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Visually-guided Reaching Under Varying Cognitive and Motor Demand in Young Adult Females with a History of Concussions

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VISUALLY-GUIDED REACHING UNDER VARYING COGNITIVE AND MOTOR DEMAND IN YOUNG ADULT FEMALES WITH A HISTORY OF CONCUSSIONS

by

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ABSTRACT

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Every day, vision guides one's actions to help one successfully navigate through a complex environment. When our visual and motor systems interact efficiently, we may not fully appreciate how flawless and beneficial this process can be to our daily functioning. Yet, one's available neural resources needed to successfully perform visually-guided movements do have limits. When an individual suffers a brain injury, such as a concussion, the available resources may be compromised. Examining the extent of this decreased resource pool requires challenging the cognitive abilities enough to observe a behavioral deficit. The purpose of this study was to examine the long-term effects of a history of concussions in young adult females on visuomotor behavior during a visually-guided reaching task of various complexities. We hypothesized that by manipulating an increase of both cognitive and motor demand, visuomotor behavior would decrease more in individuals with a history of concussion than those without a history of concussion. Twenty females without a history of concussion (age: 21.2 ± 2.16 years) and twenty females with a history of concussion (age: 22.3 ± 2.43 years) quickly and accurately performed a delayed reach to a previously cued location. To control for confounding factors, information was collected regarding the participants' head injury history, lifestyles, and level of sports participation. The visually guided reaching task was manipulated by varying the complexities of cognitive and motor demand to alter attentional load. As both cognitive and motor load increased, task performance decreased for both groups ($p < .05$). However, contrary to our primary hypothesis, no differences in task performance were found between the two experimental groups ($p > .05$). While confounding variables of age, sex, time since last concussion (i.e. acute vs. long-term), stimulant use, sleep patterns, and prescription medication for mood disorders were either controlled or considered during the analysis, participants in the two groups did differ on level of sports participation ($p < .05$), when accounting for this difference, still no changes in performance were identified ($p < .05$) on the dependent measures. The young adult females with a history of concussion demonstrated no deficits in visuomotor behavior on an attention-mediated reaching task as compared to control participants. Future studies should include an assessment of both motivation and competitiveness of the participants. Furthermore, longitudinal studies are needed to assess if the normal declines in visuomotor behavior due to healthy aging are accentuated by a history of concussion.

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Chapter 1: Introduction

Mild traumatic brain injuries, or concussions, have become a public health concern of large magnitude (National Center for Injury Prevention and Control, 2003). An estimated 1.6 million to 3.8 million sports related concussions occur annually in the U.S. (Langlois, Rutland-Brown, & Wald, 2006); however, the actual incidence of concussions may be higher due do athletes not reporting their injury (Echlin et al., 2010; McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004). The annual cost of concussions is estimated at $16.7 billion, but this number may be a gross underestimation since non-hospitalizations are not considered in this figure (National Center for Injury Prevention and Control, 2003). Because mild traumatic brain injuries have become a public health concern, concussions have also captured the attention of the mainstream media. From the PBS Frontline special *League of Denial: The NFL's Concussion Crisis* to the feature-length film, *Concussion,* starring Will Smith, more and more individuals are being made aware of this injury. In March 2015, after only one year in the NFL, 24-year-old Chris Borland retired from professional football. Borland, diagnosed with two concussions before his NFL career started, decided that continuing to play football in the NFL was not worth the risk due to possible long-term effects of head injuries (Fainaru-Wada & Fainaru, 2015). This decision resurfaced discussions of the potential long-term effects of concussions, as well as the effects of multiple concussions. Once thought to be a minor injury that an athlete should just "tough out and play through", concussions warrant the attention from both the medical and scientific community to better understand this injury.

While awareness for the prompt identification and appropriate immediate treatments for concussions continues to advance, a concurrent need exists to understand the long-term effects of concussions, as well as the effects of multiple concussions. Experimental assessment of both the long-term effects of concussions and the effects of multiple concussions on individuals usually falls into one of two categories: cognitive function testing or motor function testing. Neuropsychological investigations of cognitive function in individuals who have sustained multiple concussions revealed overall cognitive decline (Guskiewicz et al., 2005; Teasdale & Engberg, 1997), poorer verbal memory (Covassin, Elbin, Kontos, & Larson, 2010; Covassin, Moran, & Wilhelm, 2013; Iverson, Echemendia, Lamarre, Brooks, & Gaetz, 2012), longer processing speed (Collins et al., 1999; Gardner, Shores, & Batchelor, 2010; Shuttleworth-Rdwards & Radloff, 2008), poorer visuospatial memory (Covassin et al., 2010), and attentional deficits (Collins et al., 1999; Wall et al., 2006). Motor deficits identified in previously concussed individuals found decreased postural stability and bradykinesia (De Beaumont, Henry, & Gosselin, 2012), reduced upper limb movement accuracy and slowed ballistic velocity (Heitger et al., 2006), and increased choice reaction times (Brown, Dalecki, Hughes, Macpherson, & Sergio, 2015). Although independently assessing cognitive and motor functioning has its merits, a gap exists in the current body of literature that may prevent researchers from detecting behavioral deficits. Cognitive and motor systems cannot only function independently, but also interact with each other. Furthermore, the attentional resources needed to complete any task are finite. However, traditional methods of testing individuals who have sustained a concussion often fall short of sufficiently challenging the participants to their attentional capacity limits. Thus, behavioral deficits may otherwise go undetected. Therefore, a need exists to examine this cognitive-motor interaction with a task that sufficiently challenges a previously concussed individual to the limit of their capacity of attentional resources.

Every day, vision guides one's actions to help one successfully navigate through a complex environment. Visuomotor behavior can be exemplified with tasks as simple as reaching for a pot on the stove to remove it before the pot boils over; to walking down a sidewalk while talking to a friend, yet still avoiding any cracks or potholes as to avoid a fall; or more complex behavior such as when driving a car during rush hour traffic and taking corrective actions to avoid a motor vehicle accident. When our visual and motor systems interact efficiently, we may not fully appreciate how beneficial flawless visuomotor behavior can be to our daily functioning. However, when damage to the brain occurs, either due to injury or disease, deficits in visuomotor behavior can arise. These deficits can have adverse effects on day-to-day activities, which may lead to a decreased quality of life. Deficits in visuomotor behavior have been studied in various populations who have suffered from either brain damage or disease including stroke or Alzheimer's disease. Stroke survivors have also shown deficits in visuomotor behavior (i.e. visual attention) that were significantly correlated with increased fall rates and decreased capability to perform activities of daily living (Hyndman & Ashburn, 2003). Patients diagnosed with Alzheimer's disease have shown impaired visuomotor integration correlated to cognitive decline that has implications for successfully completing more complex visuomotor tasks such as ascending a flight of stairs (Tippett & Sergio, 2006).

Visuomotor behavior has also been investigated in individuals who have sustained one or more concussions, although the results have been equivocal. Visuomotor behavioral deficits, when compared to healthy controls, include: slower reaction times in a reverse choice lower extremity stepping task (Gagnon, Swaine, Friedman, & Forget, 2004), impaired upper limb visuomotor performance on a 1D tracking task (Heitger et al., 2004; Heitger et al., 2006), decreased visuomotor processing speed on Trail Making Test A and B (Shuttleworth-Rdwards & Radloff, 2008), decreased obstacle avoidance while performing a secondary attention task (Catena, van Donkelaar, Halterman, & Chou, 2009), and altered gait kinematics during a varying obstacle avoidance task (Baker & Cinelli, 2014). Conversely, others have found no difference in reaction times on upper extremity pointing task (Gagnon et al., 2004) and no differences in reaction times during a pointing task with varied target size (Locklin, Bunn, Roy, & Danckert, 2010).

Potential factors leading to the inconsistent results reported above include variation in time since injury, age and sex of the participants, and the number of previous concussions, and level of cognitive demand by altering task complexity. First, time since injury varied from acute up to long-term, thus mixing acute and long-term effects (Locklin et al., 2010). Second, ages of participants have varied from children (7-16 years old), to young adults (ages 18-23, 15-25, 18-27 & 17-23) to a wide range of ages (15-37 & 15-56 years old), which could give conflicting results due to possible effects of age on post concussive recovery (Covassin, Elbin, Harris, Parker, & Kontos, 2012; Wall et al., 2006). Third, post-concussion experimental investigations have suggested differences between males and females, thus warranting the need to investigate each sex separately (Covassin et al., 2012), yet in previous visuomotor investigations, both sexes were included in the final analysis with no consideration to sex differences. Fourth, in previous studies of visuomotor behavior in previously concussed individuals, the number of previous concussions is not always reported. While Locklin and colleagues (2010) reported the number of previous concussions from their participants (1-6 previous concussions), all participants were included in the analysis as a single group. Furthermore, the cumulative effects of multiple concussions on cognitive-motor function has yet to be fully elucidated and demands on-going investigation (Belanger, Spiegel, & Vanderploeg, 2010; Collins et al., 2002; Covassin et al., 2013; De Beaumont et al., 2012; Iverson, Brooks, Lovell, & Collins, 2006; Iverson et al., 2012). Finally, even though cognitive demand has varied in some experiments of visuomotor behavior in previously concussed individuals, questions have arisen as to whether enough cognitive load was used to truly tax the participants' abilities (Locklin et al., 2010). Perhaps the experimental tasks have not sufficiently challenged the participants and actual behavioral deficits have been masked in the findings.

Statement of Purpose

The purpose of this study is to examine the long-term effects of a history of multiple concussions in young adult females on visuomotor behavior during a visually-guided reaching task of various complexities. We hypothesize that by manipulating an increase of both cognitive and motor demand, visuomotor behavior will decrease most in participants with a history of three or more concussions as compared to individuals with either one or two previous concussion or no history of concussion.

Delimitations

Results of this study may only be generalized to individuals or populations that are similar to the sample population. Specifically, these results are applicable only to females, ages 18-29 who have sustained multiple concussions, and are currently asymptomatic by current standards.

Assumptions

The following assumptions are made:

- Participants will be truthful and honest when answering survey questions.
- Participants give their best and equal effort during each trial of the visually-guided reaching task and have a consistent state of arousal.

Significance

With an estimated 3.8 million cases occurring annually, concussions continue to be a public health concern requiring an ongoing need to learn more about the long-term effects of multiple concussions. Furthermore, novel experimental designs, such as examining visuomotor behavior, can provide insights into possible deficits that may have previously been undetected using cognitive or motor methodology independently. In addition, individuals with a history of concussion are typically not sufficiently challenged to the limits of their attentional resources. Their available resources to complete a given experimental task outweigh the cognitive demands of the task thus actual behavioral deficits may be masked. While investigations in the past have examined deficits in visuomotor behavior in previously concussed individuals, significant variation in factors such as time since injury, age and sex of the participants, concussion history (one versus multiple concussions), as well as varying the cognitive demand by altering task complexity may have complicated any interpretation of the broader body of literature. To our knowledge, this study will be the first to control for these factors while examining the long-term behavioral deficits prevalent in an understudied population who has received multiple brain injuries. The results of this study will help identify behavioral deficits that may negatively influence activities of daily living that may result in a decreased quality of life. From this exploratory knowledge, future experimental designs can be developed to build on the results of this study to determine if a causal link can be established between repetitive concussions and deficits in visuomotor behavior. Furthermore, this study can be used as a stepping-stone to aide in developing rehabilitative protocols to insure individuals who have sustained multiple concussions can experience an unimpeded quality of life.

Definition of terms

Acute. Acute refers to the timeframe immediately after the injury has occurred when the individual is still symptomatic. Most (80-90%) concussion cases resolve within seven to ten days post-injury (McCrory et al., 2013) thereby determining the acute phase to be this same timeframe.

Concussion. Also called a mild Traumatic Brain Injury (mTBI). Concussion is "…a complex pathophysiological process affecting the brain, induced by biomechanical forces" (McCrory et al., 2013). An in-depth discussion of the definition of a concussion will be conducted in the review of literature section.

Long-Term. While no clear definition of long-term post-concussion exists, previous investigators have used six months, or longer, post injury to classify an individual in the long-term phase. Therefore, we also will use the six month or longer post injury marker. It should be noted, the term *chronic* is sometimes used synonymously with *long-term*. Chronic implies lingering effects from the initial injury while long-term implies the individual is asymptomatic, thus long-term is exclusively appropriate for this investigation.

Mild Cognitive Impairment. Mild Cognitive Impairment is a clinical diagnosis of cognitive decline that is greater than expected based on an individual's age and education level but is not yet dementia. Activities of daily living are minimally affected (Feldman & Jacova, 2005; Gauthier et al., 2006).

Visuomotor Behavior. Visuomotor behavior can be defined as the use of visual information to guide motor actions (Goodale, 1998). Visuomotor behavior will be further defined in the review of literature section.

Chapter 2: Review of Literature

Introduction

Mild traumatic brain injuries, or concussions, have captivated the news media as well as become a major health concern. Every week a new story seems to creep into the popular press regarding concussions. Whether the backdrop is youth sports, professional athletes, military personnel, or civilians, concussions have affected millions of lives. Despite the increase in attention over the last two decades by both the scientific and lay communities, many of the questions regarding mTBI remain unresolved. One such aspect of concussions that is mired in conflicting results is the long-term effects of multiple concussions on an individual. Contributing to the conflicting results are both the widely distributed demographics of the participants as well as the various methodologies used. Thus, controlling for confounding factors as well as designing an appropriate task to test for long-term deficits due to concussions is a much needed gap. Visually-guided reaching may offer insight into behavioral deficits due to multiple concussions that have been undetected by more traditional methods. Furthermore, visually-guided reaching is an essential function of daily living such as reaching for a glass, opening a door, brushing one's teeth, and driving a car. This investigation of the long-term effects of concussions on visuomotor behavior will carefully control for confounding factors to offer insights previously gone undetected. This review of literature will discuss the following topics: (1) Mild traumatic brain injury/concussion including definition of the injury, pathophysiology of mTBI, incidence and cost, problematic issues with self-report of mTBI; (2) Sequelae of mTBI including post-injury cognitive behaviors, post-injury motor behaviors; (3) Factors influencing post-mTBI outcomes including sex differences, age differences, severity of injury, multiple mTBI; and (4) Visuomotor behavior including definitions, visual attention to motor intention, attentional resources, deficits in visuomotor behavior, and visuomotor behavior and mTBI

Mild Traumatic Brain Injury/Concussion

Mild traumatic brain injury, or concussion, has been mired in ambiguity that has led to problematic issues in the empirical literature. Before any behavioral outcomes resulting from a concussion can be discussed, an overview of the injury is warranted to help alleviate some of the ambiguity. This overview has four aims: (1) define the injury for the purposes of this study, (2) discuss the pathophysiology of the injury, (3) analyze the incidence and cost of the injury, and (4) examine problems associated with the self-report of the injury. The overall purpose of this overview is to provide clarity as to why this study should investigate individuals whom have sustained a concussion.

Definition of the Injury

One of the persistent issues with mild traumatic brain injuries (mTBI), commonly referred to as concussions, is the definition of the injury. Both in the lay vernacular and the empirical literature the terms “mTBI” and “concussion” have been used synonymously to describe the same injury to the brain (Centers for Disease Control and Prevention, 2013; McCrory et al., 2013; Wiebe, Comstock, & Nance, 2011). However, it has also been suggested that *mTBI* should refer to non-sport injuries to the brain while *concussion* is used to describe sport-related injuries to the brain (Harmon et al., 2013; Sojka, 2011). While this differentiation may be relevant for clinical treatment, epidemiological investigations and severity grading scales (Sojka, 2011), separating the two terms suggests each term applies to a unique injury with different definitional criteria.

To resolve the definitional debate between mTBI and concussion, an examination of accepted definitions from the empirical literature is warranted. The American Congress of Rehabilitation Medicine has defined a mTBI as induced by an initial trauma to the head causing an acceleration/deceleration of the brain, which leads to a "physiological disruption of brain function as manifested by at least one of the following: (1) any period of loss of consciousness, (2) any loss of memory for events immediately before or after the accident, (3) any alteration in mental state at the time of the accident (e.g., feeling dazed, disoriented, or confused) and (4) focal neurological deficit(s) that may or may not be transient" (Kay et al., 1993, p. 86). Furthermore, brain imaging techniques such as computed tomography, magnetic resonance imaging and electroencephalogram may appear normal (Kay et al., 1993).

Conversely, the 4th International Conference on Concussion in Sport has currently defined a concussion as:

> Concussion is a brain injury and is defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces. Several common features that incorporate clinical, pathologic and biomechanical injury constructs that may be utilized in defining the nature of a concussive head injury include:
>
> (1) Concussion may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an "impulsive" force transmitted to the head.
> (2) Concussion typically results in the rapid onset of short-lived impairment of neurologic function that resolves spontaneously. However; in some cases, symptoms and signs may evolve over a number of minutes to hours.

(3) Concussion may result in neuropathological changes, but the acute clinical symptoms largely reflect a functional disturbance rather than a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies.

(4) Concussion results in a graded set of clinical symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive symptoms typically follows a sequential course. However, it is important to note that in some cases symptoms may be prolonged.

McCrory et al. (2013, p. 179)

When comparing the two definitions, more similarities exist than do differences. Both events begin with a biomechanical insult, which leads to an acceleration and deceleration of the brain. Both a mTBI and concussion result in some type of transient loss or altered state of neurological function. A loss of consciousness may occur; however, it is not required for the injury to be classified as either a concussion or mTBI. Alteration of mental state is common to both classifications. Both definitions highlight that structural changes of the brain are not detected by current neuroimaging techniques. Finally, while anterograde or retrograde amnesia is one of the possible criteria for a mTBI, amnesia is also one of the clinical symptom of concussions (McCrory et al., 2013; McLeod, Bay, Heil, & McVeigh, 2008).

Based on an evaluation of the two definitions and for this study, the term “mTBI” and “concussion” will be considered synonymous. Furthermore, the following definition will be used. A mild traumatic brain injury, or concussion, is a brain injury induced by a biomechanical force which results in the acceleration and deceleration of the brain. This leads to a pathophysiological process resulting in transient, altered neurological function. A loss of consciousness, as well as amnesia, may or may not occur. The injury itself cannot be detected by any traditional structural neuroimaging techniques (e.g. computed tomography scans or magnetic resonance imaging); however, newer neuroimaging techniques (e.g. diffusion tensor imaging) show promise for detecting a mTBI (Niogi & Mukherjee, 2010) .

Pathophysiology of mTBI

While the exact pathophysiology of a mTBI in human (Figure 1) has yet to be fully understood, animal models using mild fluid percussion have suggested a cascade of events that leads to an acute failure of neuronal function, or mTBI. The initial biomechanical insult

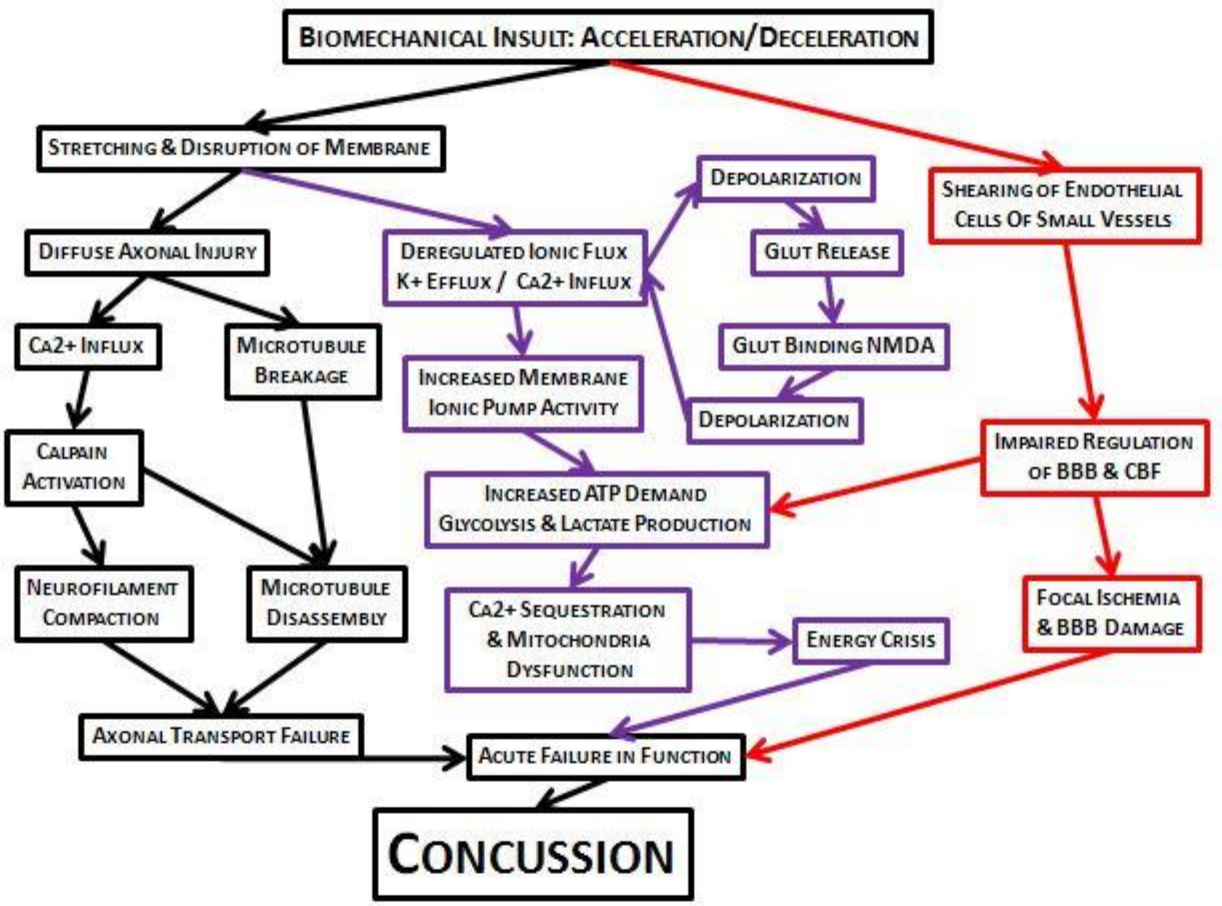

Figure 1. Proposed Pathophysiology of a Concussion. Abbreviations: GLUT: Glutamate. NMDA: N-methyl-D-aspartate; BBB: Blood Brain Barrier, CBF: Cerebral Blood Flow. Color Code: Black – Axon, Purple – Soma, Red – Vasculature. Modified from Blennow et al, 2012; Giza & Hovda, 2014.

causes an acceleration and deceleration of the brain in the cranium leading to a stretching and disruption of the cellular membrane of the neuron, both in the soma and axon (Giza & Hovda, 2001). In the axon, diffuse axonal injury (DAI) appears to be the primary mechanism of injury due primarily to decelerations (Blennow, Hardy, & Zetterberg, 2012). While axons are generally pliable, when they are subjected to accelerations and decelerations, axons become fragile and can tear due to shearing forces. DAI will set off two events, mechanical breakage of microtubules (Tang-Schomer, Patel, Baas, & Smith, 2010) as well as an influx of calcium ions (Barkhoudarian, Hovda, & Giza, 2011). Both of these events lead to a failure of axonal transport and an acute failure in function (Blennow et al., 2012).

