1997). Wechsler Adult Intelligence Scale-III (WAIS-III). *New York: Psychological Corporation*.

West, R., Murphy, K. J., Armilio, M. L., Craik, F. I. M., & Stuss, D. T. (2002). Lapses of Intention and Performance Variability Reveal Age-Related Increases in Fluctuations of Executive Control. *Brain and Cognition, 49*(3), 402-419.

Wilde, E., McCauley, S., Hunter, J., Bigler, E., Chu, Z., Wang, Z., . . . Li, X. (2008). Diffusion tensor imaging of acute mild traumatic brain injury in adolescents. *Neurology, 70*(12), 948.

Amanda R. Rabinowitz

Education

The Pennsylvania State University, University Park, PA
Doctor of Philosophy in Psychology, August 2012

Alpert Medical School of Brown Univeristy, Providence RI
Predoctoral Internship in Clinical Psychology—Neuropsychology Track, June 2012

The Pennsylvania State University, University Park, PA
Masters of Science in Clinical Psychology, May 2008

University of Pennsylvania, Philadelphia, PA
Bachelor of Arts in Psychology & Cognitive Neuroscience, May 2003

Select Awards & Honors

2011 Wisniewski Family Enhancement Award, Penn State Psychology Department
2010 Benton-Meier Neuropsychology Scholarship, American Psychological Foundation
2010 Penn State Research and Graduate Office (RGSO) Dissertation Enhancement Award
2010 Penn State RGSO Dissertation Support Award
2010 Penn State Graduate Student Exhibition Award, 3rd Place (Soc. and Beh. Sciences)
2010 RGSO Travel Award
2009 PSU Psychology Department Outstanding Publication by a Graduate Student
2008 The International Neuropsychological Society Meritorious Poster

Select Publications:

Ramanathan, D., **Rabinowitz., A.R.,** Barwick, F.H., & Arnett, P.A. (2011). Validity of Affect Measurements in Evaluating Symptom Reporting in Athletes. *Journal of the International Neuropsychological Society.* 18, 101-107.

Rabinowitz, A.R., Arnett, P.A. (2011). Reading-based IQ estimates and actual premorbid cognitive performance: Discrepancies in a college athlete sample. *Journal of the International Neuropsychological Society.* 18, 139-143.

Rabinowitz, A.R., Fisher, A., & Arnett, P.A. (2010). Neurovegetative symptoms of depression in patients with multiple sclerosis: Fatigue not depression. *Journal of the International Neuropsychological Society*. 16, 46-55.

Rabinowitz, A.R. & Arnett, P.A (2009). A longitudinal analysis of cognitive dysfunction, coping, and depression in multiple sclerosis. *Neuropsychology, 23*(5), 581-591

Pettinati, H.M, Kampman, K.M, Lynch, K.G., Xie, H., Dackis, C., **Rabinowitz, A.R.,** O'Brien, C.P. (March, 2008). A double-blind, placebo-controlled trial of the combination of disulfiram and naltrexone for the treatment of co-occurring cocaine and alcohol dependence. *Addictive Behaviors,* 33, 651-667

Pettinati, H.M., O'Brien, C.P., **Rabinowitz, A.R.**, Wortman, S.M., Oslin, D.W., Kampman, K.M., Dackis, C., Lynch, K.G. (December, 2006). The status of naltrexone in the treatment of alcohol dependence: specific effects on heavy drinking. *Journal of Clinical Psychopharmacology,* 26, 610-625