Action Boundary Perception Accuracy Deficits in Recently Concussed Young Athletes

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Following sport-related concussion (SRC), athletes have 2 times increased risk for lower extremity musculoskeletal injury. Perceptual-motor control may be a contributory factor, as motor control deficits have repeatedly been demonstrated in athletes with recent SRC even after clearance for return-to-play. Specifically, deficits in accuracy and actualization of action boundary perception (ABP), or the ability to perceive the limits of available actions to a given athlete, have been demonstrated in collegiate athletes who reported an SRC an average of 264 days prior to testing. The purpose of the present study was to evaluate changes in ABP behavior in more acutely concussed young athletes (Concussed), as well as to further characterize contributing factors to the Perception Action Coupling Task (PACT), a novel test of ABP behavior. Recently concussed (≤21 days prior) 12-18 year old athletes (n=48) and healthy controls (n-24) were recruited to participate in a cross-sectional testing protocol, consisting of the PACT, Immediate Post-concussion Assessment and Cognitive Testing (ImPACT), Vestibular-Ocular Motor Screen (VOMS), Balloon Analog Risk Task (BART), and surveys to measure mental effort for each of the above tests, as well as symptoms of depression, anxiety, impulsivity, and perceived physical development. Concussed was presented the option to return for follow-up testing of all measures after clearance for return-to-play. Concussed demonstrated deficits in ABP accuracy (~5%). Concussed reported significantly higher impulsivity (~9%). At follow-up, Concussed had significantly improved PACT accuracy and response time. Post-hoc analyses revealed an association between higher mental effort for BART and higher anxiety with increased PACT movement time. Conversely, higher impulsivity reduced movement time.

Higher effort for VOMS reduced initiation time, whereas higher effort for neurocognition reduced accuracy. This is the second study to demonstrate decreased ABP accuracy in concussed athletes, using the PACT. This study also demonstrated the multifactorial nature of ABP, as mental effort during BART, VOMS, and ImPACT, as well as feelings of anxiety and impulsivity, impacted several components of ABP behavior. ABP accuracy has a relationship with SRC, likely through the constellation of symptoms that result from SRC.

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Preface

In many ways, I feel these words will be the most important of the 25,000+ this document contains. I am overcome with a deep sense of humility and gratitude as I prepare to submit this document out to my committee for review. I have many people I wish to thank for helping guide me along this path, towards a career I am grateful to begin. Thank you to Mark Watts for first instilling in me an appreciation for the science that underlies physical training, and for showing me that passion is a job requirement. Thank you to Jack Hatem, for being a mentor and a voice of reason in an important period of a young man’s life. Thank you to Dr. Eric Winters and Dr. Brian Hortz, for guiding me back to a path I had briefly lost. Dr. Winters, I will never forget the compassion and empathy you showed me following my concussion. Dr. Hortz, I want you to know that I did not trip at the finish line.

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1.0 Introduction

Sport-related concussion (SRC) is a major public health problem, as up to 3.8 million occur annually in the United States alone.[78] In sport, a concussion occurs as a result of direct or indirect impact that causes a linear or rotational force being imparted to the skull or to the brain.[38] Concussion is a diffuse injury, with extremely high inter-individual variability, both in terms of presentation and recovery.[27] Clinical evidence suggests that the first week of concussion recovery produces a largely "global" response among individuals. The global response is characterized by a majority of individuals' experiencing cognitive/fatigue/migraine-type symptoms, with secondary issues possibly including emotional, physical, and sleep-related factors.[22] Conversely, >7 days post-injury specific clinical trajectories begin to predominate.[22] These individual responses to concussion can be categorized by "drivers", or a set of interrelated symptoms that characterize the individual's experience after the injury.

Collins et al.[22] offered a treatment model that describes 6 recovery trajectories: cognitive/fatigue, vestibular, ocular, post-traumatic migraine, cervical, and anxiety/mood. Table 1 elaborates on common presentation signs and symptoms observed based on the patient's individualized experience. Often, certain trajectories present with other components (i.e., "secondary drivers"), such as in the case of anxiety/mood patients, who often present with a vestibular component[22, 75]. Thus, the first week of concussion recovery represents a critical period in which clinicians should identify primary and secondary drivers of the injury's presentation and develop an individualized rehabilitation plan. The heterogenous nature of concussion necessitates a targeted treatment approach that addresses the specific needs of the athlete until evaluation for return to play (RTP).