In the soma, the cell membrane stretches and tears as in the axon which leads to a chain of events and impaired neuronal function. The micro-tears result in an imbalance of ions across the cell membrane of the neurons (Giza & Hovda, 2001). The uncontrolled exchange of ions triggers depolarizations and action potentials which releases the excitatory neurotransmitters, primarily glutamate, leading to a cycle of more depolarizations, action potentials, and glutamate release (Barkhoudarian et al., 2011). The constant activity of the neuron results in an imbalance of intra- and extracellular ions which causes increased ionic pump activity in the membranes to restore homeostasis (Mayevsky & Chance, 1974). However, this comes at a cost of increased demand for adenosine triphosphate (ATP), resulting in increased glycolysis and lactate production (Blennow et al., 2012). Calcium ions are sequestered to the mitochondria and mitochondrial dysfunction follows (Verweij et al., 1997). These events lead to an energy crisis in the neuron and an acute failure in function (Giza & Hovda, 2001).

The axon and soma of the neuron are not the only structures to be damaged by the initial concussive blow. In the cerebral vasculature, the initial acceleration and deceleration causes shearing of the endothelial cells of the small blood vessels (Blennow et al., 2012). Impaired regulation of the blood brain barrier and cerebral blood flow follows which leads to focal ischemia, blood brain barrier damage and contributes to the energy crisis in the soma since glucose and oxygen cannot be delivered efficiently; all contributing to an acute failure in function (Giza & Hovda, 2014).

The previous three failures in acute function in the soma, axon and cerebral vasculature lead to a mTBI (Blennow et al., 2012). Interestingly, in most animal models of mTBI, little cell death has been reported (Giza & Hovda, 2014). However, some cell death is thought to occur. For any neurons that have not been destroyed due to necrosis from the initial insult, axonal swelling and axotomy occurs in the axon which leads to apoptosis as well as calcium-mediated apoptosis in the soma (Barkhoudarian et al., 2011; Giza & Hovda, 2014).

Recently, events occurring during the pathophysiology of a concussion have been linked to clinical and behavioral outcomes. The energy crisis in the neurons has been linked to vulnerability for additional injuries (Giza & Hovda, 2014). Impaired cognition, decreased processing speeds as well as slower reaction times are thought to be due to either axonal injury or impairment of neurotransmitters (Giza & Hovda, 2014). Finally, both breakdown of the microtubules as well as cell death, either by necrosis or apoptosis, are likely associated with long-term behavioral impairments.

Taken together, the pathophysiology of mTBI is a complex event leading to acute altering of neurological function. The events of the cascade can manifest in behavioral deficits which can be measured.

Incidence and cost

As with the definition of a mTBI, determining the annual incidence of the injury is not without discrepancies. The Centers for Disease Control and Prevention (CDC) currently tracks all traumatic brain injuries (TBI), whether the injury is mild, moderate or severe, and reports the statistics as a whole without categorizing each level of the injury. In 2010, at least 2.5 million TBIs were reported in the United States with approximately 75% of the cases being classified as mild (Centers for Disease Control and Prevention, 2013). The estimated percentage is based on discharge rates, that is, patients discharged within the same day are deemed to have sustained a mTBI (Laker, 2011). Furthermore, the reported cases only include emergency room visits, hospitalizations and deaths, thus injuries having occurred or being treated outside of these venues are not reported. Therefore, the annual incidence is thought to be higher than currently reported estimates (National Center for Injury Prevention and Control, 2003).

When examining the incidence of sports related mTBI, the annual incidence rate is between 1.6 million and 3.8 million cases (Langlois et al., 2006). While this estimate attempts to include cases when no medical treatment is sought, the actual number could still be higher due to individuals not reporting their injury (Echlin et al., 2010; Langlois et al., 2006; McCrea et al., 2004). Furthermore, with sports-related mTBI, males have a higher incidence rate than females, with the main driver of this difference being American football (Lincoln et al., 2011; Marar, McIlvain, Fields, & Comstock, 2012). However, when examining shared sports such as soccer, basketball, volleyball and ice hockey, females have a higher incidence rate that males (Dick, 2009;

Marar et al., 2012) with some sports (baseball/softball, basketball, and soccer) the incidence rate of mTBI for females is twice that of males (Lincoln et al., 2011).

As with the annual incidence rate of mTBI, the annual cost of mTBI could also be an underestimation. In 2001, the estimated cost of TBI was $56 billion with mTBI accounting for $16.7 billion (National Center for Injury Prevention and Control, 2003). The 2010 numbers from the CDC have updated the cost of TBI to $76.5 billion (Centers for Disease Control and Prevention, 2013). While the cost of mTBI in 2010 is not given, based on the updated TBI cost, the $16.7 billion figure from 2001 is expected to be larger. Furthermore, as with the incidence rate, treatment outside of a hospital or emergency department are not included in these figures (National Center for Injury Prevention and Control, 2003). Also, injuries which are not reported also could drive the number up in terms of lost productivity or wages. Therefore, any estimate of the annual economic cost of mTBI is likely an underestimation.

Problematic Issues with Self-report of mTBI

Because mTBI cannot be detected by current neuroimaging techniques, diagnosis of the injury relies primarily on self-report symptoms by the patient, which presents inherent flaws: awareness of the injury and truthfulness of the individual. A survey of varsity high school football players (N = 1532, all males), only 47.3% of the athletes sustaining a concussion during that season reported his injury (McCrea et al., 2004). Also, a prospective study using independent physicians as observers of two junior hockey teams found the actual incidence of concussions was seven times higher than previously reported in the literature (Echlin et al., 2010). However, underreporting a mTBI is not a behavior exclusive to males. In a retrospective questionnaire of the previous season completed by university-level soccer players (N = 201, 110 females), only 19.8% of the athletes who had experienced the symptoms of a concussion realized the head injury was a concussion (Delaney, Lacroix, Leclerc, & Johnston, 2002).

To help collect the true history of previous mTBI, a concussion symptom survey (CSS) has been developed (LaBotz, Martin, Kimura, Hetzler, & Nichols, 2005). The CCS (Appendix D) lists fourteen common symptoms of concussions by frequency of occurrence, which are consistent with the empirical literature (LaBotz et al., 2005; Marshall, Guskiewicz, Shankar, McCrea, & Cantu, 2015; McLeod et al., 2008). When compared to a pre-participation physical examination (PPE), which only asks two generalized questions about previous head injuries, the CSS captured three times as many cases of concussions than the PPE (LaBotz et al., 2005, p. 74). Therefore, the addition of a concussion symptom survey can be beneficial when collecting mTBI history to ensure a truer picture of the injury occurrence in an individual.

Summary

The true impact of mTBI is feared to be an underestimate due to differences defining the injury, issues with reporting the occurrence and associated costs to national databases, as well as individuals simply not reporting the injury. Given the nature of *this* injury and the annual incidence of concussions, mTBI warrant the attention of the scientific community and specifically this study.

Sequelae of mTBI

As discussed in the previous section of this review, a physical insult to the head can set off a chain of events resulting in a concussion. After the injury has occurred, measurable changes in both cognitive and motor behaviors have been well-documented in the literature. During the acute post-injury phase, little debate exists regarding the effects of mTBI on both cognitive and motor behaviors. However, the effect of a concussion on cognitive and motor behaviors during the long-term (defined as six months or greater) post-injury phase are not without controversy. Possible reasons for the mixed results include differences in the demographics of the participants and issues arising from the methodologies used to assess the behaviors. Both of these reasons will be discussed as well as direction for the design of the experimental task in this study.

Post-Injury Cognitive Behaviors

The acute effects of mTBI on cognitive function have been well documented and have supported a deficit in overall cognitive function during the acute post-injury stage (Table 1). Regardless of methodology, the consistent finding is that mTBI have a moderate detrimental effect on overall cognitive function.

Table 1. Summary of Meta-Analyses of Cognitive Functioning Post mTBI (Acute)

First Author	Year	Studies Included	Total Effects	*d*	Injury Type	Comparison Group	Time Post Injury (days)
Belanger(a)	(2005)	39	41	*0.54**	NS	CON	< 90
Belanger(b)	(2005)	21	23	*0.49**	SP	CON	1-4
Broglio	(2008)	39	34	*-0.81***	SP	BASE, CON	1-2
Dougan	(2014)	78	91	*-0.54***	SP	CON	1-10

*positive *d* = better performance by controls; **negative *d* = poorer performance by injured individuals; Abbreviations: NS: Non-sport injury, SP: Sport injury, BASE: Baseline, CON: Healthy Controls

Contributing to the decline in overall cognitive functioning during the post-injury acute stage are decrements in specific domains of cognitive function. Deficits have been reported in: verbal memory (Collins et al., 1999; Covassin et al., 2013); processing speed (Colvin et al., 2009); executive functioning (Belanger et al., 2005), working memory (Belanger et al., 2005; Belanger & Vanderploeg, 2005), visual memory (Covassin et al., 2012; Covassin, Schatz, & Swanik, 2007), visuospatial abilities (Belanger et al., 2005; Bleiberg et al., 2004) and visual attention (Catena et al., 2009; Drew et al., 2007; Halterman et al., 2006; van Donkelaar et al., 2005). Taken together, the evidence supports during the acute post-injury stage, mTBI has a detrimental effect on cognitive function.

Table 2. Long Term Effects of mTBI on Cognitive Function

Cognitive Domain	Support for Deficit	No Evidence of Deficit
Overall Cognitive Function	Teasdale & Engberg (2003)* Guskiewicz et al. (2005)*	De Beaumont et al. (2009)*
Verbal Memory	Covassin et al. (2010)** Guskiewicz et al (2005)*	Baillargeon et al. (2012)* Broglio et al. (2009)** Iverson et al. (2006)** Gardner et al. (2010)** Guskiewicz et al. (2002)* Theriault et al. (2011)* Wall et al. (2006)*
Information Processing Speed	Bernstein (2002)* Cicerone (1996)* Covassin et al. (2010)** Gardner et al. (2010)** Ellemberg et al. (2007)*	Broglio et al. (2009)** Iverson et al. (2006)** Wall et al. (2006)*
Visuospatial Short-term Memory	Covassin et al. (2010)**	Baillargeon et al. (2012)* Gardner et al. (2010)** Iverson et al. (2006)** Theriault et al. (2011)*
Visuospatial Attention	Cicerone (1996)* Wall et al. (2006)*	Baillargeon et al. (2012)* Guskiewicz et al. (2002)* Theriault et al. (2011)*

*Paper-and-Pencil Test **Computerized Test

The long-term (six months or greater post-injury) effects of mTBI on cognitive function is not without debate. For every study that shows a long-term deficit in a particular aspect of cognitive function post-mTBI, another study shows no deficit in that same measured behavior (see Table 2).

Two possible explanations contribute to the conflicting results: first, the characteristics of the individuals studied, and second, the method or test used to assess cognitive function. The make-up of the individual is an important factor to consider when examining behaviors post-injury. Recent evidence suggests that the behaviors and experiences post-injury are highly individualized and may be influenced by age, sex, genetics, medical history, mood disorders, history of previous brain trauma and other environmental factors (Wäljas et al., 2015). Considering this, special attention should be paid to the demographics of the participants. Given the multitude of possible variables, controlling for every possible variable in one study would be a daunting task (McCrea, 2016). However, some variables, such as sex, age, and concussion history, can be controlled and when it has been done, the results have shown long-term cognitive deficits in individuals with a history of mTBI as compared to healthy controls. Including only young adult females with a history of one previous concussion, the previously concussed participants demonstrated longer processing speeds as compared to young female adults with no concussion history (Ellemberg et al., 2007). Furthermore, Covassin and colleagues (2010) also controlled for age, sex, and concussion history and found deficits in verbal memory, processing speed, and visual memory in individuals with a history of concussion compared to healthy controls. The differences in behavioral outcomes in previously concussed individuals for the factors of age, sex, and a history of multiple mTBI will be discussed in detail later in this review.

The second possible explanation for the mixed results in the assessment of cognitive behaviors in the long-term post-injury phase is the methods used to measure the behavior. Two methodologies have predominately been used: paper-and-pencil neuropsychological tests and specialized computer tests. While both types of testing do have their merits, each method also has limitations that may have contributed to the conflicting findings.

Paper-and-pencil tests have two limitations: practice effects and ceiling effects. In previous studies using paper-and-pencil tests, some individuals were given the same test multiple times within a short timeframe (Ellemberg et al., 2007). The fear is that actual behavioral deficits may be masked simply because the individual has become familiar with the test (Ellemberg et al., 2007; Schatz, Pardini, Lovell, Collins, & Podell, 2006). The second limitation to paper-and-pencil is a ceiling effect. It has been proposed that traditional paper-and-pencil test may not be challenging enough to detect cognitive deficits due to mTBI in some individuals (Ragan & Kang, 2007). However, when coupled with another task, paper-and-pencil tests have detected cognitive deficits in previously concussed individuals as compared to non-concussed individuals. Using a concurrent math problem to increase cognitive demand, participants performed a cross-out task of the numbers two and seven embedded in a series of numbers. Individuals who were previously concussed demonstrated poorer performance than individuals with no previous concussions (Cicerone, 1996). This finding is important as it suggests that individuals with a history of mTBI may have limited neural resources that unless sufficiently challenged, will not elicit deficits in visuospatial attention when compared to healthy control participants. Both of these limitations with traditional paper-and-pencil tests are problematic and can help explain the mixed results found in cognitive function in individuals with a history of concussion.

To help alleviate the limitations inherent in paper-and-pencil tests, computerized tests such as the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) and CogSport were developed and utilized to detect cognitive deficits in previously concussed individuals (Iverson et al., 2012; Iverson, Lovell, & Collins, 2005). Computerized tests were designed to eliminate potential practice effects (Lovell & Collins, 2002). However, computerized tests are not without limitations either. First, computerized tests were designed to aid in the diagnosis and treatment of concussions during the acute phase (Lovell & Collins, 2002). Furthermore, recent evidence has proposed that concussed individuals make a functional recovery based on outcomes of clinical tests but not necessarily a brain recovery (McCrea, 2016). Perhaps then computerized tests are able to capture these larger deficits during the acute post-injury stage but not sensitive enough to capture subtler behavioral deficits that may occur during the long-term stage (Broglio, Ferrara, Piland, & Anderson, 2006). Second, computerized tests primarily use the click of a computer mouse to track responses. While mouse clicks are a relevant motor action in today's society, they require very little cognitive and motor effort and integration to successfully execute the task. Instead, tasks requiring functional movements that involve cognition to interact with and guide motor action, such as a visually-guided reaching task, may offer a better alternative to examining deficits in previously concussed individuals in the long-term post-injury stage.

The results from both paper-and-pencil and computer tests examining long-term deficits in cognitive function in previously concussed individuals have been conflicting. The possibility exists that brain injury has occurred but these aforementioned methods are not consistent in capturing any cognitive deficits due to the initial injury. In an attempt to identify possible brain injury not detected by paper-and pencil or computer tests, researchers have recently utilized electrophysiological measurements of visuospatial attention in individuals who have sustained a mTBI. Briefly, electroencephalography (EEG) measures the electrical activity of an individual's brain while performing an experimental task (Broglio et al., 2009). One measurement obtained from EEG are event related brain potentials (ERP) that record electrical neural activity either in response to, or result of, a stimulus (Broglio et al., 2009). One ERP of interest in the mTBI literature has been the P300, or P3, wave (Broglio et al., 2009; De Beaumont et al., 2009). This wave can be divided into two subcomponents, the P3a and P3b waves; the former is associated with stimulus selection during visuospatial attention tasks while the latter is associated with the allocation of resources to update working memory during a visuospatial attention task.(Baillargeon et al., 2012; Broglio et al., 2009; De Beaumont et al., 2009). The P3b wave reaches its maximum amplitude over the parietal lobe of the brain and this occurs 300-700 ms after the stimulus is presented (Baillargeon et al., 2012; Broglio et al., 2009). The P3b wave is of particular interest for the purposes of this discussion.

Using the aforementioned EEG methods, the consistent finding has been an attenuated P3b wave in individuals who have a previous mTBI as compared to healthy controls (Baillargeon et al., 2012; Broglio et al., 2009; De Beaumont, Brisson, Lassonde, & Jolicoeur, 2007; De Beaumont et al., 2009). The reduced amplitude of the P3b wave suggests that an individual with a history of mTBI may have either fewer neurons available or have fewer neurons being synchronously activated to perform the given task than a healthy individual. However, when examining the behavioral measures used to elicit the P3b wave, no differences have been found between the two groups (Baillargeon et al., 2012; Broglio et al., 2009; De Beaumont et al., 2007; De Beaumont et al., 2009). Furthermore, when using a pencil-and-paper neuropsychological test or computerized test, the groups did not perform significantly differently (Baillargeon et al., 2012; Broglio et al., 2009). While these behavioral results could be interpreted as a previously concussed individual being more efficient at the tasks than healthy individuals, an alternate explanation is that the tasks themselves did not sufficiently challenge the individuals and thus a ceiling effect occurred. The consistent finding that long-term deficits in the resources allocated to visuospatial attention exist as observed in the P3b wave, however, these deficits were previously undetected behaviorally using traditional methods of testing.

Even though the aforementioned methods (i.e. paper-and-pencil tests, computerized tests or EEG) will not be used in the current study, the following three concepts from the results of previous studies can be used to help focus the attributes of a visually-guided reaching task in this proposal. First, a gap appears to be that traditional methods of assessing cognitive functioning (i.e. paper-and-pencil tests or computerized testing) do not challenge the individual to a level in which deficits in behavioral outcomes can be observed. By altering the cognitive demand, and challenging an individual to their capacities of available neural resources, any deficits in behavioral outcomes are predicted. Second, previous assessments focused heavily on cognitive processing with little emphasis on an interaction with functional movement. Although using a pencil or clicking a computer mouse does have some relevance in everyday activities, other functional movements, such as visually-guided reaching, are performed numerous times daily. Using vision to successful complete a reaching task is essential to performing everyday activities of daily living to maintain a level of independence. These tasks can vary from reaching for a piece of fruit in the refrigerator, applying toothpaste to a toothbrush, removing a boiling pot of water from the stove, and steering a motor vehicle. Third, visually-guided reaching involves an integration of cognitive processes with motor output to successfully obtain the goal of a reaching task. Therefore, integrating cognitively demanding processes with functional movement creates a measure that is both realistic to everyday activities and challenging enough to detect deficits in behaviors in individuals with a history of mTBI.

Post-Injury Motor Behaviors

Although cognitive behaviors following a mTBI have received a majority of the focus in the literature, post-injury motor behaviors have also garnered some interest. Postural control and gait have received the primary focus of these studies whereas upper-limb movements, such as visually-guided reaching, have been limited in the mTBI literature.

During the acute post-injury stage, previously concussed individuals have demonstrated increased reaction times (Colvin et al., 2009; Covassin et al., 2012; Covassin et al., 2013; Eckner, Kutcher, Broglio, & Richardson, 2014; Gagnon et al., 2004; Heitger et al., 2004; Warden et al., 2001), bradykinesia in the upper extremity (Heitger et al., 2004), and decreased accuracy while performing a cursor tracking task with a steering wheel (Heitger et al., 2004). Collectively, these results suggest a decrement in upper extremity motor behavior following a mTBI during the acute post-injury stage.

When assessing reaction times of individuals with a history of concussion who are in the long-term (at least six months post-injury) stage, the results have been mixed. Using computerized testing, no differences in reaction times have been found in previously concussed individuals as compared to healthy controls (Covassin et al., 2010; Gardner et al., 2010; Iverson et al., 2006; Locklin et al., 2010). The reaction times measured were simple reaction times, which typically do not require participants to use more complex cognitive functioning to respond to the stimulus. However, when measuring choice reaction times, previously concussed individuals demonstrated longer reaction times than healthy controls (Ellemberg et al., 2007). This study was unique due to the participants and the experimental task. All of the participants were young adult females and the experimental group included participants with only one previous mTBI at least six months post-injury. Participants were presented with twelve different stimuli using the combinations of four colors and three shapes. The participants were required to press one of two keys on a computer keyboard based on the stimulus. If the stimulus was either a circle or the color red (six possible combinations), a certain key was pressed. For the remaining six combinations, a different key was pressed. Interestingly, no difference was found between the groups for response accuracy even though the previously concussed individuals took longer to respond (Ellemberg et al., 2007).

Using visually-guided reaching, reaction times have also been measured in previously concussed individuals in the long-term post-injury stage. Locklin and colleagues (2010) designed a task that required participants to reach to a target. The spatial location of the target was fixed from trial-to-trial but the size of the target altered every trial. While Fitts' Law (speed-accuracy trade-off) held true, no difference in reaction times was found between the participants with a history of mTBI and healthy controls. What was lacking in this task, as identified by the researchers, was a level of difficulty to sufficiently challenge the participants (Locklin et al., 2010). Furthermore, it was suggested that altering the spatial location of the target from trial-to-trial could offer enough challenge to the motor planning aspect of the task to elicit a behavioral response (Locklin et al., 2010). This suggestion is an important consideration and will be incorporated into the visually-guided reaching task in this study.

Contrasting these results, previously concussed individuals in the long-term post-injury stage have exhibited increased reaction times as compared to healthy controls while performing a cursor displacement task requiring cognitive and motor integration (Brown et al., 2015). In this task, participants displaced a cursor on a computer screen to a peripheral target under different experimental conditions using their finger. The task conditions varied in complexity from a simple trace, altering the plane (horizontal and vertical) in which the finger and cursor moved, rotating the cursor movement as to move in the opposite direction of the finger movement, and adding a memory component (Brown et al., 2015). As one would expect, as the level of difficulty of the task increased, so did the reaction times. Additionally, and relevant to this discussion, the group with a history of concussion had increased reaction times as compared to the non-concussed group across the experimental conditions (Brown et al., 2015). Two critical aspects of this particular task differentiated it from previous tasks used to examine motor behavior in individuals with a previous mTBI. First, the task required the individuals to integrate cognitive processing with motor function to successfully complete the motor task. Second, the levels of complexity were altered to sufficiently challenge the participants. As seen with the work of both Brown et al. (2015) and Ellemberg et al. (2007), by increasing the cognitive demand of the task, individuals with a history of mTBI display increased reaction times as compared to individuals with no history of mTBI. Both of these aspects will be incorporated into the visually-guided reaching task for the current study.