Table 1 Concussion clinical trajectories, as offered by Collins and Kontos et al.

Trajectory	Common Presentation	Neurocognitive Deficits	VOMS Deficits
Vestibular	Dizziness, fogginess, nausea, anxiety, overstimulation in complex environments	Processing Speed Reaction Time	Horizontal/Vertical Gaze Stability Optokinetic Sensitivity
Oculomotor	Frontal headache, fatigue, distractibility, difficulty in visually based classes, pressure behind the eyes, difficulties with focus	Visual Memory Reaction Time	Near-point convergence Accommodation
Cognitive/ Fatigue	General fatigue, increased fatigue at end of day, non-specific headache, difficulty concentrating	Memory Processing Speed Reaction Time	WNL
Anxiety/ Mood	Overall increase in anxiety (increased rumination, hypervigilance, overwhelmed, sadness, hopelessness), sleep disturbances are possible	WNL	Mildly + or WNL
Post-Traumatic Migraine	Unilateral, moderate to severe intensity headache; pulsating quality; nausea and photosensitivity	Memory	WNL
Cervical Spine	Headache and neck pain	WNL	WNL

*WNL= within normal limits

1.1 When is it safe for a concussed athlete to return-to-play?

A seminal question of SRC research is determining when an athlete can safely RTP. The 5th International Conference on Concussion in Sport Consensus Statement advocates for a graduated, six-step return to sport protocol (Table 2).[94] General guidelines for the protocol state that each step should take a minimum of 24 hours, unless symptoms worsen during a given stage. If symptoms worsen, the athlete would be returned to the previous stage for at least another 24 hours. Additionally, if symptoms persist past 10-14 days for an adult, specialist referral is recommended for further evaluation.

Table 2 Graduated return-to-play strategy, as advised by current sport-related concussion consensus statement

Stage	**Activity**
1	No Activity
2	Light Aerobic Exercise
3	Sport-Specific Exercise
4	Non-Contact Training Drills
5	Full Contact Practice
6	Return to Play

Initially, 24-48 hours of “relative” physical and cognitive rest is recommended. Stage 1 involves reintroduction of activities based on normal work/school activities, which are guided by symptoms. That is, if symptoms are strongly provoked by these activities, the volume and intensity of these activities is reduced. Stage 2 calls for light aerobic exercise, by walking or stationary cycling, with the exclusive goal of increasing heart rate to monitor for symptom provocation. Stage 3 consists of sport-specific exercise, adding dynamic movements via running or moving drills. Stage 4 includes non-contact drills to activate coordination processes and increase cognitive load. Progressive resistance training can also be included at this stage. Stage 5 is a full-contact practice, followed by Stage 6 which is defined as return-to-play. While undoubtedly an improvement in the return-to-play process following concussion, there are still gaps in this process that are left unresolved.

This RTP process is still too reliant on subjective symptom reporting from the athlete, as this protocol is largely based on symptom provocation as a marker of recovery. An athlete’s motivation to participate could lead them to deny symptoms that are occurring in order to RTP sooner.[93] Increased awareness of concussion’s signs and symptoms, as well as the potentially serious consequences of the injury, is postulated to lessen the prevalence of this practice. However, there is still a need for an objective, clinic-friendly RTP evaluation that can provide useful information of an athlete’s true RTP-readiness. Computerized neurocognitive testing is useful in identifying acute disruptions of cognitive processes,[57, 87] but a growing body of evidence suggests neuromuscular deficits are evident past-symptom resolution and even RTP.

1.2 Neuromuscular Deficits in the Sub-Acute Phase of Concussion

Balance disruption is reported by nearly 40% of athletes in the first week following concussion.[76] Balance, in the context of concussion, has been traditionally measured through static clinical measures of the vestibulospinal system. One such measure is the Balance Error Scoring System (BESS) test, which is commonly utilized in clinics for ease and low cost of implementation.[27, 56, 92, 102] More sensitive, laboratory-based measures have documented significant changes from baseline Sensory Organization Test scores via the Neurocom Balance System in concussed football players.[54] Typically, however, BESS and Sensory Organization Test scores resolve within 3-5 days post-injury in athletes.[92] While a modified BESS test has been proposed, in some cases with the inclusion of more sensitive measures to detect subtle postural differences (i.e., inertial sensors), the test is still static.[11, 72] Because dynamic movement is a critical aspect of athletic performance, more specific evaluations that include the vestibular system are warranted .[56, 92]