Previous studies of bradykinesia in individuals with a history of mTBI have reported inconsistent results. Both a tracking task with a steering wheel (Heitger et al., 2006) and a rapid supination-pronation task (De Beaumont et al., 2009) have produced slower movement velocities in previously concussed individuals as compared to healthy controls. However, a different group of previously concussed individuals performing the previously mentioned rapid supination-pronation task had no differences in movement velocity as compared to healthy controls (De Beaumont et al., 2011). Possible explanations for the inconsistent findings are the various ages of the participants as well as mixing individuals with a history of multiple concussions in the experimental group. Both of these factors will be discussed later in this review; however, both of these variables will be controlled in the current study. Therefore, movement time required to complete the visually-guided reaching task will be measured.

A limited amount of studies has examined the accuracy of upper-limb movements in previously concussed individuals in the long-term post-injury stage. This refers to the control and execution of the arm movement after in initiation of the movement (as measured by reaction time) and the before the completion of the movement (as measured by target accuracy). Using a steering wheel to track a cursor over a set path, previously concussed individuals displayed diminished upper limb accuracy compared to healthy controls (Heitger et al., 2006). Yet, using the previously mentioned cursor displacement task developed by Brown et al. (2015), no differences between previously concussed individuals and healthy controls were reported in the path length used to complete the task. It should be noted, the former study required participants to follow a set path to complete the task while the latter did not. This additional constraint on the movement pattern may have been enough to elicit the difference between groups. While the results presented are conflicting, the steering wheel task required movement in one dimension and the cursor-task only had movement in two dimensions. The visually-guided reaching task in this study will require movement in three dimensions. This added aspect may be enough to elicit s difference in movement accuracy between individuals with a history of concussion and those without a history of concussion.

One final variable to be discussed regarding motor behaviors of previously concussed individuals is end point accuracy and variability of an upper limb movement. Brown et al. (2015) did investigate both the end point accuracy and variability between the two groups in their previously discussed experiment. No difference in end point accuracy was found between the participants with a history of concussions and no history of concussion. However, end point variability was increased for the previously concussed group compared to the non-concussed group. Even though no difference was found between the two groups for end point accuracy, this measure should still be assessed to also determine within-subject end point variability.

Based on these findings, the use of a visually-guided reaching task to assess motor behaviors in individuals with a history of concussion who are in the long-term post-injury stage fills a gap in the literature. Reaction time, movement time, movement accuracy (path length) and end point accuracy are all variables to be considered in this study. Furthermore, increased within-subject end point variability has been supported in individuals with a history of mTBI as compared to healthy controls. However, within-subject variability has yet to be examined in previously concussed individuals for reaction time, movement time and movement accuracy. Therefore, the following dependent variables should be measured in the visually-guided reaching task: reaction time, reaction time variability, movement time, movement time variability, path length, path length variability, and end point accuracy and variability.

Summary

The effects of mTBI on the cognitive and motor behaviors during the long-term post-injury stage have yet to reach a consensus. Therefore, the investigation of the long-term effects on cognitive and motor behaviors following a concussion requires further examination. Based on the findings, three themes have emerged. First, a more homogenous sample may limit possible factors that have masked the true result. This theme will be discussed in the next section of this review. Second, the visually-guided reaching task in this study fills a gap in the literature by (1) offering a sufficient cognitive challenge to the individuals that has not always been present in previous experiments, (2) incorporating the use of functional movement, and (3) integrating cognitive and motor behaviors to complete the task. Third, multiple dependent measures will be collected to obtain a full picture of the reaching movement. These measures will include: reaction time, reaction time variability, movement time, movement time variability, path length, path length variability, and end point accuracy and variability. By using these principles, this study will take into account identified gaps in the literature and may help resolve the inconsistent results surrounding the long-term effects of mTBI on an individual.

Factors Influencing Post-mTBI Outcomes

One of the possible explanations for the conflicting results when measuring the effects of mTBI on cognitive function during the long-term post injury stage is the heterogeneity of the participants (see Post-Injury Cognitive Behaviors section). Often, participants of both sexes, or various age groups, or having different concussion histories (single injury vs. multiple injuries) are included in the same experimental group. Considering the individualized nature of this injury (Wäljas et al., 2015), perhaps a better practice is to limit as many factors as possible by shifting towards a more homogenous sample. Yet, before this determination can be made, an evaluation of potential factors influencing post-mTBI outcomes should be examined.

Sex Differences

When evaluating the sex of the participants in previous mTBI studies, two issues are noticeable. First, an imbalance appears to exist in the amount of studies dedicated to males as opposed to females. Typically, males have been the primary participants in the majority of concussion studies. The second issue is that when females are included in the study, both sexes are typically combined into the experimental group. Though this may seem to be an acceptable practice, evidence presented over the last decade may suggest the contrary. Therefore, an examination of sex differences in previously concussed individuals is warranted for two reasons.

First, females represent an understudied population in the mTBI literature. Second, previously concussed males and females should be divided into separate groups to control for any possible differences as outlined below.

One of the differences between males and females who have sustained a mTBI is the disproportionate amount of studies in the literature dedicated to males. Researchers have noted this skew with the majority of concussion studies being conducted on male sports such as football, hockey, and boxing (Covassin et al., 2007). In a recent meta-analysis of 78 studies, female athletes were underrepresented (Dougan et al., 2014). A separate meta-analysis of 39 studies combining 4,145 concussed and control participants in the analysis reported that 92.9% of the individuals were males (Broglio & Puetz, 2008). Females who have sustained a mTBI represent an understudied population in the literature thus warrant an increased focus.

In addition to the disparity between males and females in the demographic make-up of mTBI studies, researchers have reported differences in cognitive performance measures. When looking at overall cognitive performance following mTBI, females were cognitively impaired 1.5 times more often than males (Broshek et al., 2005). In a meta-analysis of 78 studies involving concussed individuals as compared to controls during the first ten days post-injury, with 91 effects, the psychological deficits in females (d = - 0.87) were worse than in males (d = - 0.42) (Dougan et al., 2014). In the same meta-analysis, when comparing just adults, adult females had greater psychological deficits than adult males (d = - 0.62, - 0.15 respectively) (Dougan et al., 2014). When looking at specific domains of cognitive functioning, differences between sexes still exist. Females have demonstrated worse performance in tasks assessing visual memory (Covassin et al., 2012; Covassin et al., 2007; Covassin et al., 2006) as well as verbal memory (Covassin et al., 2006).

However, not all investigations of cognitive domains following mTBI have reported differences between sexes. In the cognitive domain of processing speed, no differences were found between males and females when assessed by two different computerized, neurocognitive tests (Broshek et al., 2005; Covassin et al., 2006).

Males and females have mixed responses in reaction time post mTBI. When assessing during the acute post-injury stage, females have slower reaction times than males (Broshek et al., 2005; Colvin et al., 2009). However, when assessing baseline scores of males and females who have sustained a previous mTBI, no difference was found between sexes (Covassin et al., 2006).

Although the previous investigations suggest that generally if differences between the sexes exist, females have poorer outcomes; this assertion is not always the case. In athletes who have sustained multiple concussions, females performed better than males on verbal memory, visual memory, processing speed and reaction time (Covassin et al., 2010).

Even though speculation exists as to why differences between sexes have been reported in behavioral methods, that topic is beyond the scope and focus of this study. Instead, two apparent needs exist. First, females are vastly understudied in the mTBI literature, thereby justifying an exclusive examination of females in this study. Second, even though a definite difference does not exist between sexes on all behavioral measures, the current findings suggest that a difference between sexes may exist. Therefore, the conservative approach to limit confounding variables is to assess males and females separately when assessing behaviors in individuals with a history of mTBI.

Age Differences

Previous studies investigating the effects of concussions on visuomotor behavior have not always controlled for age. For example, Heitger and colleagues' (2006) previously concussed participants ranged from 15 to 56 years old while other researchers rigorously controlled the age range of their participants (Brown et al., 2015; Locklin et al., 2010). Before age can be considered as a factor that needs to be controlled, a discussion of possible age differences in outcomes post-mTBI is warranted.

The assessment of within-group cognitive function after sustaining a mTBI has supported a difference in the magnitude of the deficit between age groups, that is, adults have less of a behavioral deficit than adolescents. In a meta-analysis of 78 studies involving concussed individuals, as compared to age-matched controls, during the first ten days post-injury, with 91 effects, adolescents (d = - 0.60) had greater psychological deficits than adults (d = - 0.25) (Dougan et al., 2014). Concussed college-aged students perform better when measuring verbal and visual memory (Covassin et al., 2012; Field, Collins, Lovell, & Maroon, 2003) than concussed high school students during the fourteen days post-injury when compared to their respective baseline assessments. Baseline scores of previously concussed collegiate and high school students have supported differences in processing speed with the college students performing better (Covassin et al., 2012). Sustained and divided attention assessed with paper and pencil tests of jockeys on an average of 6.45 years post injury, older jockeys performed better than younger ones (Wall et al., 2006). Both of the studies by Covassin et al. (2012) and Wall et al. (2006) suggest that the age of an individual affects the long-term post-injury cognitive function of an individual.

Yet, not all findings have supported within-group differences between age groups. No within-group differences between high school and college students have been found during the fourteen days post injury on reaction time and processing speed (Covassin et al., 2012) or on baseline assessments of previously concussed athletes on reaction time, verbal and visual memory (Covassin et al., 2012). A comparison of youth (nine to twelve years old), adolescents (thirteen to sixteen years old) and adults at least six months post injury using a battery of paper and pencil neuropsychological tests assessing visuomotor speed, verbal memory, visuospatial memory, visual attention, mental flexibility, information processing speed, and working memory, revealed no within-group differences between the age groups (Baillargeon et al., 2012).

While the previous findings suggest mixed results for the within-group differences between age groups after sustaining a mTBI, within-group differences *may* exist. Furthermore, the potential interaction of time since concussion and age is not clear. To control for this possible variable and align the proposed study with previous papers, a fixed age range of participants will be used. Furthermore, the time since the initial injury will also be recorded as a possible explanation for any conflicting results.

Severity of Injury

During the acute post-injury stage after sustaining a concussion, an increase in the severity of the injury does relate to greater deficits in cognitive function. Two symptoms considered to be markers of a more severe mTBI, namely loss of consciousness (LOC) and post-traumatic amnesia (PTA), appear to have a transient detrimental effect on cognitive function during the acute recovery stage (McCrea, Kelly, Randolph, Cisler, & Berger, 2002). However, after 48 hours, and up to 90 days later, patients made a clinical recovery with measurements of cognitive function returning to baseline levels (McCrea et al., 2002). Injury severity (i.e. LOC and PTA) appear to influence the immediate cognitive functioning of individuals sustaining a mTBI; however, the initial decline in cognitive function is reconciled within two days post injury.

Based on this evidence, the severity of a mTBI may influence behavioral assessments during the acute post-injury phase; however, this influence appears to resolve quickly. Long-term evidence provides no support for a significant relationship between severity of the injury and behavioral outcomes. Furthermore, Sosnoff and colleagues (2011) recently chose not to assess injury severity based on the bias inherent in self-reporting severity of the injury. Therefore, for the purpose of this study, severity of the injury will not be assessed.

Multiple mTBI

The effect of multiple mTBI on an individual is a topic mired in inconsistent results. Even though evidence exists to support that a previous concussion puts an individual at a greater risk for a future concussion (Schulz et al., 2004), the cumulative effects of a history of multiple concussions on cognitive and motor behaviors has yet to be fully elucidated (Belanger et al., 2010; Collins et al., 2002; Covassin et al., 2013; De Beaumont et al., 2012; Iverson et al., 2006; Iverson et al., 2012). However, due to the nature of re-injury as well as possible cumulative effects, the inclusion of individuals with a history of multiple concussions should be considered.

As with long-term (greater than six months) cognitive and motor behaviors post-mTBI, evidence exists both support of and against a cumulative effect of multiple mTBI. Individuals with multiple concussions, as compared to individuals with none or one previous concussion, have displayed overall cognitive decline (Guskiewicz et al., 2005; Teasdale & Engberg, 1997), poorer verbal memory (Covassin et al., 2010; Covassin et al., 2013; Iverson et al., 2012), longer processing speed (Collins et al., 1999; Gardner et al., 2010; Shuttleworth-Rdwards & Radloff, 2008), poorer visuospatial memory (Covassin et al., 2010), and attentional deficits (Collins et al., 1999; Wall et al., 2006). Conversely, no difference has been found between individuals with multiple concussion and those with none or one concussion in: overall cognitive ability (Belanger et al., 2010), verbal memory (Broglio et al., 2006; Gardner et al., 2010; Iverson et al., 2006; Wall et al., 2006), processing speed (Broglio et al., 2006; Iverson et al., 2006; Wall et al., 2006), visuospatial memory (Broglio et al., 2006; Gardner et al., 2010; Iverson et al., 2006) and reaction times (Broglio et al., 2006; Collie, McCrory, & Makdissi, 2006; Gardner et al., 2010; Iverson et al., 2006). Even though these results are conflicting, a few trends did appear. If an individual had three or more concussions, they typically performed worse on the respective measure (Covassin et al., 2010; Gardner et al., 2010; Guskiewicz et al., 2005; Iverson et al., 2012). However, if an individual had one or two previous mTBI, the results were mixed. It appears as if three or more previous mTBI may be a threshold while the behavioral differences between an individual with one or two previous concussions may or may not exist.

Because of the conflicting results, further study of the possible cumulative effects of multiple concussions is warranted. Furthermore, some possible explanations for the conflicting results have been proposed. First, perhaps the long-term effects of multiple mTBI do not exist (Broglio et al., 2006). This explanation has to be considered; however, due to the inconsistency in results, further examination needs to be done to fully accept this explanation. Second, traditional methods of assessing the long-term effects of concussions (i.e. computerized testing) may not be sensitive enough to detect any deficits (Broglio et al., 2006). If this assertion is true, then alternate methods, such as a visually-guided reaching task, may help settle the debate to the long-term effects of multiple concussions. Third, the concern that individuals either over or under report their injury could place individuals in the incorrect experimental group and mask significant results (Covassin et al., 2010). The use of the concussion history questionnaire developed for this study can help alleviate this limitation;

however, any study that requires self-report of mTBI from the participants is subject to this limitation. In addition, the evidence supports that having three or more concussions results in poorer behavioral outcomes than having one or two previous injuries. However, the measured differences between one or two previous concussions are not as clear. Given this, it is imperative to stress that the participants be truthful and recall as best as possible their concussion history. Therefore, for the purposes of this study, individuals with one or two previous mTBI will be assigned to one experimental group and individuals with three or more previous mTBI will be assigned to a separate group with both groups being compared to healthy controls.

Summary

Based on the evidence, sex, age, and multiple concussions are factors to be controlled in this study; however, the initial severity of the mTBI will not be collected. Furthermore, the following criteria will be used based on the literature. First, female participants will be the only individuals included in this study. All participants will be young adults, 18 – 29 years old. Finally, participants will be assigned to one of three groups based on concussion history: no previous concussions, one to two previous concussions and three or more previous concussions. By selecting a homogenous sample, the goal is to control for factors that may have influences the results of previous investigations.

Visuomotor Behavior

Every day, vision guides one's actions to help one successfully navigate through a complex environment. The use of visual information to guide motor actions, or visuomotor behavior, can be exemplified with tasks as simple as reaching for a pot on the stove to remove it before the pot boils over; to walking down a sidewalk while talking to a friend, yet still avoiding any cracks or potholes as to avoid a fall; or more complex behavior such as when driving a car during rush hour traffic and taking corrective actions to avoid a motor vehicle accident. Yet, an individual is constantly flooded with visual information that requires some method to select relevant cues while ignoring distractions; a process known as visual attention. To allocate visual attention, an individual will draw from a "pool" of available resources. However, one's available attentional resources needed to successfully perform visually-guided movements do have limits. As a task increases in difficulty, or if a secondary task is introduced, the demand to complete the original task may exceed the availability of attentional resources. Furthermore, when damage to the brain occurs, either due to injury or disease, the available attentional resources are compromised. Both of these scenarios can lead to deficits in visuomotor behavior. These deficits can have adverse effects on day-to-day activities, which lead to a decreased quality of life.

Definitions

The term 'visuomotor behavior' can have a very broad meaning that needs clarification for this study. Visuomotor behavior can be defined as the use of visual information to guide motor actions (Goodale, 1998). Additionally, successful completion of a visuomotor task relies upon the deployment of visual attention. For the purposes of this study, "motor actions" will refer to upper limb reaching movements. Furthermore, the reaching movements in this study will be both voluntary and goal-directed. The "use of visual information to guide" as well as "visual attention" both require a more detailed explanation.

An individual is constantly inundated with visual information; however, an attempt to process all visual stimuli by higher cognitive centers in the brain would be a nearly impossible task. Instead, some method of selecting relevant and ignoring irrelevant visual information is required; a process known as visual attention (Theeuwes, 1993). Visual attention can be viewed as both a spotlight to enhance relevant information and a filter to limit irrelevant information. If a specific visual stimulus is considered to be relevant to the individual, the neurons processing this image are excited while the neurons processing irrelevant stimuli are inhibited, even if the relevant and irrelevant stimuli are simultaneously in the visual field (Kastner & Ungerleider, 2000; O'Craven, Rosen, Kwong, Treisman, & Savoy, 1997). Visual attention is a method of selecting relevant visual information without overwhelming one's sensory process with irrelevant stimuli.

The determination between relevant and irrelevant visual information and the subsequent deployment of visual attention depends on the stimulus itself or the objective of the task (Egeth & Yantis, 1997). From these criteria, one of two types of visual attention, bottom-up or top-down, will be utilized. If a visual stimulus is either unexpected, salient or behaviorally important (or any combination of the three), the visual information is determined to be relevant (Corbetta & Shulman, 2002; Egeth & Yantis, 1997). In this scenario, bottom-up, or stimulus-driven, visual attention is employed. On the other hand, if the objective of an individual is to attend to a specific visual stimulus, then that visual information is relevant and top-down, or goal-directed, attention is utilized (Kastner & Ungerleider, 2000). Both visual attention processes arise from different areas in the brain and have different behavioral functions.

Bottom-up, or stimulus-driven, visual attention is when an external stimulus captures one's visual attention causing a shift in attentional focus (Theeuwes, 1993). For example, an individual is driving a car and attending to the cars in front of them. Suddenly, the bright, flashing lights of an emergency vehicle appear in the rear-view mirror. The flashing lights are both unexpected and behaviorally important. The driver shifts her attention to the flashing lights and takes appropriate action (slowing down and pulling over) to respond to the stimulus. During bottom-up visual attention, the processing of information begins in the sensory cortex and flows to the reticular formation in the brainstem (McDowd, 2007; Petersen & Posner, 2012) and the temporoparietal cortex and inferior frontal cortex predominately in the right hemisphere (Corbetta & Shulman, 2002). The purpose of bottom-up visual attention is to react quickly to relevant, salient stimuli without involving higher cognitive areas in the brain.

Top-down, or goal-directed, visual attention is under voluntary control of the individual (Egeth & Yantis, 1997). An example of goal-directed visual attention could be looking for a loved one in a crowd of people. As one visually searches the crowd, the individual is looking for features such as the loved one’s face, hair style, or clothing to identify the person. In top-down attention, higher cognitive areas (frontal lobe) send information through the parietal lobe and to the primary visual cortex via the dorsal frontoparietal network (Corbetta & Shulman, 2002; McDowd, 2007). As visual attention is guided by top-down processing, relevant visual information (the loved one’s face or hair style in the example) are enhanced while irrelevant distracting visual information (different faces or hair styles in the example) are suppressed (Kastner & Ungerleider, 2000). The goal of top-down visual attention is to guide an individual’s focus through a sea of distractors and towards the objective of their visual search.

Although bottom-up and top-down visual attention are presented as two separate processes that act independently of each other, the reality is that both bottom-up and top-down visual attention interact with each other (Egeth & Yantis, 1997). The visually-guided reaching task in this study will require the participants to use both bottom-up and top-down visual attention. The initial identification of the location stimulus in the task will rely on bottom-up visual attention; however, the majority of the reaching task will involve top-down attention to produce an arm movement to an appropriate target guided by visual information.

Visual Attention to Motor Intention

After a visual stimulus is perceived and coded for attributes such as shape, edges, and color, the information will flow to the temporal lobe via the ventral stream and the parietal lobe via the dorsal stream. The temporal lobe will have the major task of identifying *what* the stimulus is while the parietal lobe will determine *where* the stimulus is located in space (Mishkin, Ungerleider, & Macko, 1983). The latter pathway is relevant to this study.

In the parietal lobe, specifically the posterior parietal lobe, spatial maps of the visual field are represented (Culham & Kanwisher, 2001). Functional magnetic resonance imaging studies have revealed that the maps are topographically organized, contralateral to the visual field, and located in the intraparietal sulcus (Silver, Ress, & Heeger, 2005). The role of the maps is to provide a spatial representation of the visual stimuli selected by top-down attention. It should also be noted that visual attention can influence the spatial maps even before a visual stimulus is presented. If a location in the visual field is pre-cued to focus one's attention, such as in Posner's classic paradigm, the neurons corresponding to the pre-cued spatial location will increase their activity above baseline levels (Muller, Bartelt, Donner, Villringer, & Brandt, 2003). The increase in the activity of the neurons associated with the pre-cued spatial location will serve as an anticipatory function and can have a benefit to any behavioral measures such as reaction times. In the visually-guided reaching task in this study, spatial maps will be used by the participants. First, after the initial location stimulus is presented, participants will map the location of the stimulus to begin the planning of the visually-guided reach. Second, participants will receive a go cue to begin the reach. All go cues will be from the same location regardless of the task conditions. If any benefit is gained from having the spatial location of the go stimulus being pre-cued, it should be the same for all trials performed by the participants.

The next step in the processing of visually-guided information is motor intention. Motor intention can be thought of as a preparatory stage to movement (Desmurget & Sirigu, 2009); however, the location in the cortex where this stage occurs is still in the posterior parietal cortex. The neurons activated for the motor intention of a reaching movement have a specialized area, the medial intraparietal area located dorsal to the intraparietal sulcus (Culham & Kanwisher, 2001). The neurons in the medial intraparietal area function on a coordinate system (Desmurget, Pelisson, Rossetti, & Prablanc, 1998). A motor map exists that is analogous to the spatial maps from the intraparietal sulcus. Using the motor map, an initial trajectory of a reaching movement can be planned (Desmurget et al., 1998). To accomplish this process, the neurons in the medial intraparietal area corresponding to the desired targeted spatial location are activated above baseline firing rates while the neurons not corresponding to the intended location are inhibited (Snyder, Batista, & Andersen, 2000). In the visually-guided reaching task from this study, motor trajectories, a part of motor intention, will be manipulated. This manipulation will be accomplished two ways. First, under one scenario the initial target location and the desired target location will be in different locations requiring participants to plan a new movement trajectory. Second, a choice variable will be introduced where participants will be presented with an initial target location and one of two possible target locations thus requiring two possible motor trajectories to be considered. For more detail of the actual task requirements, please refer to the Methods section.

Motor intention, which occurs in the posterior parietal cortex, is the stage during the visually-guided reaching task that will be manipulated in this study. By requiring individuals to alter their motor trajectories based on the criteria laid out in the experimental task, any deficits with planning a visually-guided reach are predicted.

Attentional Resources

To better explain how attention is utilized, one could imagine their available attentional resources are a pitcher of water and tasks requiring attention are a glass. When performing tasks with low attentional demand, enough "water" is available to fill up the "glass." However, when the attentional load of a task increases (a bigger glass), or if more tasks are required to be performed (more glasses to fill), not enough "water" is available and decrements in performance on an attention-mediated task may be observed.

The attentional resources available to an individual are limited (Franconeri, Alvarez, & Cavanagh, 2013). Attentional resources are often referred to as a "pool" or "reservoir" and when one performs a given task, resources from this "pool" are allocated to complete the task (Wickens, 1991). Attentional resources allotted to a task allow the information from that task to be processed by higher cognitive areas (Wickens, 1991). Conversely, if attentional resources are not allocated to a given task, the information from that task are not processed by higher cognitive areas (McDowd, 2007). The allocation of attentional resources will also include shifting between multiple tasks: however, each task is still drawing from the same allotment of resources (McDowd, 2007). The ability to successfully complete a task will depend on the nature of the task and the available resources to complete the task. Typically, the availability of attentional resources exceeds the demands of the task, or tasks, and performance on the task is successful (Kahneman, 1973). However, what happens if either the demands of the task increase or the available resources of the individual are compromised?

The first possibility of manipulating the association between the available resources of an individual and the completion of a task is to alter the demands of the task. Two possible techniques to alter the attentional demands of the task exist: increase the difficulty of the task or introduce interference from a secondary task. In the first scenario, an increase of the cognitive/attentional load of a task will increase the overall demand of the task, thus requiring more attentional resources to be allocated to the task (Franconeri et al., 2013; Sweller, 1988). If the demand of the task exceeds the availability of attentional resources, then performance on the task suffers (Lavie, 2010). In the analogy of the pitcher of water (attentional resources) and the glass (task), this would be the equivalent of increasing the size of the glass. The second scenario involves introducing a secondary task while the initial task is still being performed; a concept referred to as interference (Kahneman, 1973; Logan, 1985). Interference can be accomplished by either adding a secondary cognitive task (Cicerone, 1996; Pashler, 1994) or a secondary motor task (Beurskens, Steinberg, Antoniewicz, Wolff, & Granacher, 2016; Phillips, Wynn, Gilhooly, Della Sala, & Logie, 1999). If interference is introduced while an individual is performing a given task, the secondary task will draw from the same capacity of attentional resources (Kahneman, 1973; Logan, 1985). If the demand of the interference and the initial task exceeds that of the available attentional resources, performance on either, or both, of the tasks will suffer (Kahneman, 1973; Wickens, 1991) or the tasks are prioritized (McDowd, 2007; Pashler, 1994). The aforementioned examples of the effects of introducing interference to a primary task have been explained by a capacity model of attentional resources. An alternate explanation for a decrease in task performance due to the introduction of interference is through a bottleneck model of attention. In this model, both the primary and secondary task are attempted to be performed serially; however, a bottleneck occurs and only one task can be successfully performed at a time (Pashler, 1994). Regardless of which model of attention is used to explain the effects of interference on a primary task, both models point to a decrease in task performance. Returning to the pitcher of water (attentional resources) and glass (task) analogy, introducing interference could be seen as introducing a second glass. One can either attempt to fill both glasses at once and running out of water, which may result in neither glass being filled completely (capacity model) or the second option is to fill each glass independently, which would take an increased amount of time to accomplish this task (bottleneck model).

The second possibility of manipulating the interaction between the available resources of an individual and the completion of a task is that an individual may have a compromised capacity of attentional resources. Factors such as sleep loss (Zohar, Tzischinsky, Epstein, & Lavie, 2005), age (Jones et al., 2006), stress (Hellawell & Brewin, 2002) clinical depression (Lemelin et al., 1996), anxiety (Bishop, 2009) stroke (Bonato, Priftis, Marenzi, Umilta, & Zorzi, 2010), Alzheimer's disease (Alescio-Lautier et al., 2007) and mTBI (Broglio et al., 2009) may all lower ones available attentional resources and negatively affect the deployment of attention. Referring back to the pitcher of water and glass analogy, the individual would have less water in the pitcher at the beginning of the task. However, one must be sufficiently challenged to exhaust the available attentional resources to observe a decrement in task performance.

Given the aforementioned reasons, four possible scenarios are derived: (1) the available capacity of resources meets the demand of the task or tasks and performance does not suffer, (2) the difficulty of the task exceeds the available attentional resources and task performance suffers, (3) multiple tasks draw from the same allotment of attentional resources and performance on some or all of the tasks suffers or are prioritized, and (4) an individual has a decreased amount of initial attentional resources and the demand from a sufficiently challenging task (from either scenario two or three) will exceed the available attentional resources and performance will suffer. The aim of this study is to apply the principles from scenarios two and three to individuals in scenario four. The visually-guided reaching task in this study will vary the cognitive load and introduce motor interference to a population of individuals suspected to have diminished attentional resources.

Visuomotor Behavior and mTBI

The number of studies dedicated to investigating visuomotor behavior in individuals who have sustained a mTBI in the long-term post-injury is limited. Of these limited numbers of studies, fewer have investigated visually-guided reaching (Locklin et al., 2010). However, visually-guided reaching is a task one performs daily. Whether it is getting dressed, preparing a meal, performing daily chores, opening a door or playing a sport, visually-guided arm movements are a part of one's daily activities. Given the functionality of visually-guided reaching, the investigation of the outcomes of this behavior after a concussion is warranted.

Locklin and colleagues (2010) designed a visually-guided reaching task based on Fitts' Law. A full description of the task is discussed in the Post-Injury Motor Behaviors section of this review. Briefly, the task required participants to reach to a spatially-fixed target that varied in size. The dependent measure was reaction time with no significant difference found between individuals with and without a history of concussion. While the participants were required to initially determine the target location, the target remained spatially fixed from trial-to trial. This methodology did not require the participants to alter their spatial maps or motor trajectories to various locations. Thus, the participants were not sufficiently challenged (Locklin et al., 2010). Furthermore, this task became a measure of bottom-up attention; participants were simply reacting to a stimulus. As recommended by the researchers, altering the spatial location of the target from trial-to-trial could offer enough challenge to the motor planning aspect of the task to elicit a behavioral response (Locklin et al., 2010). By doing so, participants would be required to alter either their spatial planning or motor trajectory to complete the task. Adding this variation to the task would then require participants to use top-down attention to complete the reaching task.

Contrasting these results, Brown and colleagues (2015) challenged previously concussed individuals with a cursor displacement task (described in the Post-Injury Motor Behaviors sections of this review). The task required cognitive and motor integration by the participants as the difficulty of the task increased with each additional perturbation. The same task has been used previously with individuals with Alzheimer's disease to detect deficits in visuomotor behavior (Tippett, Krajewski, & Sergio, 2007; Tippett & Sergio, 2006). Deficits in visuomotor behavior, as measured by increased reaction times, movement times, and end point variability, were reported in previously concussed individuals as compared to healthy controls. Furthermore, during the highest level of cognitive demand in the experiment, movement times were significantly longer in the previously concussed individuals than the non-concussed group. However, this difference was not seen during the lower level of cognitive demand of the task (Brown et al., 2015). Two novelties from the design of the experimental task made this study unique. First, the participants were required to make cognitive decisions to guide their motor movements; that is, a correct cognitive choice was required to successfully execute the reaching task. Second, this design required participants to use top-down attention to complete the task. This was accomplished by requiring individuals to create a motor trajectory that was not in the same spatial direction of the initial visual stimulus. Both of these attributes (cognitively challenging a participant and manipulating their motor trajectories) of the experimental task will be incorporated into the visually-guided reaching task of this study.

Based on these findings, the following conclusions can be drawn. First, based on the importance and usefulness of visuomotor behavior (i.e. visually-guided reaching) and the lack of studies investigating the long-term effects of concussions on this behavior, a gap exists. Second, participants should be cognitively challenged to a sufficient level during the task. Increased cognitive load of the task can be accomplished by requiring participants to make a cognitive decision that directly affects the motor outcome. Additionally, spatially altering the focus of motor trajectory from the initial visual stimulus will require participants to use top-down attention. Therefore, both of these aspects will be included into the visually-guided reaching task in this study.

Summary

Visually-guided movements aid in the successful navigation through a complex environment. Visual attention assists with this function by accentuating relevant stimuli and attenuating irrelevant distractors. The successful completion of a visually-guided reaching task relies on a finite availability of resources. Typically, the available attentional resources one uses sufficiently meets the demands of the task. However, altering the demands of a task such as increasing the cognitive load or introducing interference from another task can push an individual to the limits of their resource capacities. Additionally, the availability of attentional resources can be compromised presumably in individuals with a history of mTBI. The inability to match the attentional resource requirements of a visually-guided movement can manifest as behavioral deficits. These deficits can negatively affect one’s activities of daily living and thus lead to a diminished quality of life. This study will use participants from a population with suspected diminished attentional resources. The experimental task will both alter cognitive load and introduce motor interference to challenge the participants to the limits of their resource capacities. From this, decrements in the performance of the visually-guided reaching task are predicted.

Conclusion

Mild traumatic brain injuries, or concussions, are a major health concern. Due to discrepancies in defining the injury, difficulty collecting the incidence rates to national databases, and individuals failing to report their injury, the actual impact of concussions is feared to be an underestimate. Additionally, investigations of the long-term cognitive and motor behavioral outcomes after sustaining a mTBI show conflicting results. The inconsistencies in the literature can be attributed to the heterogeneity of the participants and the methodology used by the researchers. The results from the literature support behavioral differences between sexes and age groups after sustaining a concussion. To select a more homogenous sample, young adult females will be exclusively included. Furthermore, the long-term effects of multiple concussions on an individual have yet to be fully elucidated. Based on the evidence that having three or more mTBI results in poorer behavioral outcomes than having one or two previous concussions, participants will be divided into three separate groups based on concussion history. The methods used in previous investigations of cognitive behaviors post-concussion have traditionally used paper-and-pencil or computerized tests. Both of these methods have limitations such as a ceiling effect or limiting the use of functional movement in the task that may have masked the true results. The experimental task in this study fills a gap in the literature by offering a sufficient cognitive challenge to the individuals that has not always been present in previous experiment and incorporating the use of functional movement. Furthermore, previous investigations of the long-term effects of concussions have used either predominately cognitive *or* motor tasks to assess the respective behaviors. Visually-guided movements rely on an integration of cognitive and motor behaviors to successfully complete a task. Therefore, a visually-guided reaching task will be designed to bridge the gap in the literature. Visually-guided reaching requires individuals to allocate visual attention to complete the task. Yet, the available resources needed to complete a task are limited. Two ways to challenge an individual to reach the capacity of their attentional resources are to increase the cognitive load and introduce interference from a secondary task. Both of the aforementioned manipulations will be used in the experimental task. Finally, an individual may have compromised attentional resources due to an insult to the brain either from disease or injury. Individuals who have sustained a concussion are suspected to have reduced attentional resource capacities. By selecting a homogenous sample and designing a sufficiently challenging task, this study will fill a gap in the literature as identified by this review. Based on this review of the literature, the following hypotheses are predicted:

Hypothesis 1a.

By increasing the cognitive demand of the visually-guided reaching task through the addition of a mental rotation of the targeted location, individuals will demonstrate increased reaction time and variability or increased movement time and variability. No change in path length and variability, end point accuracy and variability, and target selection accuracy are predicted.

Hypothesis 1b.

The predicted outcomes from Hypothesis 1a will be accentuated in individuals with a history of concussion as compared to control participants.

Hypothesis 2a.:

By increasing the cognitive demand of the visually-guided reaching task through the introduction of a choice component, individuals will demonstrate increased reaction time and variability, increased movement time and variability, and increased path length and variability. No changes are predicted in end point accuracy and variability as well as target selection accuracy from a baseline measure.

Hypothesis 2b.:

Poorer performance on the dependent measures from Hypothesis 2a will be greater in individuals with a history of concussions as compared to individuals with no history of concussion.

Hypothesis 3a.:

By increasing the cognitive and motor demand of the visually-guided reaching task through the introduction of a secondary motor task in addition to a choice component, individuals will demonstrate increased reaction time and variability, increased movement time and variability, increased path length and variability, decreased end point accuracy, increased end point variability, and decreased target selection accuracy from both a baseline measure and the experimental choice measure.

Hypothesis 3b.:

The respective increases and decreases in the dependent measures predicted in Hypothesis 3a will be accentuated in individuals with a history of concussions as compared to controls.

Chapter 3: Methods

The purpose of this study was to examine the long-term effects of multiple concussions in young adult females on visuomotor behavior during a visually-guided reaching task. Several confounding factors such as time since injury, age and sex of the participants, as well as the number of previous concussions may adversely influence the findings and thus were controlled. Furthermore, parametrically altering task complexity (both cognitive and motor demands) challenged the available resources a previously concussed individual possessed. Therefore, the experimental model of this investigation was designed to meet the above criteria.

Participants

Forty-one healthy young adult females, ages 18-28 years, with normal or corrected-to-normal vision and either no history of concussion or at least one self-reported concussion were recruited. Due to technical difficulties during data collection, the data from one participant was corrupted and was not included in the final analysis. Males were excluded for three reasons. First, a difference exists between sexes when using cognitive tests to evaluate individuals with a history of concussions (Covassin et al., 2010; Covassin et al., 2012). Second, in shared sports such as soccer, basketball or volleyball, females have a higher incidence of concussions as compared to males (Marar et al., 2012). Third, females represent an understudied population in the literature thus warranting a need for increased investigation (Broglio & Puetz, 2008; Covassin et al., 2007). Additional exclusion criteria included: an inability to sit comfortably for up to an hour and a half, self-reported neurological deficits other than a concussion, a diagnosed learning disorder, a diagnosis of ADD/ADHD or dyslexia, a current psychological disorder which requires medication (other than a mood disorder), and an arm or spinal cord injury in the last six months. A power analysis was conducted using G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007) that revealed at least 18 participants per group were required to achieve adequate power. Informed consent (Appendix C) as approved by the Institutional Review Board of the University of Wisconsin-Milwaukee was obtained from the potential participants (IRB# 15.260). All participants received compensation upon completion of the study.

Procedure

After obtaining informed consent, participants' vision was screened (Appendix D) using a Snellen eye chart to check near visual acuity (Hallowell, 2008). Participants completed a Concussion History and Symptom Survey (Appendix E). Section 1 (Concussion History) obtained participants' previous history of diagnosed (by a medical provider), and undiagnosed concussions. The purpose of this section was threefold. First, participants recorded the length of time from their most recent concussion, if applicable. Second, participants verified they have been medically cleared from the most recent concussion. Third, both diagnosed and undiagnosed concussion history was documented therefore assessing the actual number of previous concussions. Since the intake of total concussion history was obtained via self-report, the number of diagnosed and undiagnosed concussions was summed to arrive at a total number of previous concussions for each participant. Section 2 (Concussion Symptom History and Evaluation) served two purposes. First, the Symptom History checklist recorded symptoms from other head injuries not diagnosed as a concussion. LaBotz et al. (2005) developed this Concussion Symptom survey as a more sensitive measurement of previous concussion history, thus it was included to fully capture the number of previous concussions. The second checklist, Symptom Evaluation, was from the Sport Concussion Assessment Tool 3 or SCAT3 (Guskiewicz et al., 2013). The purpose of this checklist was to verify that participants are currently asymptomatic by current standards.

The Concussion History and Symptom Survey classified participants into one of two experimental groups: no concussion history (CONTROL) and concussion history (CONC). While the original design of this study intended for three experimental groups, only twenty participants with a history of concussion were recruited within a six-month timeframe. Thus, all participants with a self-reported history of concussion were combined into one group. A Participant Lifestyle Questionnaire (Appendix F) assessed lifestyles that might affect how participants performed on this task. These included sleep patterns, nicotine use, caffeine use, and prescription medication for mood disorders which all have been supported in the literature to alter cognitive function or reaction times (Durlach, 1998; Hindmarch, 2004; Paul, Gray, & Lange, 2002; Sabbe, van Hoof, Hulstijn, & Zitman, 1996; Stocker, Khan, Henry, & Germain, 2017). Participants also answered a Sports Participation Questionnaire (Appendix G) to assess the frequency, type, and competitive level of any sports played by the participants (Tegner & Lysholm, 1985). Participants completed the Edinburgh Handedness Inventory (Appendix F) to assess hand dominance (Oldfield, 1971). Scores on this inventory determined the hand used during the experimental trials. The participants' dominant arm (from shoulder to the tip of the index finger) was measured. This measurement was used to compare to the theoretical path lengths so that the maximal path lengths would be less than 80% of the total arm length. This comparison ensured no participant performed reaches with maximal extension of the arm, which could have led to fatigue and thus influenced the dependent measures.

A MiniBird kinematic system (Ascension Technology, Burlington, VT) collected movement data during the experiment. A customized LabView program (BloomTech, Richfield, WI) was used to calculate the variables of interest, sampling the analog data at

111 Hz. The sensor was secured to the participants' dominant (based on the score of the Edinburgh Handedness Inventory) dorsal-side index finger with medical tape. The same customized LabView program presented the visual stimulus for the reaching tasks on a Dell laptop computer (Dell Inc., Round Rock, TX). The laptop computer was connected to a LCD projector (Hitachi Consumer Electronics Co. Ltd., Yokohama, Japan) that displayed the reaching task on a custom-built projection screen.

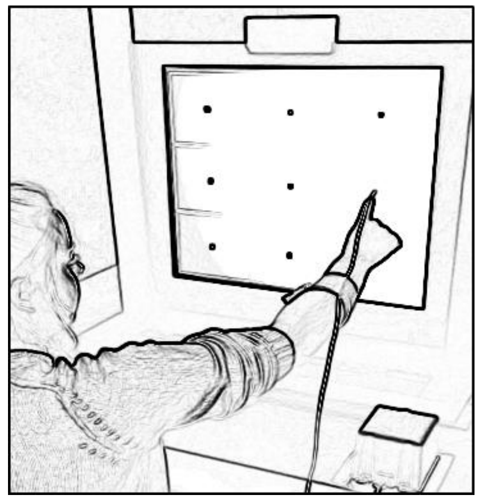

Figure 2. Experimental Set-up

Participants sat upright on a stationary chair in front of the projection screen. The projection screen rests on top of a table (73 cm high) and was set back 40 cm from the front of the table. The projection screen displayed a 3 X 3 grid of white squares as shown in Fig. 2. Each square measured 14 cm X 14 cm and was aligned so that the border between the top and middle row was approximately at eye level of the participants. In the center of each square was a central target measuring 1 cm X 1 cm, which remained visible during the duration of the experimental procedure. Each participant completed a calibration process before the onset of the data collection. The purpose of the calibration process was to determine the location of each of the eight targets and the home position in three-dimensional space.

Participants performed each of two trial types under three different conditions. In the first trial type, participants touched the center of the cued peripheral square after a brief delay (SIMPLE). In the second trial type, participants touched the center of the square three spaces in the clockwise direction from the original location cue, again after a brief delay (spatial remapping; SPRE). The cued target location (the eight peripheral squares) in both trial types was indicated by the target square briefly turning yellow. The go cue was always

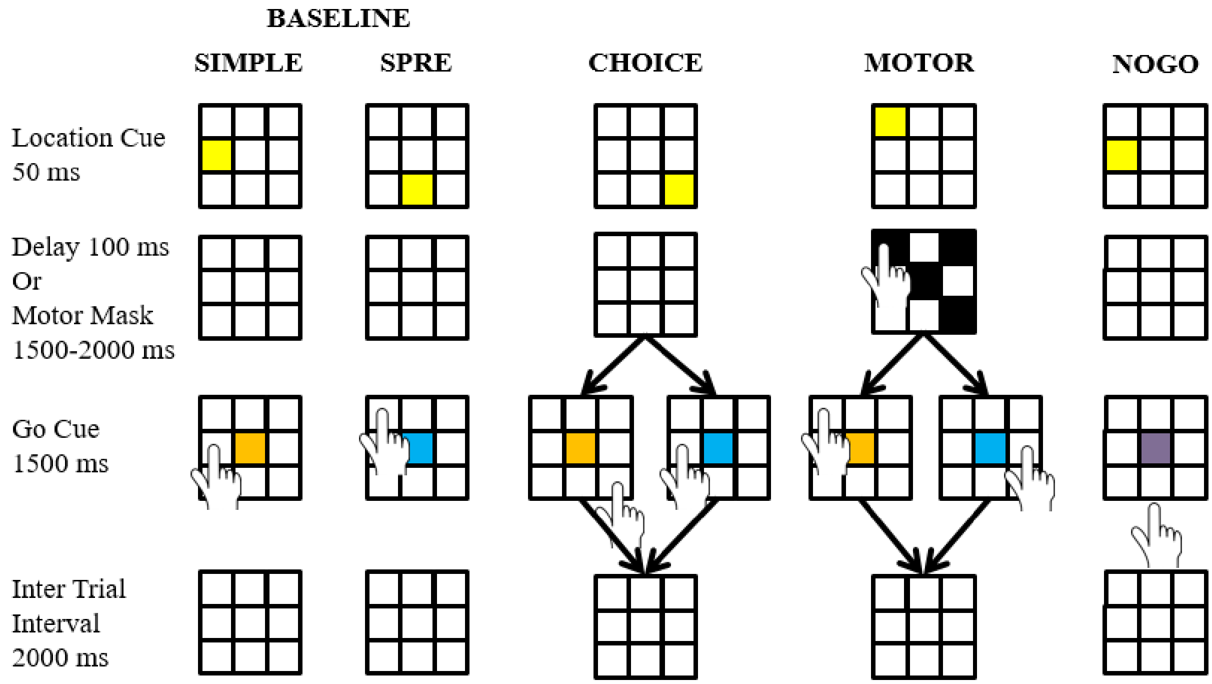

Figure 3. Trial sequence for the three visually-guided reaching task conditions The overall task was for participants to touch a square based on task instructions. Above are examples of each task condition. In the BASELINE-SIMPLE task, participants touched the previously cued square after a brief delay. In the BASELINE-SPRE, participants mentally rotated the target location clockwise three spaces from the original cue location. The CHOICE condition, participants applied either the SIMPLE rule or the SPRE rule based on go cue color. The MOTOR condition required participants to touch the four black squares in a self-selected order during the delay before touching the appropriate square based on task rule. Catch trials, signaled by a purple go cue, required participants to inhibit movement during the go cue and occurred occasionally (10% of total trials) in each of the task conditions.

presented in the center square, and the trial type was indicated by the color of the cue (orange – SIMPLE; blue – SPRE). If the go cue was purple (NOGO), participants withheld their reach as a catch trial. Zero to three catch trials occurred in every block of 16 trials for all of the task conditions described below such that catch trials represented 10% of the total trials in a task condition.