1.2.1 Complex gait tasks

Deficits in balance and postural control following concussion are most robustly elicited by complex gait tasks, such as those involving planning, attention, and even those conducted simultaneously with another neurocognitive task.[12, 16-18, 53, 105-107] Impairments in complex gait tasks, which activate multiple areas of the cortex, have demonstrated impairments up to 30 days following concussion.[12, 53] When approaching obstacles in a navigation task, Baker et al.[2] reported increased variability around medial-lateral center of mass control in concussed subjects. Dual-task conditions reveal neuromuscular control deficits during gait, in the form of conservative adaptations and increased sway both acutely and beyond return to full activity following concussion.[16-18, 105-107] Concussion resulted in persistent (up to 30 days) planning and attention deficits in an ecologically valid, complex environment in a case study of an elite athlete.[39] These observed deficits, which more closely mimic the experience of athletic competition through simultaneous locomotion and cognitive load, further support the notion that concussed athletes may not be completely rehabilitated and/or ready to return to play.

1.2.2 Improving post-concussion neuromuscular evaluations

A recent scoping review focused on increased musculoskeletal injury risk following concussion called for more challenging neuromuscular tasks that better reflect athletic demands to address these issues.[63] The authors postulated that divided attention during activity with "increased cognitive load", such as athletic competition, could place the individual at increased risk of sustaining musculoskeletal injury following concussion.[63] This hypothesis is based on the consensus finding that, during dual-task concussion evaluations, greater deficits are observed as cognitive tasks increase in complexity.[63, 66] Attentional and motor impairments have both been demonstrated in concussed athletes, and it's possible that the recently concussed brain is unable to properly divide cognitive resources when confronted with various stimuli simultaneously.[16, 61, 63, 97, 105] However, the implication of this paradigm is that athletes are *indirectly* perceiving sensory information before consciously selecting an action. In other words, the athlete is receiving sensory information, interpreting the information and responding.

Viewing this issue from an ecological movement perspective yields a very different picture. From this perspective, humans perceive to move, but they also move to perceive.[50] That is, visually guided action is tightly coupled with perception, so much so that the two processes may not be fully distinct.[43] In this sense, athletes are capable of *directly* perceiving opportunities for action, or affordances, within their environment.[44, 51] Sensory information is not being received and processed before formulating a motor response. Rather, perceiving an affordance is directly perceiving an opportunity for action based on intuitive understanding of one's own abilities and prospective control guided by sensory input.[43] For example, a closing gap between two defenders may afford passing through for a smaller, more agile ball carrier in football or rugby while the identical gap may not be passable for a larger, less agile player (Figure 1).[44, 131] Further, after suffering a head injury, this intuitive understanding of one's abilities may be temporarily disrupted. When considered in this way, the underlying mechanism for increased musculoskeletal injury following concussion may not be overloaded attention but rather dysregulation in the perceptual processes that govern movement.