Participants performed these two types of trials under three task conditions (Fig. 3). During the BASELINE condition, participants completed entire blocks of either SIMPLE trials or SPRE trials. The SIMPLE BASELINE was the easiest condition in terms of overall cognitive demand. The SPRE BASELINE condition added a level of cognitive complexity to the task as participants had to mentally rotate the target location (Fig. 4). During the CHOICE reaching condition, another level of cognitive demand was added (Fig. 4). The target cue was presented as before, but the participants did not know if the trial was to be SIMPLE or SPRE until the go cue was presented, thus requiring participants to quickly identify the color of the go cue, apply the associated rule, and make an accurate reach to the correct square. Also, the number of potential motor trajectories increased from one to two in this condition, increasing motor load. SIMPLE and SPRE trial types were counterbalanced in this task condition. The third condition (MOTOR) was the same sequence as the CHOICE condition; however, the delay was lengthened to 1500-2000 ms when black squares appeared. Participants touched all four black squares in a self-selected order and returned to the home position as quickly as possible to wait for the go cue for the originally targeted position. The motor mask was randomly assigned to locations on the grid, and the location of one of the four black squares was counterbalanced between being congruent and incongruent to the original location cue. This condition added motor interference (Fig. 4), and thus increased the motor load, to the task condition as participants would potentially have difficulty pre-planning their reach to the originally cued target location. For this study, motor load was defined as the performance of any motor task in addition to the motor tasks in the baseline conditions.

Due to the nature of the task and to limit learning bias, the following assignment of task conditions was used (Fig. 5). The SIMPLE BASELINE and SPRE BASELINE

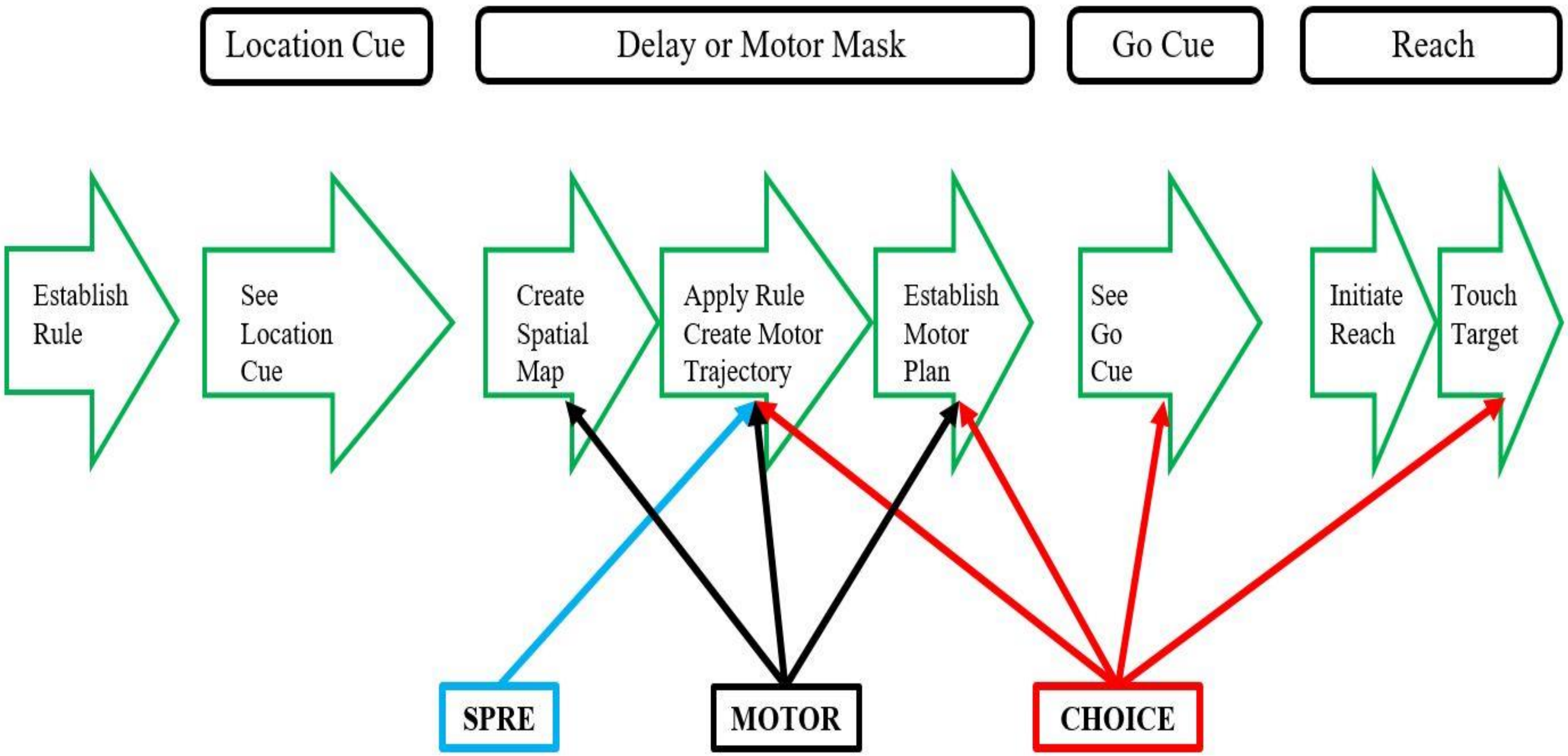

Figure 4 Proposed manipulations of cognitive and motor demand for each task condition. The top row (black boxes) represent the sequence of events for the visually-guided reaching task. The middle row (green arrows) depict the hypothesized cognitive and motor processes of an individual performing the reaching task. The bottom row represents the experimental manipulations and the proposed interactions with the performance of the task. Note: the MOTOR condition also incorporated the CHOICE manipulation.

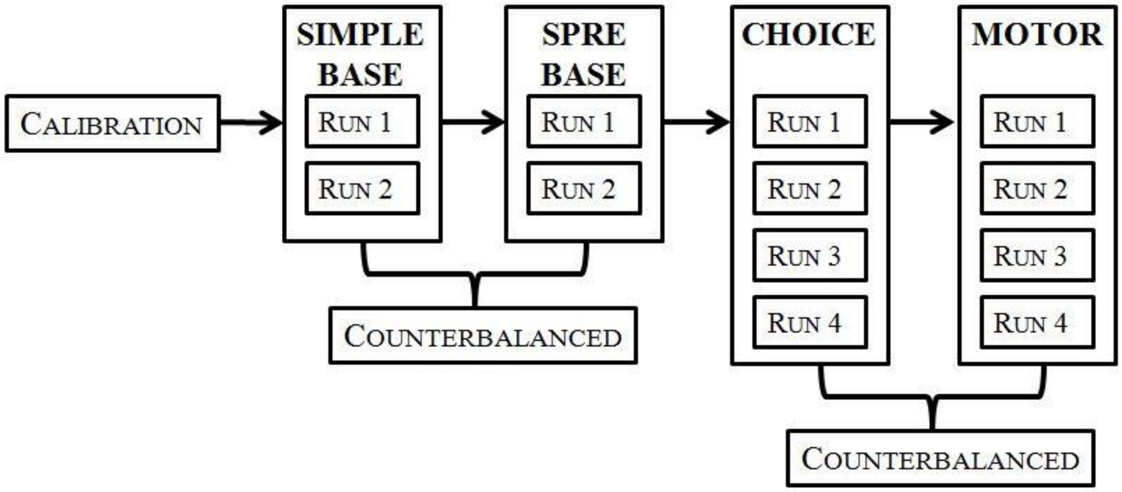

Figure 5. Flow Chart of Reaching Task. Runs within each block were randomized between participants.

conditions were counterbalanced among participants and were the first two conditions participants performed. The CHOICE and MOTOR conditions were also counterbalanced and always followed the two baseline conditions. Participants received practice trials before each new task condition and obtained >70% target selection accuracy to proceed to the corresponding experimental task condition. Of the additional practice trials needed to obtain >70% target accuracy ((Table 3), only one participant (CONTROL, MOTOR) needed additional trials due to not achieving the minimum accuracy threshold. All other additional trials were due to timing errors (either participants initiated movement before the go cue was presented or did not return to the home

Table 3. Practice Trials per Task Condition

	Total Practice Trials (number of participants)	
Condition	CONTROL	CONC
SIMPLE	7 (n = 17) 14 (n = 3)	7 (n = 20)
SPRE	7 (n = 17) 14 (n = 3)	7 (n = 18) 14 (n = 2)
CHOICE	10 (n = 20)	10 (n = 20)
MOTOR	10 (n = 15) 20 (n = 5)	10 (n = 13) 20 (n = 6) 30 (n = 1)

location within the duration of time allocated for the motor mask). Participants also received rest breaks as needed to prevent fatigue.

Analysis

Independent variables were trial type (SIMPLE and SPRE), task condition (BASELINE, CHOICE, MOTOR) and concussion history (CONTROL, CONC). Dependent variables were target selection accuracy, reaction time, reaction time variability, movement time, movement time variability, path length, path length variability, end point accuracy and end point variability (horizontal and vertical). A mixed 2 X 3 X 2 repeated measures ANOVA was run separately for each dependent measure using SPSS software (v. 22 IBM, New York, NY). Significance level was set at $\alpha = .05$ with adjustments made for multiple comparisons using the Holm-Bonferroni method (Holm, 1979).

A customized LabView program calculated the variables of interest. Target selection accuracy was a percentage of reaches to correct target locations. Target selection was based on the participant's index fingertip getting within a "target ellipse" measuring 6.0 cm in X and Y direction and 1.0 cm in the Z direction of the target. Reaction time was the elapsed time from the presentation of the go cue to the initial movement of the participant's index finger as calculated by the time the finger moved more than 2.0 cm in any direction ("home base ellipse") from the home base after the 'go' cue presentation. Movement time was measured as the elapsed time from the initial movement of the participants' finger until a "target ellipse" was reached. The path length variable was a normalized value by dividing the actual path length by the shortest 3D distance between the home base and the target location. The formula for each participant's path length was:

$$PATH = \sum\sqrt{(x_l - x_k)^2 + (y_l - y_k)^2 + (z_l - z_k)^2} \qquad (1)$$

Where “k” was the initial position and “l” was the final position.

The formula for normalized path length was:

$$PATH_{norm} = \frac{PATH_{exp}}{PATH_{calc}} \tag{2}$$

Reaction time variability, movement time variability, and path length variability were all calculated from the respective within-subject standard deviations. End point accuracy was measured as horizontal and vertical accuracy separately (z-plane was fixed as the participants were touching a 2D screen), and defined as the distance from the calibrated target location to the experimental touch of the target. Absolute values were used for each measure. From the end point accuracy values, standard deviations were calculated for both the horizontal and vertical directions, thus producing end point variability in either direction.

For the final analysis, trials were excluded based on three criteria. First, trials with reaction times less than 150 ms and greater than 2000 ms were excluded from the final analysis (RT error). Second, a No Touch error occurred if the touch did not register due to either the participant missing the trial (e.g. the participant missed the location cue) or failing to pass the boundaries of the target ellipse. In this case, the entire trial was excluded from the final analysis. Third, if a participant touched the incorrect target location, only the dependent variable “target selection accuracy” was included from that trial in the final analysis. Table 4 lists the average errors and range for both experimental groups across trial type and task condition.

Table 4. Errors by Type of Error, Trial Type, and Task Condition

	Condition	Type of Error	CONTROL Avg. (Range)	CONC Avg. (Range)
SIMPLE	BASELINE	RT Error	0.25 (0 – 3)	0.35 (0 – 2)
		No Touch	0.45 (0 – 4)	0.20 (0 – 1)
		Incorrect	0.05 (0 – 1)	0.00 (0)
	CHOICE	RT Error	0.25 (0 – 4)	0.00 (0)
		No Touch	0.35 (0 – 2)	0.25 (0 – 2)
		Incorrect	0.00 (0)	0.00 (0)
	MOTOR	RT Error	0.55 (0 – 4)	0.15 (0 – 1)
		No Touch	0.25 (0 – 2)	0.00 (0 – 0)
		Incorrect	0.55 (0 – 3)	0.85 (0 – 4)
SPRE	BASELINE	RT Error	0.20 (0 – 2)	0.15 (0 – 3)
		No Touch	0.10 (0 – 1)	0.10 (0 – 1)
		Incorrect	0.40 (0 – 2)	0.30 (0 – 2)
	CHOICE	RT Error	0.20 (0 – 2)	0.00 (0 – 0)
		No Touch	0.10 (0 – 1)	0.20 (0 – 1)
		Incorrect	0.80 (0 – 4)	0.70 (0 – 2)
	MOTOR	RT Error	0.75 (0 – 7)	0.10 (0 – 1)
		No Touch	0.25 (0 – 2)	0.05 (0 – 1)
		Incorrect	1.50 (0 – 6)	2.55 (0 – 8)

Participants completed 32 trials of each Trial Type per Task Condition

Chapter 4: Results

The long-term effects of concussions in young adult females on visuomotor behavior during a visually-guided reaching task were examined in this study. Time since injury, as well as the age and sex of the participants, were controlled as these factors may mask any predicted outcomes. Two principal hypotheses were developed for this study. The first hypothesis was that by increasing the cognitive demand of the visually-guided reaching task through the introduction of a choice component, individuals will demonstrate increased reaction time and variability, increased movement time and variability, increased path length and variability, decreased end point accuracy and increased end point variability from a baseline measure. Furthermore, individuals with a history of concussions will display poorer performance on the visually-guided reaching task than the control group. The second hypothesis was that by increasing the cognitive and motor demand of the visually-guided reaching task through the introduction of a secondary motor task in addition to a choice component, individuals will demonstrate increased reaction time and variability, increased movement time and variability, increased path length and variability, decreased end point accuracy and increased end point variability from both a baseline measure and the experimental choice measure. Furthermore, individuals with a history of concussions will display poorer performance on the visually-guided reaching task than the control group.

Concussion History and Symptoms

Twenty females without a history of concussion (CONTROL age: 21.2 ± 2.16 years, left-handed n = 1) and twenty females with a history of concussion (CONC age: 22.3 ± 2.43 years, left-handed n = 1) participated in the study. Both the total number of self-reported concussions (CONC 3.0 ± 1.6) and the time since the most recent concussion (CONC 33.24 ± 36.12 months) were recorded. Of the 60 total concussions reported, 33 (55%) were diagnosed by a medical practitioner (MD, ATC, PT, RN). An evaluation of previous head injuries and the resulting symptoms identified four participants from the CONTROL group who may have sustained an unreported concussion. All participants completed the Symptom Evaluation of the SCAT3 (Guskiewicz et al., 2013) from which a total symptom score (out of 22) and a total severity score (out of 132) were calculated. SCAT3 total symptoms scores (CONTROL 0.3 ± 0.91; CONC 3.6 ± 5.28) significantly differed between groups ($t_{(38)} = -2.80$, $p < .05$) as well as total severity scores (CONTROL 0.5 ± 1.79; CONC 6.0 ± 10.98) ($t_{(38)} = -2.21$, $p < .05$). Concussion characteristics of the participants with a history of concussion are displayed in Table 5.

Table 5. Summary of the Concussion History and Symptom Survey of Participants with a History of Concussion

Participant	Age	# of Self-Reported Concussion	Time since Last Concussion (Months)	SCAT3 Symptom Score (22)	SCAT3 Severity Score (132)
1	20	3	30	0	0
2	27	1	156	4	7
3	22	3	75	0	0
4	21	4	60	0	0
5	21	5	11	13	24
6	23	2	6	4	4
7	24	6	24	0	0
8	23	4	6	8	11
9	28	5	12	20	45
10	19	1	54	0	0
11	19	4	14	2	2
12	23	4	8	0	0
13	22	1	9	2	2
14	23	2	7	5	6
15	19	3	28	0	0
16	22	3	24	0	0
17	20	1	24	8	12
18	24	1	24	5	5
19	22	5	24	0	0
20	24	2	72	1	1
Mean ± SD	**22.3 ± 2.43**	**3.0 ± 1.6**	**33.24 ± 36.12**	**3.6 ± 5.28**	**6.0 ± 10.98**

Participant Lifestyles

All participants reported as non-smokers/nicotine users and all participants refrained from the intake of caffeine at least two hours before their scheduled testing session. Participants reported their two-week nightly average amount of sleep (CONTROL 6.7 ± 0.86 hours; CONC 6.6 ± 1.01 hours) and the total hours of sleep from the night before their experimental session (CONTROL 6.6 ± 1.09 hours; CONC 6.9 ± 1.45 hours). A one-way ANOVA ($F_{(3, 76)} = 0.22$, $p > .05$) revealed no difference in hours of sleep between the two groups, nor any differences between the hours of sleep from the night before compared to the two-week nightly average. One participant from the CONTROL group (Effexor, 75 mg/daily) group and four participants from the CONC group (Sertraline, 50 mg/daily (n = 2); Fluoxetine, 40 mg/daily; unspecified thyroid medication, 75 mg/daily) reported taking a prescription medication for a mood disorder. All participants who reported prescription medication for mood disorders were on their respective medication for at least six months (range: 0.5 – 5.0 years) and had taken their respective medication before the testing session.

Current Sports Participation

Tegner Activity Level Scale (Tegner & Lysholm, 1985) scores (out of a possible score of 10) were collected for both groups. An independent t-test ($t_{(38)} = -2.67$, $p < .05$) revealed a significant difference between the two groups (CONTROL 5.6 ± 1.70; CONC 7.2 ± 2.07)

Visually-Guided Reaching Task

Results of the 2 X 3 X 2 repeated measures ANOVAs are displayed in Table 6. Descriptive statistics from the repeated measures ANOVAs are shown in Appendix I.

The lowest Target Selection Accuracy was 91.98% (CONC, SPRE Trial Type, Motor Task Condition) with the remaining accuracies ranging from 95.08 % – 100.00 %. Given the a priori prediction that the poorest performance on the visually-guided reaching task would occur during the largest cognitive and motor demand, further analysis was conducted. Paired t-tests revealed a significant difference in the SPRE trial type between the BASELINE and MOTOR condition for target selection accuracy within both the CONC group ($t_{(19)} = 4.32$, $p < .001$; BASELINE 99.06 ± 1.79; MOTOR 91.98 ± 7.02) and the CONTROL group ($t_{(19)} = 3.26$, $p < .005$; BASELINE 98.72 ± 2.41; MOTOR 95.08 ± 4.91). However, an independent t-test ($t_{(38)} = 1.62$, $p = .054$) revealed no significant difference in the MOTOR condition for the SPRE trial type for target selection accuracy between the two groups (CONTROL 95.08 ± 4.91; CONC 91.98 ± 7.02).

Results of the repeated measures ANOVAs for the other dependent measures revealed significant main effects for Trial Type ($p < .05$) cross dependent measures of Target Selection Accuracy (Fig. 6a), Reaction Time (Fig. 6b), Reaction Time Variability (Fig. 6c), Movement Time (Fig, 7a), Movement Time Variability (Fig. 7b), Path Length (Fig. 7c), Path Length Variability (Fig. 7d), and Horizontal End-Point Variability (Fig. 8b). Significant main effect for Task Condition ($p < .05$) was found for all dependent measures (Fig. 6-8). Significant interactions of Trial Type X Task Condition ($p < .05$) were found for Target Selection Accuracy (Fig. 6a), Reaction Time (Fig. 6b), Movement Time (Fig. 7a), Movement Time Variability (Fig. 7b), Path Length (Fig. 7c), and Path Length Variability (Fig. 7d). No significant interactions were revealed for the main effect of group membership or the interactions of Trial Type X Group ($p > .05$), Task Condition X Group ($p > .05$), and Trial Type X Task Condition X Group ($p > .05$).

Table 6. Results of repeated measures ANOVAs of Trial Type X Task Condition X Group for all Dependent Variables

Dependent Measure	**Trial Type F (1, 38) *p* (η^2)**	**Trial Type X Group F (1, 38) *p* (η^2)**	**Task Condition F (2, 76) *p* (η^2)**	**Task Condition X Group F (2, 76) *p* (η^2)**	**Trial Type X Task Condition F (2, 76) *p* (η^2)**	**Trial Type X Task Condition X Group F (2, 76) *p* (η^2)**	**Group F (1, 38) *p* (η^2)**
SELECTION ACCY	***41.191**** ***.000 (.520)***	.478^{ns} .493 (.012)	***28.736**** ***.000 (.431)***	2.912^{ns} .079 (.071)	***7.193**** ***.002 (.159)***	1.426^{ns} .247 (.036)	1.076^{ns} .306 (.028)
RT	***56.543**** ***.000 (.606)***	.326^{ns} .571 (.009)	***92.294**** ***.000 (.708)***	.339^{ns} .708 (.009)	***21.287**** ***.000 (.359)***	.555^{ns} .568 (.014)	.673^{ns} .417 (.017)
RT VAR	***60.536**** ***.000 (.614)***	.038^{ns} .847 (.001)	***39.858**** ***.000 (.512)***	.180^{ns} .816 (.005)	1.877^{ns} .164 (.047)	0.756^{ns} .462 (.020)	.008^{ns} .931 (.000)
MT	***91.266**** ***.000 (.706)***	.287^{ns} .595 (.007)	***40.946**** ***.000 (.519)***	.868^{ns} .417 (.022)	***35.642**** ***.000 (.484)***	.270^{ns} .737 (.007)	.259^{ns} .614 (.007)
MT VAR	***69.440**** ***.000 (.646)***	.003^{ns} .960 (.000)	***45.741**** ***.000 (.546)***	.030^{ns} .962 (.001)	***6.829**** ***.003 (.152)***	1.056^{ns} .348 (.027)	.414^{ns} .524 (.011)
PATH	***57.406**** ***.000 (.602)***	1.433^{ns} .239 (.036)	***35.331**** ***.000 (.482)***	.054^{ns} 0910 (.001)	***24.212**** ***.000 (.389)***	1.431^{ns} .246 (.036)	.095^{ns} .760 (.002)
PATH VAR	***47.332**** ***.000 (.555)***	.926^{ns} .342 (.024)	***34.155**** ***.000 (.473)***	0.024^{ns} .960 (.001)	***9.998**** ***.000 (.208)***	1.980^{ns} .155 (.050)	.007^{ns} .935 (.000)
HORZ ACCY	5.937^{ns} .020 (.135)	.909^{ns} .346 (.023)	***22.129**** ***.000 (.368)***	.013^{ns} .985 (.000)	4.449^{ns} .015 (.105)	.109^{ns} .896 (.003)	.074^{ns} .787 (.002)
HORZ VAR	***16.082**** ***.000 (.297)***	.399^{ns} .532 (.010)	***19.458**** ***.000 (.339)***	.186^{ns} .786 (.005)	3.820^{ns} .027 (.091)	1.134^{ns} .327 (.029)	.000^{ns} .986 (.000)
VERT ACCY	.152^{ns} .698 (.004)	.002^{ns} .965 (.000)	***8.048**** ***.002 (.175)***	.817^{ns} .425 (.021)	.683^{ns} .503 (.018)	.020^{ns} .978 (.001)	.296^{ns} .589 (.008)
VERT VAR	.078^{ns} .782 (.002)	.993^{ns} .325 (.025)	***6.743**** ***004 (.151)***	.762^{ns} .447 (.020)	.600^{ns} .550 (.016)	.263^{ns} .767 (.007)	.022^{ns} .883 (.001)

Abbreviations: RT: Reaction Time; RT VAR: Reaction Time Variability; MT: Movement Time; MT VAR: Movement Time Variability; PATH: Path Length; PATH VAR: Path Length Variability; HORZ ACCY: Horizontal End-Point Accuracy; HORZ VAR: Horizontal End-Point Variability; VERT ACCY: Vertical End-Point Accuracy; VERT VAR: Vertical End-Point Variability; SELECTION ACCY: Selection Accuracy; ns: non-significant; asterisk/italics/bold denotes $p < 0.05$ after Holm-Bonferroni correction.

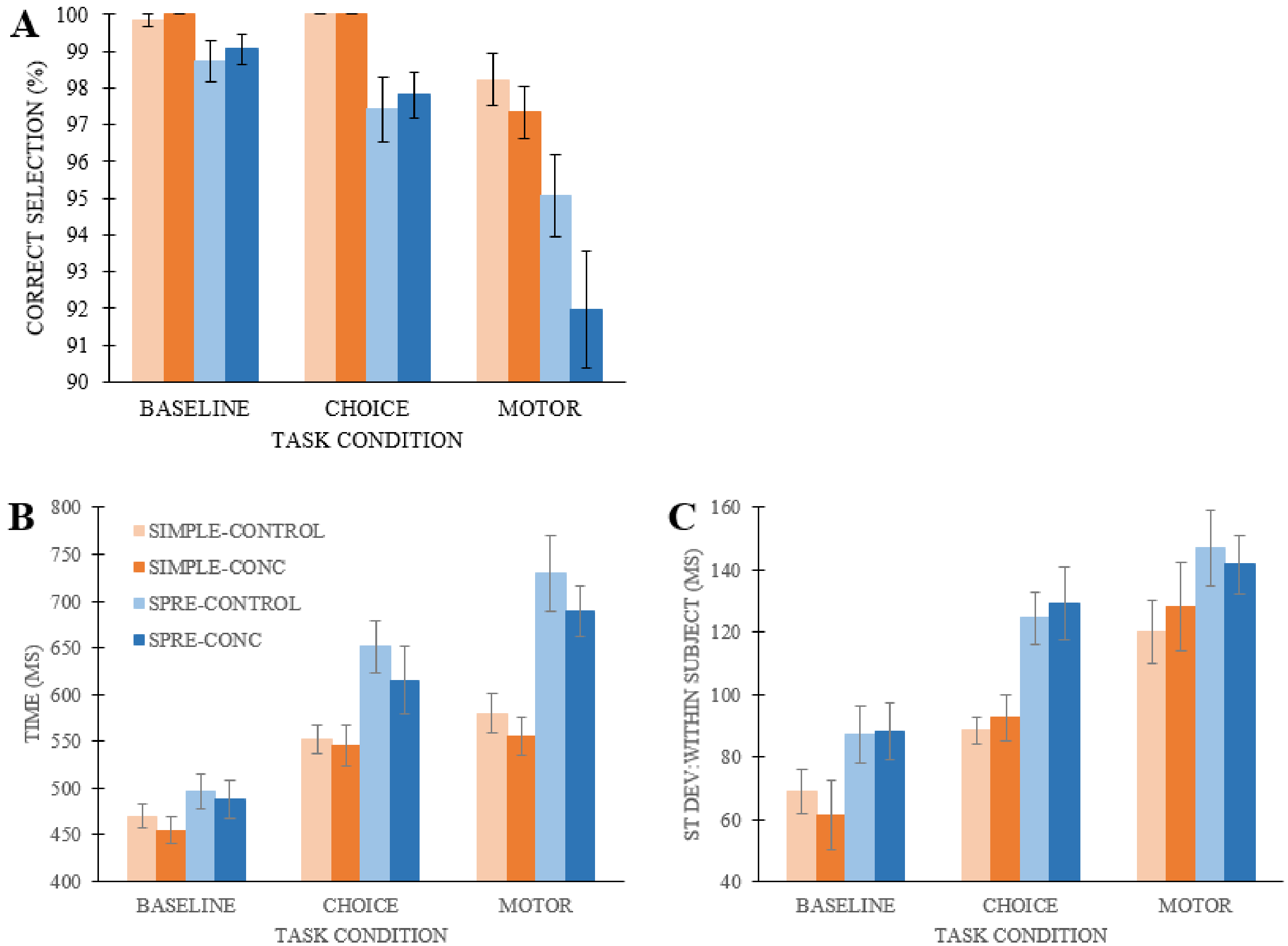

Figure 6 Target Section Accuracy, Reaction Time, and Reaction Time Variability. *A.* **Target Selection Accuracy** Both main effects of Trial Type ($p < .05$) and Task Condition ($p < .05$) were significant as well as the interaction between Trial Type and Task Condition ($p < .05$). ***B.* Average Reaction Time** Both main effects of Trial Type ($p < .05$) and Task Condition ($p < .05$) were significant as well as the interaction between Trial Type and Task Condition ($p < .05$). ***C.* Reaction Time Variability** Both main effects of Trial Type ($p < .05$) and Task Condition ($p < .05$) were significant, however the interaction between Trial Type and Task Condition ($p > .05$) was not significant. Error bars represent Standard Error of the Mean (SEM).

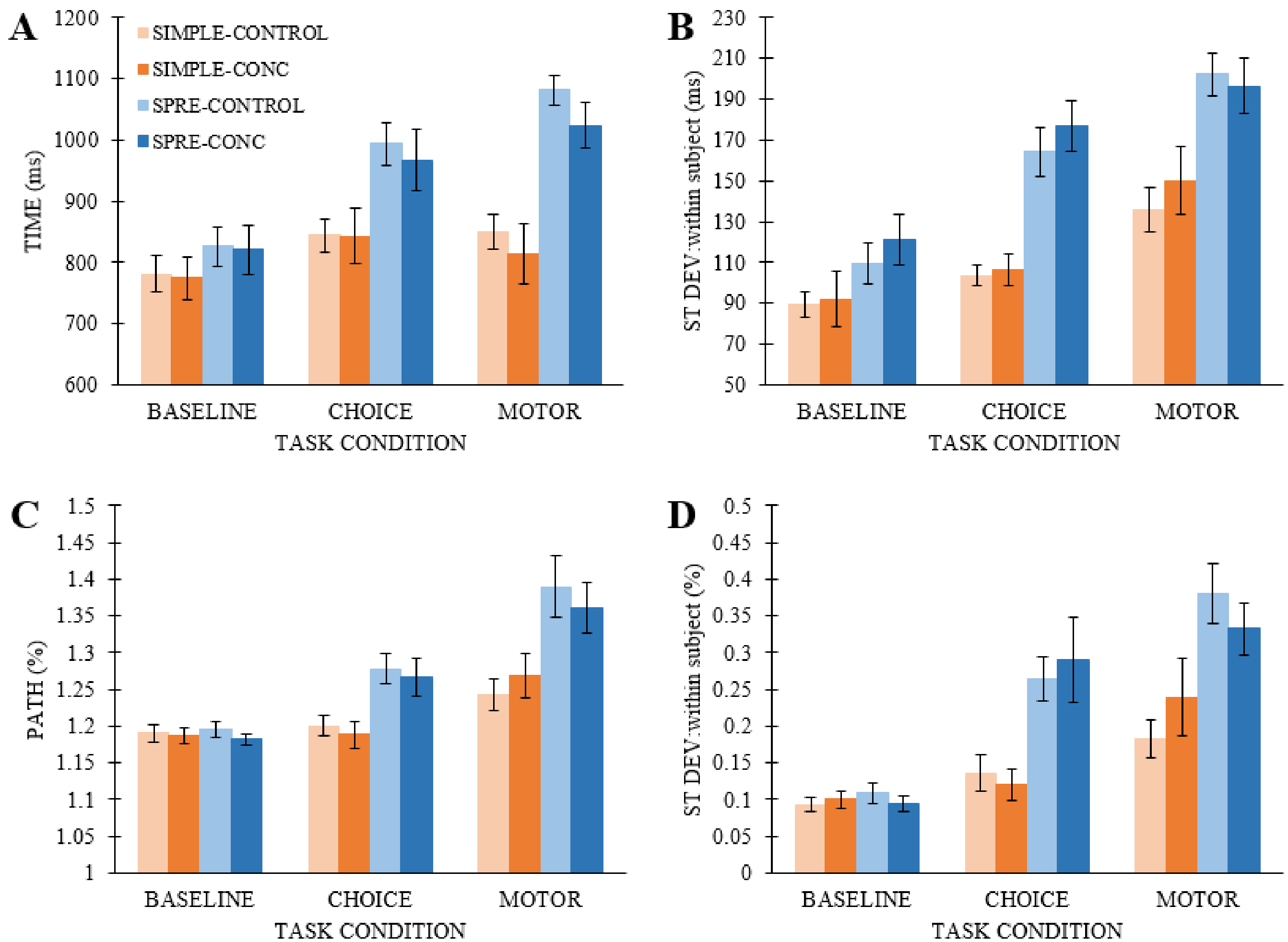

Figure 7 Movement Time, Path Length, and their Associated Variability. *A.* Movement Time Both main effects of Trial Type ($p < .05$) and Task Condition ($p < .05$) were significant as well as the interaction between Trial Type and Task Condition ($p < .05$). ***B.* Movement Time Variability** Both main effects of Trial Type ($p < .05$) and Task Condition ($p < .05$) were significant as well as the interaction between Trial Type and Task Condition ($p < .05$). ***C.* Path Length** Both main effects of Trial Type ($p < .05$) and Task Condition ($p < .05$) were significant as well as the interaction between Trial Type and Task Condition ($p < .05$). ***D.* Path Length Variability** Both main effects of Trial Type ($p < .05$) and Task Condition ($p < .05$) were significant as well as the interaction between Trial Type and Task Condition ($p < .05$). Error bars represent Standard Error of the Mean (SEM).

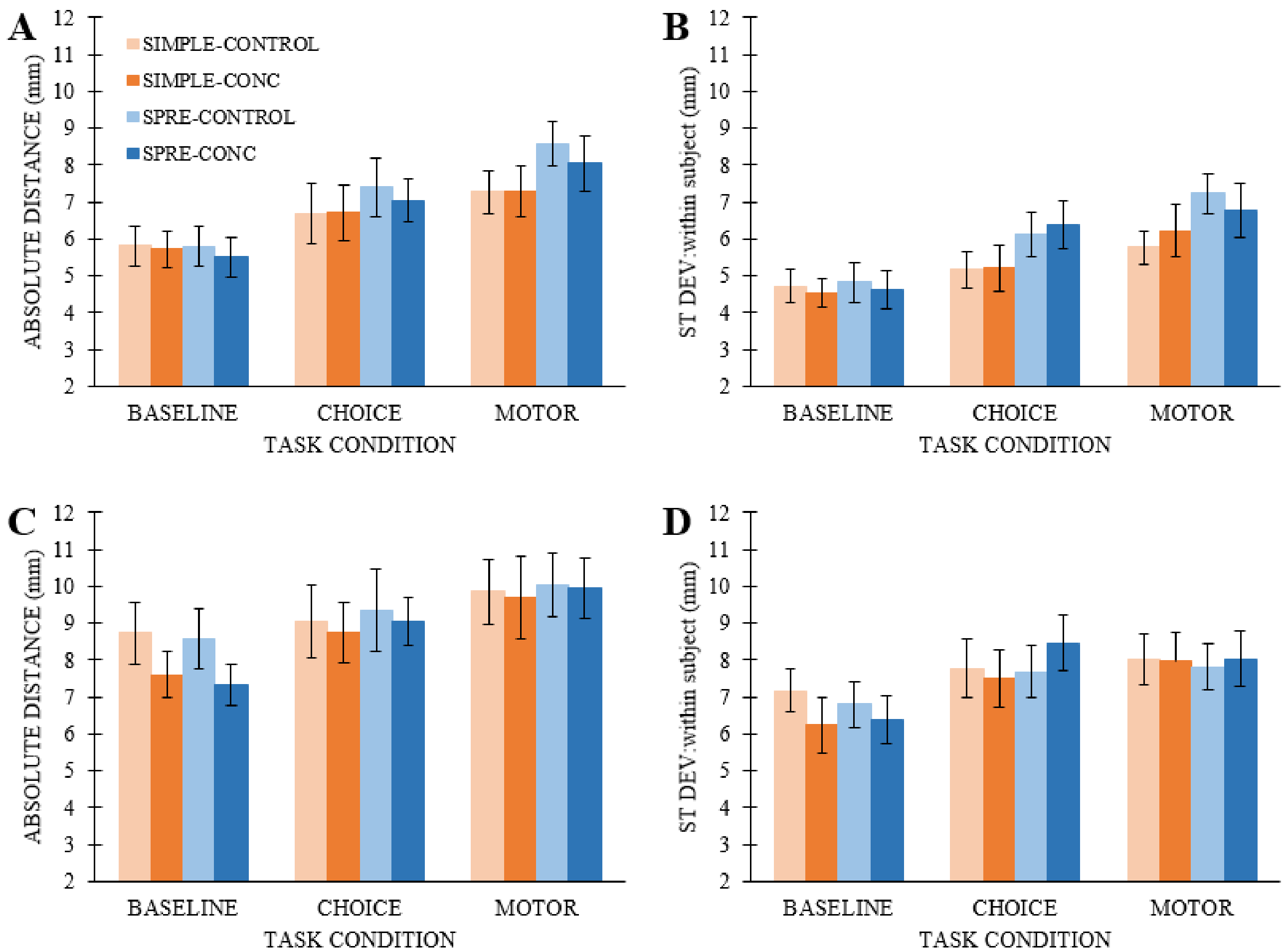

Figure 8 End-Point Accuracy and Variability. ***A.*** **Horizontal Accuracy** Main effect of Task Condition ($p < .05$) was significant however the main effect of Trial Type ($p > .05$) and the interaction between Trial Type and Task Condition ($p > .05$) were not significant**.** ***B.*** **Horizontal Variability** Both main effects of Trial Type ($p < .05$) and Task Condition ($p < .05$) were significant, however the interaction between Trial Type and Task Condition ($p > .05$) was not significant. ***C.*** **Vertical Accuracy** Main effect of Task Condition ($p < .05$) was significant however the main effect of Trial Type ($p > .05$) and the interaction between Trial Type and Task Condition ($p > .05$) were not significant. ***D.*** **Vertical Variability** Main effect of Task Condition ($p < .05$) was significant however the main effect of Trial Type ($p > .05$) and the interaction between Trial Type and Task Condition ($p > .05$) were not significant. Error bars represent Standard Error of the Mean (SEM).

Additional Analyses

To confirm that a Type II error was not committed relative to the between-subjects factor of concussion history, various analyses were conducted to address potential pitfalls to the experimental design. Each analysis was performed independent of the other analyses.

First, to control for the differences revealed from the Tegner Activity Level Scale, participants in the CONTROL group with a score of 5 or lower were removed (n = 8), leaving 12 participants in the control group. An independent t-test ($t_{(30)} = -0.95$, $p > .05$) revealed no longer any difference between the two groups in activity level with this change in group membership (CONTROL 6.6 ± 1.08; CONC 7.2 ± 2.07). However, after this adjustment, still no significant differences were found between the previously concussed group and the controls in any dependent measure.

Next, the four participants in the CONTROL group with a suspected but unreported concussion were removed from the CONTROL group (leaving n = 16), and the analyses were repeated. No significant differences were found between the CONC and CONTROL groups for any dependent measure.

Third, three participants in the CONC group self-reported a history of concussion however, all of their concussions were classified as undiagnosed (by a medical practitioner). To adjust for any influence on the dependent measures due to misreporting a concussion, the three individuals were removed from the CONC group (leaving n = 17) and the analyses were repeated. After this adjustment, no significant differences were revealed between the CONC and CONTROL groups for any dependent measure.

Fourth, previous evidence suggests that if an individual has a history of three or more concussions, they demonstrate poorer performance on a cognitive task when compared to both individuals with one to two previous concussions and control participants (Covassin et al., 2010; Gardner et al., 2010; Guskiewicz et al., 2005). In the previous analysis we had collapsed all people with a concussion into the same group due to sample sizes. For the next analysis, the CONC group was divided back into two groups based on concussion history (one or two (n = 8) vs. three or more previous concussions (n = 12)). An independent t-test ($t_{(18)} = -0.13$, $p > .05$) revealed no difference on the Tegner Activity Level Scale between the two new CONC groups with this change in group membership ($CONC_{1-2}$ 7.1 ± 2.16; $CONC_{3+}$ 7.3 ± 2.09). After this group reassignment, no significant differences were found among the three groups for any dependent measure.

Fifth, to adjust for the effects of prescription medication for mood disorders on the dependent measures (Hindmarch, 2004; Paul et al., 2002; Sabbe et al., 1996), the five participants (CONTROL n = 1) were removed from their respective groups. The analyses were performed and no significant differences existed between the CONTROL and CONC groups for any of the dependent measures.

Finally, the possibility existed that an individual was inherently better at the visually-guided reaching task regardless of their concussion history (or lack thereof). To control for this potential confound, two separate analyses were conducted.

1. Individual difference scores for both Trial Types (SIMPLE and SPRE) were calculated using the respective Task Condition statistics of: Choice – Baseline, Motor – Baseline, and Motor – Choice.

2. Individual normalized scores were calculated for both Trial Types by dividing the Task Condition statistics of Choice and Motor by its respective Baseline value.

The results of the subsequent analyses were consistent with the original results of no significant differences between control participants and those with a history of concussion. Based on the multiple analyses, and the consistent finding of no significant differences between the two experimental groups, the likelihood of a Type II error was rejected.

Summary

In this study, as cognitive and motor demand of the visually-guided reaching task increased in both visual attention and motor attention complexity, performance on the task decreased for both groups, indicating sufficient challenges to the cognitive and motor components of the task. Performance across all measures was worst on the most challenging condition and easiest for the simple baseline condition. However, no significant differences were detected between the participants with and without a history of concussion on their respective behavioral outcomes. Further analysis of the data (i.e. difference scores, baseline scores, adjusting for suspected concussions, adjusting for multiple concussions, factoring the possible effects of prescription medication for mood disorders, and adjusting for level of sports participation) still revealed no significant group interactions.

Chapter 5: Discussion

The purpose of the current study was to examine the long-term effects of a history of multiple concussions in young adult females whom were asymptomatic under current standards on visuomotor behavior during a visually-guided reaching task of various complexities. To accomplish this objective, a behavioral task was designed that varied both cognitive and motor demand of the task, as well as careful control for confounding factors of time since injury, age, and sex of the participants. As cognitive and motor demand increased, performance, as measured with both temporal and kinematic characteristics, on the visually-guided reaching task decreased for both experimental groups. However, the major finding of this study was that no significant differences existed between the individuals without a history of concussion and those with a long-term history of concussion in task performance after the manipulations of both cognitive and motor demand.

Expanding on the limited studies investigating visually-guided reaching in individuals with a history of concussion during the long-term post-injury phase, the experimental task designed for this study incorporated suggestions from previous investigations. A sufficient increase of the cognitive load of a task is required to elicit a detectable difference between individuals with and without a history of concussion (Brown et al., 2015; Locklin et al., 2010). We are confident cognitive load was sufficiently high in this experiment because both groups showed a decline in performance as load increased. Cognitive demand was manipulated by altering the location of the target from trial-to-trial, requiring a reach to an alternate location from an original cued location based on a mapping rule, and introducing a choice component between two types of reaches. Novel to this body of work was the introduction of motor interference. Decreases in performance of a motor task have been reported by either increasing the motor load of a task (Huddleston et al.,

2013) or by introducing motor interference to the task (Beurskens et al., 2016). In this study, motor interference was utilized to increase the motor load of the experimental task. Finally, this study combined both increased cognitive and motor load by combining the two elements in the MOTOR condition to further challenge the participants. These considerations were all incorporated into the experimental design of this study.

When participants were challenged to the limit of their attentional capacities in the MOTOR condition, overall performance on the behavioral task, as measured by Target Selection Accuracy, significantly decreased for both groups. Yet, no difference was found between the two groups on this same measure during the most cognitively demanding trials of the visually-guided reaching task. Furthermore, no detectable differences between the two groups in the temporal and kinematic variables were found when evaluating only successful trials of the visually-guided reaching task. In addition to the measures of central tendency for the temporal and kinematic variables, within-subject variability of the dependent measures was analyzed.

Within-subject variability is considered to be a measure of the efficiency of the allocation of attentional resources as participants are challenged by increases in cognitive load, (Kelly, Uddin, Biswal, Castellanos, & Milham, 2008). Individuals with a history of concussions are suspected to have difficulties with their allocation of attentional resources (Broglio et al., 2009). Using EEG to assess the neuroelectric system in previously concussed individuals (at least three years post-injury), Broglio et al. (2009) reported attenuated P3b waves while performing an attention-demanding (three-stimulus oddball) task. The researchers interpreted this finding as the previously concussed group having diminished capabilities to allocate attentional resources (Broglio et al., 2009). However, no differences were detected between both groups on performance of the oddball task nor a clinical assessment (i.e. ImPACT). The investigators acknowledged that the behavioral assessments may not have fully challenged the participants to detect subtle deficits in cognitive function due to a long-term history of concussion (Broglio et al., 2009). In the current study, participants were sufficiently challenged by manipulating both cognitive and motor demand. Yet, no significant differences in within-subject variability were detected between the two groups in the current study. Given these findings, the results of this study do not allow us to reject the null hypothesis that no significant differences in visuomotor behavior on an attention-mediated reaching task exist in young adult females with a history of concussions as compared to controls.