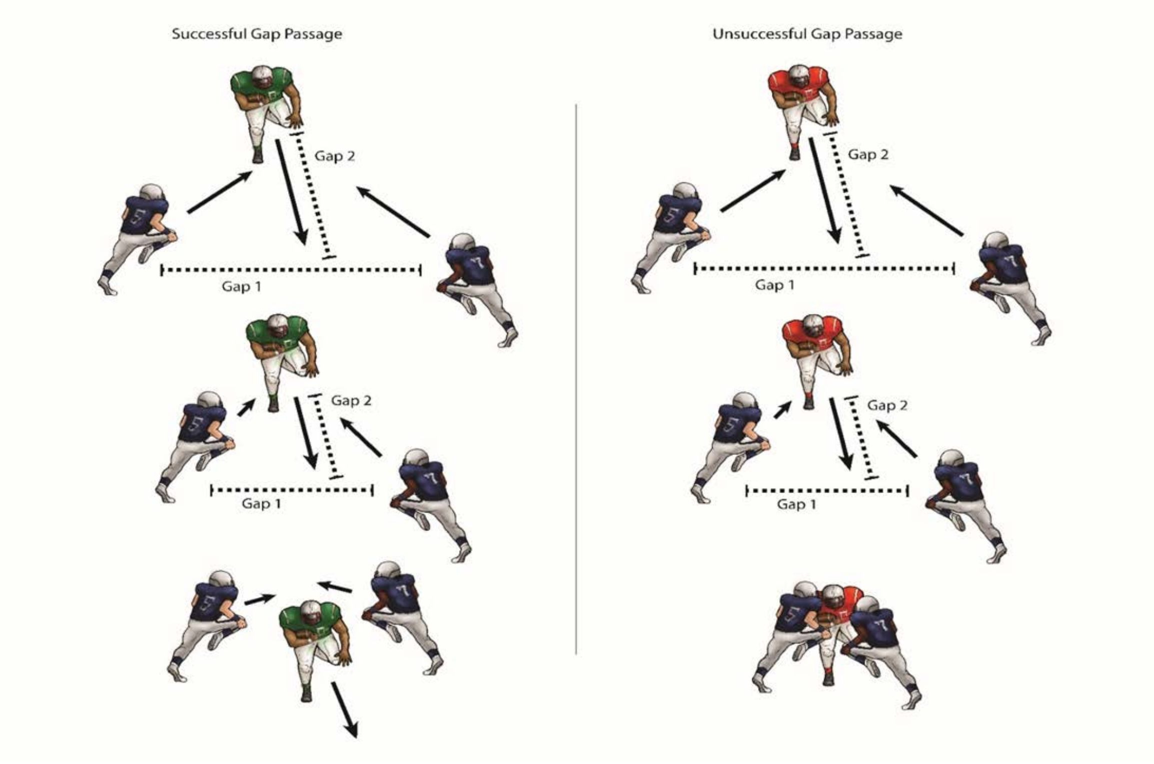


Figure 1 Simplified example of a successful vs. unsuccessful gap passage in American football. The runner's goal is to avoid being tackled, while the goal of the defenders is to tackle the runner. The runner must perceive the "passability" of the closing gaps in order to achieve the goal. Successful gap passage relates to proper perception of one's action capabilities as well as the spatiotemporal aspects of the closing gaps.

1.3 Considerations for Athletic Movement within Ecological Psychology

Athletic environments are highly dynamic and a vast array of sensory information is available at any given time.[44] People actively seek sensory information within their environment, which, in turn, prospectively guides future action.[50, 51] To explain how a person utilizes sensory information to guide action, James J. Gibson first offered the concept of affordances, or possibilities for action within a given environment.[51] Fajen's[44] elaboration on the term describes the relationship between agent and environment: "to perceive an affordance…is to perceive how one can act when confronted with a particular set of environment conditions." The critical premise of the theory is that affordances are *directly* perceivable; that is, the person is not merely a receptor of afferent information but actively seeks it.[51] For example, when observing a professional golfer prepare for a difficult putt, he or she does not stand idly behind the ball before executing the putt. Rather, the golfer moves around the ball and hole, changing his or her perspective by manipulating head and body position, in order to gather all possible visual information about the potential path the ball will take after it is struck. The golfer is actively obtaining afferent information to guide his or her impending movement.

1.3.1 Calibrating to One's Action Capabilities and Boundaries

The human body is a dynamic system, with many integrated parts, each capable of influencing the other.[34] As such, an athlete needs to possess an online understanding of one's abilities. For example, an individual's affordances are subject to limits; either external (i.e., environment based) or internal (e.g., maximum jump height). These limits are referred to as action boundaries. Conversely, an individual's action capabilities are a combination of that individual's geometric and kinetic characteristics that make a given action possible.[127] Action capabilities are constantly changing; as such, the individual needs to continually "re-learn", or ‘(re)-attune’ to their altered capabilities and boundaries. This is referred to as *perceptuomotor calibration*.[41] Changes to the system, or perturbations, need to be perceived and action recalibrated for successful movement in dynamic environments. Normal, healthy individuals can recalibrate to perturbations in dynamics of the system, such as altering vision when wearing prism glasses, even without knowledge of such changes.[40, 41, 45] Thus, as the dynamics of the environment around them change, actors are continuously recalibrating their capabilities and limits.