When using behavioral measures to detect differences between individuals with a history of concussion whom are asymptomatic and controls during the long-term post injury stage, a null result has become commonplace (Baillargeon et al., 2012; Broglio et al., 2006; Broglio et al., 2009; De Beaumont et al., 2009; Gardner et al., 2010; Guskiewicz et al., 2002; Iverson et al., 2006; Theriault et al., 2011; Wall et al., 2006). However, these previous investigations have had issues with their methodology due to either the experimental design of their respective behavioral task or the heterogeneity of their participants. All of these factors were considered in the approaches to the design of this study. The visually-guided reaching task in this study did sufficiently challenge the attentional resources of the participants as indicated by the declining performance with increased cognitive and motor load from all participants. We also controlled multiple factors to achieve a homogenous sample of participants. Even when heterogeneity between the two experimental groups was discovered, these factors were accounted for and taken into consideration during a subsequent analysis. Yet, the null result for any group interaction on the dependent measures remained.

In the current study, the asymptomatic, young adult, females with a history of concussions exhibited no detectable behavioral differences as compared to control participants on the visually-guided reaching task. Perhaps the previously concussed participants in this study functionally recovered from their injury due to either neuroplasticity, cognitive reserve, or uncompromised attentional resource capacity; however, these explanations are pure speculations and beyond the scope of this study. Yet, one question to consider is if a history of concussions affects the trajectory of normal cognitive decline due to aging over time. The normal aging process, free of any neurological disorder or injury, may lead to deficits in visual attention (Jones et al., 2006; Mahoney, Verghese, Goldin, Lipton, & Holtzer, 2010; Owsley et al., 1998), executive function (Mahoney et al., 2010), processing speed (Salthouse, 1996), and visuomotor behavior (Owsley et al., 1998). Using the visually-guided reaching task from this study, a group of older adults, free of any cognitive deficits, were tested with the same experimental design [unpublished data; (Petrovska, Fueger, & Huddleston, 2017)}. Compared to the non-concussed young adults from the current study, the older adults displayed increased reaction times and movement times. In this study, we tested young adult females who are not yet experiencing any cognitive decline. What is not known is if a history of concussions would alter this trajectory (Fig. 9) when tested longitudinally.

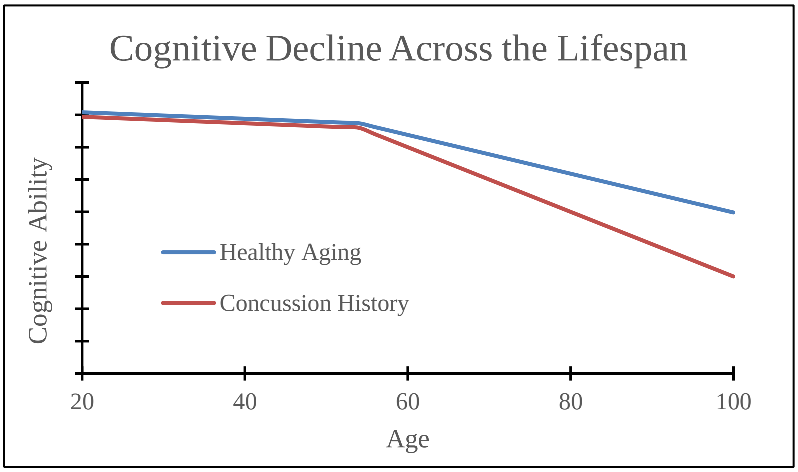

Figure 9 Potential Influence of Concussion History on Cognitive Decline Across the Lifespan. Blue line represents cognitive decline across the lifespan due to normal aging. Adapted from Hehhen & Gabrieli, 2004; Salthouse, 2009. Red line represents speculated influence of concussion history on cognitive decline.

Limitations

Results of this study may only be generalized to individuals of populations that are similar to the sample. Specifically, these findings are only applicable to young adult females, ages 18 – 28 who have a history of concussion and are asymptomatic by current standards.

Certain considerations were made to the design of this study. Ideally, a longitudinal design that included pre-injury assessment, as well as assessments made during both the acute and long-term post-injury stage would be ideal to determine causality. However, given the demographics of the population of interest, accessibility to a population of interest large enough to enroll a minimum sample size required by the power analysis, limitations of the recruitment of participants (i.e. recruiting enough participants without a concussion and then having twenty individuals from this group sustain a concussion during the duration of the study), associated costs with a longitudinal study design, practicality of testing enough participants to complete the study, as well as feasibility of having participants return for testing during the long-term post-injury phase, a cross-sectional design was chosen. Therefore, due to the cross-sectional design of this study, age-matched controls without a history of concussion were used to make comparisons to the population of interest. Furthermore, this study was a behavioral exploration thus any causal links between a history of concussions and subsequent results from the visually-guided reaching task cannot be justified. However, this initial behavioral investigation can provide a steeping-stone for future study direction and design.

Multiple surveys were conducted and demographic information was collected via self-report from the participants. These include: concussion history, history of previous head injuries not classified as concussions, current symptom score from the SCAT3, nicotine use, caffeine use, nightly sleep patterns, prescription medications for mood disorders, and sports participation. As such, these assessments may have been subjected to bias, incorrect recollection, or untruthfulness.

Great care was taken to obtain a homogenous sample; however, heterogeneity did exist between the participants in this study. While homogeneity was controlled or accounted for on demographic factors, true homogeneity among participants, due to possible variations in the location of the damage attributed to the individual's concussion, was not achieved. Given the difficulty with assessing the site of damage in individuals with a history of concussion, achieving a homogenous sample may be highly unlikely in a population of individuals with a history of concussion. Furthermore, if an assumption is made that the location of injury varied between participants, deficits in other cognitive and motor behaviors may exist but were not assessed by the visually-guided reaching task employed in this study.

As a group, the previously concussed participants in this study were asymptomatic under current standards. However, classifying an individual as asymptomatic in relation to a previous concussion does have inherent limitations. While the current standard for assessing concussion symptoms and symptom severity (i.e. SCAT3) was used in this study, this tool is designed as an aide for assessing recovery in the acute post-injury stage. The average time elapsed from the most recent concussion was 33 months. Asking an individual to make an assessment of their current symptoms and symptom severity in relation to a head injury that occurred on average almost three years ago will be subjected to individual bias. But even if the individuals were still symptomatic by current standards, the expected differences between the groups would have been accentuated with the previously concussed individuals exhibiting poorer performance on the visually-guided reaching task.

If an individual sustained her concussion in a competitive sports environment, the likelihood of entering a return to play protocol is high. The current guidelines for the return to play protocol incorporate both gradual increases in exercise and cognitive load/training (McCrory et al., 2013). Both exercise (Berlucchi, 2011; Greenwood & Parent, 2002; van Praag, 2009) and cognitive training, or neurorehabilitation, (Greenwood & Parent, 2002) can aid in recovery of function after a traumatic brain injury via neural plasticity. Previous participation in a return-to-play protocol was not assessed in this study. Therefore, the influence of a return-to-play protocol on the results of this study is unknown.

The assumption was made that participants gave their best and equal effort during each trial of the visually-guided reaching task and had a consistent state of arousal. However, the influence of individual motivation and competitiveness was not assessed. Individuals may differ in their motivation and competitiveness when completing a task. Individuals high in competitiveness, or achievement motivation, will attempt to attain a better performance at a task whether measured against themselves or another group of individuals (Nicholls, 1984). This relationship has been observed in both academic and sports settings (Duda & Nicholls, 1992) as well as in experimental tasks measuring reaction time when the difficulty of the task was varied (Capa, Audiffren, & Ragot, 2008; Wamkel, 1972). Additionally, the effects of an individual's motivation to "do well" on a behavioral task or assessment has been investigated in previous studies of individuals with a history of concussion; however, the primary focus was centered on the assessments pre- and post-injury during the acute phase (Bailey, Echemendia, & Arnett, 2006; Echemendia, Herring, & Bailes, 2009; Rabinowitz & Arnett, 2013). Simply put, the motivation of a previously concussed athlete during the post-injury assessment can lead to better performance on the evaluation so they can quickly return to their sport. Moreover, some evidence does exist for a participant's motivation to influence task performance in individuals with a history of concussion in the long-term post-injury phase (De Beaumont et al., 2011). Therefore, some participants may have had higher achievement motivation than other participants or the previously concussed participants may have been motivated to perform better on the visually-guided reaching task to downplay the long-term effects of their injury.

Future Research

The findings from this study suggest the following for future research:

1. Expand on the matching of non-concussed to previously concussed individuals by controlling for level of sports participation.
2. Assess the return to play protocols the previously concussed individuals may have experienced to determine if neurorehabilitation may have aided in functional recovery.
3. Assess the motivation and competitiveness of each participant to reveal any possible unanticipated influences on task performance.
4. Given the findings of the healthy, older adults in comparison to the non-concussed, young adults, longitudinal studies should be conducted to see in the normal declines in visuomotor behavior due to healthy aging are accentuated by a history of concussion.

Summary

The primary research hypothesis was rejected due to no significant differences between the two experimental groups after increasing both cognitive and motor demand of the visually-guided reaching task. Given the robust findings related to the experimental design of the visually-guided reaching task, in addition to the differences found when comparing the non-concussed group of younger adults in this study to a cohort of healthy, older adults using the same protocol, the methods used in this study can reveal a detectable difference between two groups.

Furthermore, the variables of age, sex, time since injury (greater than six-month post injury), effects of caffeine and nicotine, sleep loss, sports participation, suspected concussions, multiple concussions, and the effects of psychoactive drugs were all either controlled or considered during the analyses yet still yielded a null result for group differences. However, factors such as participation in a return-to-play protocol and the psychological attributes (i.e. competitiveness and motivation) of the participants were not assessed which could have influenced the results. Future studies should take these recommendations under consideration.

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Appendix A: Participant Pre-Screen Questionnaire

Pre-Screen Questionnaire

Title of Research Project: Measuring the Long-Term Effects of Concussions on Reaching Among Distractors

The following questions will help determine if you meet the criteria for inclusion into this study. It is important that you answer each question accurately. Please consider your response to each of the four questions below.

1. Are you a female between the ages of 18 and 29 years old?
2. Do you have normal or corrected-to-normal vision?
3. Are you able to sit comfortably for up to 1.5 hours?
4. We are looking for females who either have not had a concussion or have had a concussion diagnosed by a medical provider (physician, nurse, athletic trainer, physical therapist, etc.). Do you fall into one of these 2 categories? You would answer 'no' to this question if you think you have experienced any kind of head injury but never had it diagnosed.

If you answered 'no' to any of the above four questions, unfortunately you do not qualify for this study. If you answered 'yes' to all of the above questions, you may qualify for the study. Please answer the next three questions:

5. Have you been diagnosed by a doctor with a condition involving your brain or nerves other than a concussion or mood disorder?
6. Have you been diagnosed by a doctor with a learning disorder, ADD/ADHD or dyslexia?
7. Have you suffered an arm or spinal cord injury in the last 6 months?

If you answered 'no' to the last three questions and 'yes' to the first four questions, you qualify for this study. Please contact me to set up an appointment.

If you were unable to answer these questions accordingly, you will not be able to participate. We do thank you for your willingness to be part of our study.

Appendix B: IRB Manager Protocol Form

IRBManager Protocol Form

Instructions: Each Section must be completed unless directed otherwise. Incomplete forms will delay the IRB review process and may be returned to you. Enter your information in the **colored boxes** or place an **"X"** in front of the appropriate response(s). If the question does not apply, write **"N/A."**

SECTION A: Title

A1. Full Study Title:	Measuring the Long-Term Effects of Concussions on Reaching Among Distractors

SECTION B: Study Duration

B1. What is the expected start date? *Data collection, screening, recruitment, enrollment, or consenting activities may not begin until IRB approval has been granted. Format: 07/05/2011*

03/07/2016

B2. What is the expected end date? *Expected end date should take into account data analysis, queries, and paper write-up. Format: 07/05/2014*

03/07/2019

SECTION C: Summary

C1. Write a brief descriptive summary of this study in Layman Terms (non-technical language):

Concussions have become a growing concern in our society with constant reminders as to the seriousness of this injury. When a concussion warrants medical attention, usually some type of test is given before a person can be medically cleared to return to activities such as work or sports. These tests fall into two separate categories. The first category contains cognitive, or thinking, tests. The second category contains motor, or movement, tests. The results from these tests help a medical provider determine if the individual is recovered and can be medically cleared to return to activities such as work or sports. What is important with these two types of tests is that they are usually done separately. However, this is not a realistic picture of what our daily lives entail. Instead, we tend to move and think at the same time.

In this study, participants will perform a task while sitting at a computer screen. A magnetic sensor will be placed on the participants' dominant index fingertip to record reaching movement patterns. A grid of white squares laid out like a tic-tac-toe board will be displayed on the screen. Participants will be to reach to squares on the screen based on visual cues. Practice trials will be allowed.

C2. Describe the purpose/objective and the significance of the research:

The purpose of this study is to examine the long term effects of concussions on a person when asked to do a combined thinking and moving task. The findings from this study may help us better understand the interaction between cognitive (thinking) and motor (moving) behaviors in people with a history of concussions. This study may ultimately allow researchers and medical providers to better understand this interaction and aid with making decisions regarding medical assessments.

C3. Cite any relevant literature pertaining to the proposed research:

Bleiberg, J., et al. 2004. Duration of cognitive impairment after sports concussion. *Neurosurgery, 54*(5), 1073-1078.

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Marar, M., et al. 2012. Epidemiology of concussions among United States high school athletes in 20 sports. *Am J Sports Med, 40*(4), 747-755.

Parker, T.M., et al. 2007. Recovery of cognitive and dynamic motor function following concussion. *Br J Sports Med, 41*, 868-873.

Smith, A. et. al. 1999. Effects of a low dose of caffeine given in different drinks on mood and performance. *Hum Psychopharmaol Clon Exp, 14,* 473-482.

SECTION D: Subject Population

Section Notes…

- D1. If this study involves analysis of de-identified data only (i.e., no human subject interaction), IRB submission/review may not be necessary. Visit the Pre-Submission section in the IRB website for more information.

D1. Identify any population(s) that you will be __specifically targeting__ for the study. Check all that apply: (Place an "X" in the column next to the name of the special population.)

	Not Applicable (e.g., de-identified datasets)		Institutionalized/ Nursing home residents recruited in the nursing home
	UWM Students of PI or study staff		Diagnosable Psychological Disorder/Psychiatrically impaired
	Non-UWM students to be recruited in their educational setting, i.e. in class or at school		Decisionally/Cognitively Impaired
	UWM Staff or Faculty		Economically/Educationally Disadvantaged
	Pregnant Women/Neonates		Prisoners

	Minors under 18 and ARE NOT wards of the State		Non-English Speaking
	Minors under 18 and ARE wards of the State		Terminally ill
X	Other (Please identify): Females with a history of concussion		

D2. Describe the subject group and enter the total number to be enrolled for each group. For example: teachers-50, students-200, parents-25, parent's children-25, student control-30, student experimental-30, medical charts-500, dataset of 1500, etc. Enter the total number of subjects below.

Describe subject group:	**Number:**
Healthy female young adults without a history of concussion	30
Healthy female young adults with one or two reported concussion	30
Healthy female young adults with three or more reported concussions	30
TOTAL # OF SUBJECTS:	90
TOTAL # OF SUBJECTS (If UWM is a collaborating site):	N/A

D3. List any major inclusion and exclusion criteria (e.g., age, gender, health status/condition, ethnicity, location, English speaking, etc.) and state the justification for the inclusion and exclusion:

Inclusion criteria include healthy young female adults between the ages of 18-29, with either no history of concussion or have reported a concussion.

Exclusion criteria include an inability to sit comfortably for up to an hour and a half; not having normal or corrected-to-normal vision; self-reported neurological deficits other than a diagnosed concussion or mood disorder; a diagnosed learning disorder, ADD/ADHD or dyslexia; and an arm or spinal cord injury in the last 6 months. Males were excluded for two reasons. First, a difference exists between sexes when using neurocognitive tests to evaluate individuals with a history of concussions. Second, females whom have sustained a concussion represent an understudied population in the empirical literature. The rest of the exclusion criteria are needed because the tasks require the participant to make reaching motions with his arm, sit for up to an hour and a half, and perform cognitive tasks designed for normal vision.

SECTION E: Informed Consent

Section Notes…

- E1. Make sure to attach any recruitment materials for IRB approval.
- E3. The privacy of the participants must be maintained throughout the consent process.

E1. Describe how the subjects will be recruited. (E.g., through flyers, beginning announcement for X class, referrals, random telephone sampling, etc.). If this study involves secondary analysis of data/charts/specimens only, provide information on the source of the data, whether the data is publicly available and whether the data contains direct or indirect identifiers.

Recruitment will occur via two primary mechanisms. First, recruitment flyers will be placed across campus to solicit volunteers. Second, announcements will be made in various UWM Kinesiology classes. For both recruitment mechanisms, Individuals that are interested in participating in the study will email the primary investigator. The investigator will send the potential participant a prescreening form. This form will assess whether the individual fits with inclusion and exclusion criteria. If so, the individual will be prompted to inform the investigator to schedule an appointment.

E2. Describe the forms that will be used for each subject group (e.g., short version, combined parent/child consent form, child assent form, verbal script, information sheet): If data from failed eligibility screenings will be used as part of your "research data", then these individuals **are** considered research subjects and consent will need to be obtained. Copies of all forms should be attached for approval. If requesting to waive documentation (not collecting subject's signature) or to waive consent all together, state so and complete the "Waiver to Obtain-Document-Alter Consent" and attach:

Pre-screening forms will be used to determine whether or not participants meet inclusion and exclusion criteria. Failed eligibility screenings will not be included in research data. Written Informed Consent will be used to obtain consent. The Edinburgh Handedness inventory will be used to assess hand dominance. Scores on this inventory will determine the hand on which the sensors will be placed. A Participant Lifestyle Questionnaire will be used to assess lifestyles that might affect how the participants perform on this task. These include sleep patterns, nicotine use, caffeine use and mood disorder drugs which all have been supported in the literature to alter cognitive function or reaction times. A Concussion History and Symptom Survey will be administered to obtain participants previous history of concussions as well as symptoms from other head injuries not diagnosed as a concussion. A brief Vision Test will be done using a hand held Snellen chart to ensure participants can see the experiment. A Sport Participation Questionnaire will be used to assess the frequency, type, and competitive level of any sports played by the participants. Data collection sheets will be used to record trials and general notes.

E3. Describe who will obtain consent and where and when consent will be obtained. When appropriate (for higher risk and complex study activities), a process should be mentioned to assure that participants understand the information. For example, in addition to the signed consent form, describing the study procedures verbally or visually**:**

Primary investigators will obtain consent in the Visuomotor lab (Pavilion room 359) on the day of the participant's data collection.

SECTION F: Data Collection and Design
Section Notes… • F1. Reminder, all data collection instruments should be attached for IRB review. • F1. The IRB welcomes the use of flowcharts and tables in the consent form for complex/ multiple study activities.

F1. In the table below, chronologically describe all study activities where human subjects are involved.

- In **column A**, give the activity a short name. E.g., Obtaining Dataset, Records Review, Recruiting, Consenting, Screening, Interview, Online Survey, Lab Visit 1, 4 Week Follow-Up, Debriefing, etc.
- In **column B**, describe in greater detail the activities (surveys, audiotaped interviews, tasks, etc.) research participants will be engaged in. Address where, how long, and when each activity takes place.
- In **column C,** describe any possible risks (e.g., physical, psychological, social, economic, legal, etc.) the subject may ***reasonably*** encounter. Describe the **safeguards** that will be put into place to minimize possible risks (e.g., interviews are in a private location, data is anonymous, assigning pseudonyms, where data is stored, coded data, etc.) and what happens if the participant gets hurt or upset (e.g., referred to Norris Health Center, PI will stop the interview and assess, given referral, etc.).

A. Activity Name:	**B. Activity Description:**	**C. Activity Risks and Safeguards:**
Recruitment	Potential participants will contact the primary investigator via email to obtain a prescreening form.	Identity of potential participant will not be revealed and no personal information will be collected.

Prescreening	Potential participants will complete a prescreening form. The prescreening form will indirectly ask participants about general health status, history of concussions and vision. This interaction will occur via email.	Prescreening form is phrased to prevent any collection of personal information.
Informed Consent	Potential participants will be allowed to read the informed consent. The researcher will read the informed consent to the potential participant. Potential participants will be able to ask any questions about the study and asked to sign the consent form once fully informed about the study. The activity will take place in the Visuomotor Lab (PAV 359) and will take 15 minutes.	No risk associated with this activity.
Concussion Survey	Participants will complete a Concussion History and Symptom Survey regarding their previous concussion history and various symptoms caused by head injuries. The activity will take place in the Visuomotor Lab (PAV 359) and will take 10 minutes.	Participants may be exposed to minimal psychological and social risk. This risk may include perceptions from others regarding the participant's history of concussions. Participants will be assured that their answers are kept confidential and their privacy is maintained.
Vision Screen	Participants will complete a vision screen using a hand held eye chart to assess near visual acuity and verify if any corrective eyewear is worn. The activity will take place in the Visuomotor Lab (PAV 359) and will take 5 minutes.	No risk associated with this activity
Sports Participation Questionnaire	Participants will complete a Sports Participation Questionnaire to assess the type, frequency and competitive level of any sport over the past year the participant has played. The activity will take place in the Visuomotor Lab (PAV 359) and will take 5 minutes.	No risk associated with this activity

Handedness Survey	Participants will complete an Edinburgh Handedness Inventory to determine their dominant hand. The activity will take place in the Visuomotor Lab (PAV 359) and will take 5 minutes.	No risk associated with this activity
Arm Length Measurement	Participants will have to length of their dominant arm measured (from shoulder to tip of index finger). This is done to ensure the participants are close enough to the projector screen as to not overextend their reach. The activity will take place in the Visuomotor Lab (PAV 359) and will take 5 minutes.	No risk associated with this activity
Participant Lifestyle Questionnaire	Participants will complete a lifestyle questionnaire to assess their intake of mood disorder drugs, caffeine, and nicotine as well as sleep patterns. The activity will take place in the Visuomotor Lab (PAV 359) and will take 5 minutes.	Participants may be exposed to minimal psychological and social risk. This risk may include perceptions from others regarding the participant's lifestyle. Participants will be assured that their answers are kept confidential and their privacy is maintained.
Data Collection	Participants will point at squares on a computer screen to calibrate the motion sensor attached to their index finger. Participants will then perform a reaching task while sitting at the computer screen. They will look at a grid of squares laid out like a tic-tac-toe board. Participants will be asked to reach to certain squares based on visual cues. Practice will be allowed. The activity will take place in the Visuomotor Lab (PAV 359) and will take 10 minutes for calibration and 50 minutes for data collection.	Participants will be exposed to eye strain from looking at the monitor for prolonged periods of time. This risk will be no greater than reading on the internet for one to one and a half hours. Rest breaks will be given to minimize this risk. Muscle fatigue from sitting for up to one and a half hours. This risk is minimal and no greater than sitting in a car for up to one and a half hours.

		Muscle fatigue of the forearm from reaching. The risk of forearm fatigue is very minimal and regular breaks will be provided. The motion capture system used to measure reaching movements creates a magnetic field. The magnetic field is very small and does not pose a risk to participants.