1.3.2 Internal Constraints and Their Effect on Calibration

Internal constraints should also be considered in the context of recalibrating to athletic competition, as many of these internal constraints have been shown to negatively affect the perception-action coupling process. Increased anxiety during action,[31] fatigue[115] and sleep disruption[32] have been experimentally demonstrated to alter a person’s perception of actions available to them. Experimentally-induced anxiety has been shown to cause subjects to underestimate their reaching ability to grasp an object.[31] In a wall-climbing experiment, higher perceived exertion was associated with a decreased perception of maximal reach, with no actual decrease in maximal reach capabilities.[115] Similarly, sleep deprivation impairs perceived action capabilities and increases reaction time, but does not change the actual action capabilities, themselves.[32] Neurodegeneration, whether by pathology or by normal aging, has also been shown to negatively affect the recalibration process.[24, 45, 133] Taken together, it is clear that acute and chronic system perturbations can negatively impact recalibration efficacy.

1.3.3 Perceptual Attunement to Action-Relevant Information

The coupling of perception and action occurs in the spatiotemporal domain.[81] That is, actualization of an affordance requires the integration of both spatial and temporal information. A baseball outfielder judging if a fly ball is "catchable", for example, must perceive where the ball will land (if he stands still and does not move) as well as judge if he can close the gap between his current location and the landing location before the ball hits the ground. Moreover, one must be able to perceive and synthesize action-relevant information about the environment. Examples of action-relevant information include the type of surface, the objects involved and the events taking place within the environment.[44] When an athlete successfully selects certain optical variables in order to optimize performance, that athlete is said to have achieved *perceptual attunement*.[44]

Consider the example of an American football defender attempting to tackle a ball-carrier in the open field. Successfully coupling action with "correct" perceptual information (e.g., action-relevant information that indicates the ball-carrier's true intent) will lead to successful movement. Previous work in similar sporting situations indicates that tuning into the center of mass (as opposed to deceptive information like shoulder/head movement) differentiates between expert and novice tacklers.[8] Conversely, tuning into "incorrect" information (i.e., deceptive movement) could lead to poor body positioning and enhance behavioral risk by "being in the wrong place at the wrong time". The calibration and attunement process is refined by practice and experience during deliberate, goal-directed movement.[41, 43]

1.4 Concussion as a Potential Mechanism for Acute Disruption of Perceptuomotor Control and Subsequent Increased Risk for Injury

A concussive incident may represent a perturbation to one's perceptual sense of the "current state of affairs". For example, concussion is commonly associated with anxiety, fatigue, and sleep disruption.[9, 21, 22] Furthermore, many patients who suffer a concussion report or demonstrate vision and vestibular dysfunction.[15, 75, 124] Because all of these constraints have been demonstrated to interfere with perception-action coupling, it is possible that a concussive incident could disrupt one's ability to recalibrate to perceptuomotor dynamics, compared to pre-injury, "normal" calibration and performance. Incomplete recalibration could eventually lead to improper positioning during play, possibly increasing risk of injury due to being in "the wrong place at the wrong time". In other words, a concussion could decouple perception and action, potentially increasing risk for sustaining another concussion and/or musculoskeletal injury. This may occur by misestimation of performance enhancing perceptual cues and/or a perceptual disconnect of one's action capabilities/boundaries.

Therefore, the purpose of the current study was to evaluate if an affordance-based measure could assist in evaluating the recovery of the neuromuscular system following concussion, by providing a clinical measure of perceptuomotor control. A novel tablet-based measure, called the Perception Action Coupling Task (PACT) was utilized in a recent study to evaluate a relationship between impaired affordance perception after return-to-play from SRC.[37] That study reported significant differences in affordance perception accuracy and actualization of affordances in collegiate athletes with SRC history (who were tested an average of 264 days since last concussion) compared to collegiate athletes with no SRC history.[37] More evidence was necessary, and closer to the date of injury, to evaluate the viability of PACT at detecting affordance perception deficits following SRC, as well as to evaluate which characteristics may be related to PACT performance. The specific aims of this study were to: 1. evaluate between-group differences of PACT outcome measures at the acute recovery time-point (1-21 days post-injury), 2. compare risk-taking and impulsivity between healthy controls and recently concussed 12-18 year old athletes, 3. evaluate association of PACT outcome variables with outcomes from risk-taking, impulsivity, vestibular-ocular symptom gain, concussion symptoms, and neurocognitive measures, and 4. evaluate recovery trajectory of PACT outcome variables and measures of risk-taking and impulsivity, vestibular-ocular symptom gain, concussion symptoms, and neurocognitive outcome variables in a sub-group of recently concussed 12-18 year old athletes.