F2. Explain how the privacy and confidentiality of the participants' data will be maintained after study closure:

Data collected will be kept confidential at all times. Each participant will be assigned an experiment code and that code will be used to identify all data collected from that day. All papers will be kept in a locked file cabinet in the PI’s office (Wendy Huddleston, Pavillion room 361). All data collected will be stored electronically, on a passward protected computer, for future use without any identifying information tied to it in that form. Any scientific data resulting from this study may be presented at scientific meetings or published, but no data or information will ever be presented that is identifiable to specific participants. Data will be stored indefinitely after the completion of the study. The participant has the right to withdraw from the study at any time without consequence.

F3. Explain how the data will be analyzed or studied (i.e. quantitatively or qualitatively) and how the data will be reported (i.e. aggregated, anonymously, pseudonyms for participants, etc.):

Data will be recorded and analyzed quantitatively using Labview software. Data will be reported anonymously with assigned numerical codes and in aggregate form.

SECTION G: Benefits and Risk/Benefit Analysis

Section Notes…

- Do not include Incentives/ Compensations in this section.

G1. Describe any benefits to the individual participants. If there are no anticipated benefits to the subject directly, state so. Describe potential benefits to society (i.e., further knowledge to the area of study) or a specific group of individuals (i.e., teachers, foster children). Describe the ratio of risks to benefits.

There are no direct benefits for the participants individually or as a group. The results of this study, however, will enhance our general knowledge of how a history of concussions affects visuomotor behavior and may potentially lead to new tests for return-to-activity assessments.

G2. Risks to research participants should be justified by the anticipated benefits to the participants or society. Provide your assessment of how the anticipated risks to participants and steps taken to minimize these risks, balance against anticipated benefits to the individual or to society.

The potential broader benefits of this study greatly outweigh the minimal risks of the experiments in this protocol.

SECTION H: Subject Incentives/ Compensations

Section Notes…

- H2 & H3. The IRB recognizes the potential for undue influence and coercion when extra credit is offered. The UWM IRB, as also recommended by OHRP and APA Code of Ethics, agrees when extra credit is offered or required, prospective subjects should be given the choice of an equitable alternative. In instances where the researcher does not know whether extra credit will be accepted and its worth, such information should be conveyed to the subject in the recruitment materials and the consent form. For example, "The awarding of extra credit and its amount is dependent upon your instructor. Please contact your instructor before participating if you have any questions. If extra credit is awarded and you choose to not participate, the instructor will offer an equitable alternative."

- H4. If you intend to submit to the Travel Management Office for reimbursement purposes make sure you understand what each level of payment confidentiality means **(click here for additional information).**

H1. Does this study involve incentives or compensation to the subjects? For example cash, class extra credit, gift cards, or items.

[_X_] **Yes**

[__] **No [SKIP THIS SECTION]**

H2. Explain what (a) the item is, (b) the amount or approximate value of the item, and (c) when it will be given. For extra credit, state the number of credit hours and/or points. (e.g., $5 after completing each survey, subject will receive [item] even if they do not complete the procedure, extra credit will be award at the end of the semester)**:**

A $10 Amazon gift card will be awarded to each participant upon completion of the experiment.

H3. If extra credit is offered as compensation/incentive, an alternative activity (which can be another research study or class assignment) should be offered. The alternative activity (either class assignment or another research study) should be similar in the amount of time involved to complete and worth the same extra credit.

H4. If cash or gift cards, select the appropriate confidentiality level for payments (see section notes):

[_X_] **Level 1** indicates that confidentiality of the subjects is not a serious issue, e.g., providing a social security number or other identifying information for payment would not pose a serious risk to subjects.

- Choosing a Level 1 requires the researcher to maintain a record of the following: The payee's name, address, and social security number and the amount paid.
- When Level 1 is selected, a formal notice is not issued by the IRB and the Travel Management Office assumes Level 1.
- Level 1 payment information will be retained in the extramural account folder at UWM/Research Services and attached to the voucher in Accounts Payable. These are public documents, potentially open to public review.

[__] **Level 2** indicates that confidentiality is an issue, but is not paramount to the study, e.g., the participant will be involved in a study researching sensitive, yet not illegal issues.

- Choosing a Level 2 requires the researcher to maintain a record of the following: A list of names, social security numbers, home addresses and amounts paid.
- When Level 2 is selected, a formal notice will be issued by the IRB.
- Level 2 payment information, including the names, are attached to the PIR and become part of the voucher in Accounts Payable. The records retained by Accounts Payable are not considered public record.

[__] **Level 3** indicates that confidentiality of the subjects must be guaranteed. In this category, identifying information such as a social security number would put a subject at increased risk.

- Choosing a Level 3 requires the researcher to maintain a record of the following: research subject's name and corresponding coded identification. This will be the only record of payee names, and it will stay in the control of the PI.
- Payments are made to the research subjects by either personal check or cash.
- Gift cards are considered cash.
- If a cash payment is made, the PI must obtain signed receipts.

SECTION I: Deception/ Incomplete Disclosure (INSERT “NA” IF NOT APPLICABLE)
Section Notes…

- If you cannot adequately state the true purpose of the study to the subject in the informed consent, deception/ incomplete disclosure is involved.

I1. Describe (a) what information will be withheld from the subject (b) why such deception/ incomplete disclosure is necessary, and (c) when the subjects will be debriefed about the deception/ incomplete disclosure.

N/A

IMPORTANT – Make sure all sections are complete and attach this document to your IRBManager web submission in the Attachment Page (Y1).

Appendix C: Informed Consent

UNIVERSITY OF WISCONSIN – MILWAUKEE

CONSENT TO PARTICIPATE IN RESEARCH

1. GENERAL INFORMATION

Study title: Measuring the Long-Term Effects of Concussions on Reaching Among Distractors

Person in Charge of Study: **Wendy Huddleston, PhD,** Associate Professor

Department of Kinesiology: Integrative Health Care & Performance

University of Wisconsin – Milwaukee

2. STUDY DESCRIPTION

Study description: Concussions have become a growing concern in our society. Medical practitioners test the injured person's ability to think and move but seldom are people asked to think and move at the same time. It is important to test these two activities together as it better assesses what we do every day. For example, a football player has to remember a specific play, focus on the snap count, listen for any changes to the original play, shift their position and still execute the play successfully.

We are interested in what happens when we ask people with a history of concussions to do a combined thinking and moving task. The findings from this study may help us better understand the interaction between cognitive (thinking) and motor (moving) behaviors in people with a history of concussions. Your contribution to this study, along with the contributions of other participants, may ultimately allow researchers and medical providers to better understand this interaction. This experiment will be done in a laboratory located in the Pavilion (PAV359) on the University of Wisconsin – Milwaukee campus and will take approximately one to one and a half hours to complete.

Overall, up to 90 female participants between the ages of 18 – 29 will complete the experiments described below. We are asking you to participate in this research study, but please understand that your participation is completely voluntary. You do not have to participate if you do not want to, and you also may withdraw at any time without any consequence to you.

3. STUDY PROCEDURES

What will I be asked to do if I participate in the study?

At any time, please feel free to ask any questions you might have about this experiment.

If you agree to participate you will be asked to:

1. Take a brief vision test to ensure you can see the experiment. (5 minutes)
2. Answer a survey regarding your previous concussion history, which may be none, and various symptoms caused by head injuries. (10 minutes)
3. Answer a few brief questions regarding your handedness. (5 minutes)
4. Answer a few brief questions regarding your lifestyle that might affect how you perform on this task, for example sleep patterns or caffeine intake. (5 minutes)
5. Answer a few brief questions regarding your sports participation over the last year. (5 minutes)
6. Have the length of your arm measured (5 minutes)
7. Point at squares on a computer screen to calibrate the motion sensor attached to your index finger. (10 minutes)
8. Perform a reaching task while sitting at the computer screen. You will look at a grid of squares laid out like a tic-tac-toe board. You will be asked to reach to certain squares. You will be allowed to practice. (50 minutes)

4. RISKS & MINIMIZING RISKS

What risks will I face by participating in this study?

If you agree to participate in the study you will be exposed to the following risks:

1. Eye strain from looking at the monitor for prolonged periods of time. This risk will be no greater than reading on the internet for one to one and a half hours. You will be given rest breaks to minimize this risk.
2. Muscle fatigue from sitting for up to one and a half hours. This risk is minimal and no greater than sitting in a car for up to one and a half hours.
3. Muscle fatigue of the forearm from reaching. The risk of forearm fatigue is very minimal and regular breaks will be provided.
4. The motion capture system used to measure reaching movements creates a magnetic field. The magnetic field is very small and does not pose a risk to participants.

Your data we collect will be kept confidential at all times. Each experiment will be assigned an experiment code and that code will be used to identify data collected from that day. These papers will be kept in a locked file cabinet in the PI's office (Wendy Huddleston, PAV 361). All data collected will be stored for future use. Any scientific data resulting from this study may be presented at scientific meetings or published so the results will be useful for others, but no data or information will ever be presented that is identifiable to you.

5. BENEFITS

Will I receive any benefit from my participation in this study?

There are no direct benefits to you.

Are subjects paid or given anything for being in the study?

You will be paid a $10 gift card upon completion of this study.

6. STUDY COSTS

Will I be charged anything for participating in this study?

You will not be responsible for any of the costs from taking part in this research study. Free street parking is available in the surrounding community. Ramp parking is available for a small hourly charge directly at the Pavilion. You will be responsible for ramp charges if you choose to park in the Pavilion ramp.

7. CONFIDENTIALITY

What happens to the information collected?

All information collected about you during the course of this study will be kept confidential to the extent permitted by law. We may decide to present what we find to others, or publish our results in scientific journals or at scientific conferences. Only the primary investigator (Wendy Huddleston) will have access to the information. However, the Institutional Review Board at UW-Milwaukee or appropriate federal agencies like the Office for Human Research Protections may review your records.

8. ALTERNATIVES

Are there alternatives to participating in the study?

There are no known alternatives available to you other than not taking part in this study.

9. VOLUNTARY PARTICIPATION & WITHDRAWAL

What happens if I decide not to be in this study?

Your participation in this study is entirely voluntary. You may choose not to take part in this study, or if you decide to take part, you can change your mind later and withdraw from the study. You are free to not answer any questions or withdraw at any time. Your decision will not change any present or future relationships with the University of Wisconsin Milwaukee. The investigator, Wendy Huddleston, may stop your participation in this study if she feels it is necessary to do so. If you withdraw or are withdrawn early we will use the information collected to that point.

10. QUESTIONS

Who do I contact for questions about this study?

For more information about the study or the study procedures or treatments, or to withdraw from the study, contact:

Wendy Huddleston, PhD
Department of Kinesiology: Integrative Health Care & Performance
University of Wisconsin - Milwaukee
P.O. Box 413
Milwaukee, WI 53201-0413
(414)229-3368
huddlest@uwm.edu

Who do I contact for questions about my rights or complaints towards my treatment as a research subject?

The Institutional Review Board may ask your name, but all complaints are kept in confidence.

Institutional Review Board
Human Research Protection Program
Department of University Safety and Assurances
University of Wisconsin – Milwaukee
P.O. Box 413
Milwaukee, WI 53201
(414) 229-3173

11. SIGNATURES

Research Subject's Consent to Participate in Research:

To voluntarily agree to take part in this study, you must sign on the line below. If you choose to take part in this study, you may withdraw at any time. You are not giving up any of your legal rights by signing this form. Your signature below indicates that you have read or had read to you this entire consent form, including the risks and benefits, and have had all of your questions answered, and that you are 18 years of age or older.

____

Printed Name of Subject/ Legally Authorized Representative

____ _______________________

Signature of Subject/Legally Authorized Representative Date

Principal Investigator (or Designee)

I have given this research subject information on the study that is accurate and sufficient for the subject to fully understand the nature, risks and benefits of the study.

____ _______________________

Printed Name of Person Obtaining Consent Role on Study

____ _______________________

Signature of Person Obtaining Consent

Appendix D: Vision Screening

Participant Vision Screening

Researcher will ask the participants the following questions…

1) Do you use corrective eyewear (either glasses or contact lenses)?

   Yes_______ No_______

2) If yes to question #1, are you currently wearing your corrective eyewear?

   Yes_______ No_______

Hand participant the vision test card.

Have her hold the test card 14 inches from her eyes. If the participant uses corrective eyewear, make sure she is wearing them for the test.

Check each eye separately, first the right and then the left. Keep both eyes open and cover one eye with the palm of the hand.

Read the card, beginning with the top line and moving down the lines until it is too difficult to read the letters.

Record the number of the smallest line (below) that the participant read correctly.

Repeat with the other eye

RIGHT EYE _______________

LEFT EYE ________________

Appendix E: Concussion History and Symptom Survey

SECTION #1: CONCUSSION HISTORY			
Cause of Concussion	Number of Diagnosed* Concussion	Number of Non-diagnosed* Concussion	Where did you receive the blow (front, back, side of head) and how did your head move (back and forth, side to side, rotated)?
SPORTS: Include all times you were playing any sport including formal (for example: organized teams) and informal (for example: pick-up games, recreational activities)			
Sport (please specify)			
Sport (please specify)			
Sport (please specify)			
Sport (please specify)			
Sport (please specify)			
NON-SPORTS			
Fall			
Blow to the Head			
Motor Vehicle Accident			
Other (please specify)			
Other (please specify)			
TOTAL			

How long has it been since your last symptoms?	N/A	Years		Months
If you were diagnosed with a concussion, were you cleared by a medical provider to return to normal activities?		Yes	No	If Yes, How Long Ago?

*Diagnosed means diagnosed by a medical provider (physician, nurse, athletic trainer, physical therapist, etc.

SECTION #2: CONCUSSION SYMPTOM HISTORY AND EVALUATION

Please circle your response to the following questions

SYMPTOM HISTORY							SYMPTOM EVALUATION						
***Did you ever have a head injury that caused*:**	***Total number of times***						***Score yourself based on how you feel now***						
							None	Mild		Moderate		Severe	
Headache	0	1	2	3	4	≥5	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Feeling line "in a fog"	0	1	2	3	4	≥5	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Trouble falling asleep	0	1	2	3	4	≥5	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	≥5	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	≥5	0	1	2	3	4	5	6

TOTALS TO BE COMPLETED BY RESEARCHER	
TOTAL NUMBER OF SYMPTOMS (MAX 22)	
SYMPTOM SEVERITY SCORE (MAX 132)	

Appendix F: Participant Lifestyle Questionnaire

Participant Lifestyle Questionnaire

Nicotine Use

1. Are you a smoker (nicotine products)?
    a. Yes_____ No______ Choose not to answer______
2. If yes, approximately how many times a day do you smoke?
    a. _________ Times a day
3. If yes, when was the last time you smoked?
    a. _________________

Caffeine Use

1. Do you drink caffeinated beverages such as coffee, tea, soda?
    a. Yes_____ No______ Choose not to answer______
2. If yes, approximately how many ounces of caffeinated beverages to you drink daily and what beverages?
    a. ____________type of beverage ______________ ounces per day
    b. ____________type of beverage ______________ ounces per day
    c. ____________type of beverage ______________ ounces per day
    d. ____________type of beverage ______________ ounces per day
    e. ____________type of beverage ______________ ounces per day
3. If yes, when was the last time you had a caffeinated beverage?
    a. _________________

Sleep Patterns

1. Over the last 2 weeks, how many hours of sleep did you average per night?
    a. _______________ hours/night
2. How many hours of sleep did you get last night?
    a. ________________ hours

(Please turn over)

Prescription Medications

1. Are you currently taking any prescribed medication for a mood disorder (For example, depression, bipolar disorder, anxiety, ADHD)?
    a. Yes_____ No______ Choose not to answer______
2. If yes, what is the name and dosage of the medication?
    a. Name____________________________ Dosage___________________________
    b. Name____________________________ Dosage___________________________
    c. Name____________________________ Dosage___________________________
    d. Name____________________________ Dosage___________________________
    e. Name____________________________ Dosage___________________________
3. If yes, approximately how long have you been prescribed the medication?
    a. Name____________________________ Time___________________________
    b. Name____________________________ Time___________________________
    c. Name____________________________ Time ___________________________
    d. Name____________________________ Time ___________________________
    e. Name____________________________ Time ___________________________
4. If yes, did you take your medication as prescribed today?
    a. Name_____________________________
        i. Yes_____ No______ Choose not to answer______
    b. Name_____________________________
        i. Yes_____ No______ Choose not to answer______
    c. Name_____________________________
        i. Yes_____ No______ Choose not to answer______
    d. Name_____________________________
        i. Yes_____ No______ Choose not to answer______
    e. Name_____________________________
        i. Yes_____ No______ Choose not to answer______

Appendix G: Sports Participation Questionnaire

Sports Participation Questionnaire

3) What type(s) of activities (or sports) have you regularly participated in during the last year?

4) How many weeks/year?

5) How many hours/week?

(Please turn over)

Tegner Activity Level Scale

Please indicate the HIGHEST level of activity that you participated in on a regular in the past year.

Level 10	Competitive sports: soccer, football, rugby (national elite)
Level 9	Competitive sports: soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball
Level 8	Competitive sports: racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing
Level 7	Competitive sports: tennis, running, motorcars speedway, handball Recreational sports: soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running
Level 6	Recreational sports: tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week
Level 5	Competitive sports: cycling, cross-country skiing Recreational sports: jogging on uneven ground at least twice weekly
Level 4	Work: moderately heavy labor (e.g. truck driving, etc.)
Level 3	Work: light labor (nursing, etc.)
Level 2	Work: light labor Walking on uneven ground possible, but impossible to back pack or hike
Level 1	Work: sedentary (secretarial, etc.)
Level 0	Sick leave or disability

Tegner, Y. & Lysolm, J. Rating Systems in the Evaluation of Knee Ligament Injuries. Clinical Orthopedics and Related Research. Vol. 198: 43-49, 1985.

Appendix H: Edinburgh Handedness Inventory

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

Appendix I: Descriptive Statistics of repeated measures ANOVAs

		Trial Type: SIMPLE			Trial Type: SPRE		
Measure	**Group**	**BASELINE**	**CHOICE**	**MOTOR**	**BAELINE**	**CHOICE**	**MOTOR**
SELECTION	CONTROL	99.84 ± 0.72	100.00 ± 0.00	98.23 ± 3.05	98.72 ± 2.41	97.42 ± 3.80	95.08 ± 4.91
ACCY (%)	CONC	100.00 ± 0.00	100.00 ± 0.00	97.33 ± 3.10	99.06 ± 1.79	97.80 ± 2.72	91.98 ± 7.02
RT (ms)	CONTROL	470.1 ± 56.11	552.5 ± 66.26	579.9 ± 92.02	496.9 ± 82.44	651.5 ± 122.73	729.4 ± 175.86
	CONC	454.6 ± 62.95	545.7 ± 93.43	555.3 ± 87.66	487.9 ± 86.59	615.3 ± 160.36	689.5 ± 119.46
RT VAR (ms)	CONTROL	69.0 ± 30.27	88.6 ± 18.94	120.2 ± 44.53	87.2 ± 39.94	124.5 ± 36.18	147.0 ± 59.21
	CONC	61.4 ± 48.63	92.6 ± 32.36	128.3 ± 62.31	88.1 ± 40.05	129.3 ± 51.33	141.7 ± 40.92
MT (ms)	CONTROL	781.2 ± 129.29	844.3 ± 120.35	849.7 ± 124.69	826.2 ± 155.81	993.5 ± 192.64	1082.0 ± 208.83
	CONC	774.1 ± 137.48	843.4 ± 150.12	814.1 ± 107.58	821.4 ± 173.42	967.4 ± 220.74	1024.0 ± 165.01
MT	CONTROL	89.5 ± 27.43	103.7 ± 20.67	135.6 ± 47.46	109.6 ± 44.55	164.4 ± 51.89	202.3 ± 46.10
VAR (ms)	CONC	92.1 ± 57.88	106.5 ± 33.13	150.0 ± 71.93	121.0 ± 53.77	176.8 ± 54.19	196.5 ± 58.66
PATH (%)	CONTROL	1.19 ± 0.05	1.20 ± 0.06	1.24 ± 0.09	1.19 ± 0.04	1.28 ± 0.09	1.39 ± 0.18
	CONC	1.19 ± 0.05	1.19 ± 0.08	1.27 ± 0.13	1.18 ± 0.03	1.27 ± 0.11	1.36 ± 0.15
PATH	CONTROL	0.09 ± 0.04	0.14 ± 0.11	0.18 ± 0.11	0.11 ± 0.06	0.26 ± 0.13	0.38 ± 0.18
VAR (%)	CONC	0.10 ± 0.05	0.12 ± 0.10	0.24 ± 0.23	0.09 ± 0.04	0.29 ± 0.25	0.33 ± 0.16
HORZ	CONTROL	5.81 ± 2.32	6.68 ± 3.55	7.27 ± 2.57	5.80 ± 2.27	7.40 ± 3.46	8.58 ± 2.63
ACCY (mm)	CONC	5.72 ± 2.17	6.71 ± 3.23	7.28 ± 3.04	5.51 ± 2.30	7.04 ± 2.49	8.04 ± 3.34
HORZ	CONTROL	4.72 ± 1.97	5.17 ± 2.18	5.77 ± 1.98	4.82 ± 2.31	6.11 ± 2.62	7.23 ± 2.38
VAR (mm)	CONC	4.53 ± 1.63	5.21 ± 2.68	6.22 ± 3.12	4.62 ± 2.31	6.39 ± 2.81	6.78 ± 3.14
VERT	CONTROL	8.74 ± 0.84	9.04 ± 0.99	9.85 ± 3.85	8.59 ± 3.59	9.35 ± 4.81	10.04 ± 0.84
ACCY (mm)	CONC	7.60 ± 2.77	8.75 ± 3.65	9.70 ± 4.89	7.32 ± 2.38	9.05 ± 2.89	9.95 ± 3.54
VERT	CONTROL	7.17 ± 2.56	7.77 ± 3.51	8.02 ± 3.06	6.79 ± 2.79	7.68 ± 3.06	7.82 ± 2.69
VAR (mm)	CONC	6.24 ± 3.27	7.51 ± 3.36	7.97 ± 3.44	6.38 ± 2.74	8.46 ± 3.25	8.04 ± 3.21

All values are Mean ± S.D. Abbreviations: RT: Reaction Time; ms: millisecond; RT VAR: Reaction Time Variability; MT: Movement Time; MT VAR: Movement Time Variability; PATH: Path Length; %: Percentage; PATH VAR: Path Length Variability; HORZ ACCY: Horizontal End-Point Accuracy; mm: millimeter; HORZ VAR: Horizontal End-Point Variability; VERT ACCY: Vertical End-Point Accuracy; VERT VAR: Vertical End-Point Variability; SELECTION ACCY: Selection Accuracy; NOCONC: No Concussion; CONC: Concussion