2.0 Review of Relevant Literature

This chapter will further develop the rationale for the proposed study by summarizing and synthesizing the extant literature surrounding: concussion and subsequent musculoskeletal injury risk, observed neuromuscular deficits that persist past symptom resolution/return-to-play, provide an historical summary of ecological psychology research, and conclude with the implications of perceptuomotor calibration and perceptual attunement literature.

2.1 Concussion Increases Subsequent Risk of Musculoskeletal Injury in Athletes

A 2018 literature review on concussion and increased musculoskeletal injury risk concluded athletes with a recent concussion are at increased risk of sustaining a musculoskeletal injury in the following year.[63] This review was based on 10 studies published since 2009 that reported on the phenomenon in athletes of various sports and skill levels (i.e., college or professional).[10, 13, 29, 52, 59, 63, 86, 88, 101, 103, 114] A majority of these studies were prospective cohort studies, with one retrospective and one cross-sectional study included.[52, 114] Cohorts included were professional Australian football[88], mixed college athletes[10, 13, 52, 59, 86], professional rugby[29], professional soccer[101], retired professional American football[114], and professional ice hockey[103]. Several statistical approaches have been utilized to examine this phenomenon: odds ratio,[10, 13, 52, 59, 114] hazard ratio,[46, 101] injury rate ratio,[29, 86, 88] and chi-square.[103] Of these authors, odds of sustaining a subsequent musculoskeletal injury range from 1.59 to 3.39 for concussed athletes compared to non-concussed athletes over the following year. Cross et al.[29] and Lynall et al.[86] reported injury rate ratios of 1.6 for concussed athletes compared to non-concussed athletes, while Makdissi et al.[88] reported no statistical injury rate difference between groups. Nordstrom et al.[101] reported an increased hazard ratio of ~2.2 for concussed professional soccer players over a one-year follow-up. Fino et al.[46] also reported an increased hazard ratio of ~1.7 for a mixed college athlete cohort for sustaining a lower-extremity injury over a one-year follow-up. Nyberg et al.[103] reported no statistical difference in risk for injury, using chi-square values, of professional hockey players with a knee injury compared to concussed players over a 42-day follow-up period.

While 2 of these studies reported negative findings, Makdissi et al.[88] only evaluated injury rates in a single match after returning from concussion, while Nyberg et al.[103] utilized a follow-up period (42 days) that was less than half of the next shortest follow-up period (90 days). Direct comparison of results is difficult due to different cohorts, as well as data collection and statistical methods, but the body of available evidence suggests that athletes carry increased risk of sustaining an injury in the year following concussion. A viable mechanism for this increased risk has not yet been identified experimentally. However, neuromuscular control deficits may have the strongest case, as these deficits can exist longer than resolution of typical concussion deficits (e.g., balance and neurocognition).[63]

2.2 Neuromuscular Deficits in Sub-Acute Phase of Concussion

Balance impairments are one a common concussion symptoms, as balance disruption is reported by nearly 40% of athletes in the first week following concussion.[75] The Balance Error

Scoring System (BESS) test is a classic example of the types of measures utilized clinically to evaluate vestibulospinal function.[63] Typically, however, balance impairments measured in this way normalize within 3-5 days post-injury in athletes, and do not assess dynamic movement aspects associated with the vestibular system, which is a crucial component of athletic performance.[56, 92] Measures of postural control during complex motor tasks seem to reveal more persistent deficits, often with the deficits becoming more pronounced with increased task complexity.[63]

2.2.1 Complex Gait Tasks Reveal Postural Control Deficits Following Concussion

Parker et al.[105] first demonstrated postural control deficits in concussed athletes during locomotion 48 hours post-injury. Since that study, dual-task testing paradigms, or pairing locomotion with a simultaneous cognitive task like serial arithmetic, Stroop tests, or spatial memory tests, have consistently revealed postural control deficits compared to single-task tests and non-concussed controls. These studies typically measure postural control immediately following concussion, and then serially in follow-up timepoints that range from 48 hours post-injury to >6 years post-injury.[63] Examples of deficits that have been observed previously include slower gait velocity, conservative gait patterns, and poor center-of-mass control when paired with cognitive tasks.[16-18, 61, 63, 65, 91, 105-107] Critically, these deficits have been observed in athletic cohorts at one-month follow-up tests or even further in the recovery process timeline. Thus, these deficits are evident past the "normal" window of recovery in adults (10-14 days per the most recent consensus statement). Moreover, some authors have reported postural control deficits past symptom resolution and even RTP, indicating that the neuromuscular system may not be fully recovered from the injury.[61, 65]

Howell et al.[63] recently suggested that neuromuscular control deficits may be related to these differences observed during dual-task gait. Similarly, Kim et al.[71] applied the dual-task paradigm to evaluate knee motor control during cognitive load. During a rapid eccentric knee extension perturbation, subjects were unable to stiffen the knee joint appropriately when under cognitive load. Generalized neuromuscular deficits in concussed athletes have been reported previously, including decreased power generation at the hip and ankle[132], quadriceps weakness[36], and decreased maximal voluntary contraction[110, 119]. Dubose et al[35] reported increased hip stiffness and reduced knee and leg stiffness during a jump-landing task by concussed athletes when compared to baseline performance. These deficits were observed after clearance for RTP and, on average, 50 days post-concussion.[35] Neuromuscular decrements could manifest similarly when an athlete engages with their environment, as a preponderance of sensory information is received and used to guide future action.

2.3 A Historical Summary of Ecological Psychology

2.3.1 Affordances

In 1958, Gibson proposed that visually-guided movements can be prospectively controlled via online adjustments to achieve the desired end-state.[128] Gibson utilized this framework to explain routine tasks encountered in human locomotion: steering toward a goal, avoiding and/or slowing down to avoid an obstacle, and intercepting a moving target.[49] To achieve these goals, an internal model of the environment was not necessary. Rather, one could directly detect information from the environment that could be used to guide action.[49] In a later seminal paper, he would refer to this information as “affordances”, or opportunities for action within a given environment.[51] Subsequent research investigating affordances used models such as obstacle avoidance and intercepting a moving target, which presented a natural divergence into explaining sporting action and behavior.[41, 42, 44]

2.3.2 Action Capabilities and Action Boundaries

An action boundary refers to the limit of action opportunities. Defining action boundaries has dominated the research in ecological psychology since Gibson.[47] In a landmark study, Warren sought to determine the height at which a step-riser was no longer “step on-able”.[130] He found that the action was merely a function of leg-length and a critical boundary explained the subject limits. Subsequently, research evaluating “simple” tasks, such as determining the “reachability” of an external object or the “passability” of a horizontal opening, defined action boundaries for common human actions.[89, 96, 129] However, these movements are based largely on the individual’s geometric proportions.[47] For example, reachability can be defined by arm length and passability by shoulder width.[90, 129] While providing useful information, these studies do not provide the complete picture of one’s action capabilities in a dynamic environment.[47]

Indeed, action capabilities have been described as the relationship between an individual’s geometric dimensions and kinetic properties that make affordances realizable.[112, 127] Consider the example of a volleyball player who needs to judge if an opponent’s pending hit is “blockable”.

Pepping and Li[111] determined that a volleyballer's ability to perceive block height is dependent on the reach height of the player (i.e., geometric characteristics) as well as the maximum jumping height of the player (i.e., kinetic characteristics). Importantly, action capabilities and boundaries are never fixed.[41, 127] With the assumption that the athlete has matured physically (i.e., the geometric characteristics are stable), action capabilities can be thought of as a function of one's kinetic characteristics, which are constantly changing. Even highly skilled, Olympic-level athletes cannot produce identical motor patterns when repeatedly tested, especially in maximal effort tests.[4, 33, 60, 121] A host of internal and external factors could influence this daily variability, such as arousal level or the environment in which testing is occurring. While a large variance in performance would not necessarily be expected, the subtle difference in daily output may be significant during competition. In order to maintain successful performance in goal-directed action, one must continually "re-learn" their action capabilities and boundaries.[40, 41]

2.3.3 Calibration and Attunement

"Re-learning" one's action capabilities and boundaries is referred to as perceptuomotor calibration. When healthy subjects are subjected to a perceptual perturbation, they can recalibrate even without knowledge that the system has changed.[40, 41, 44] Another crucial component of perceptuomotor control is the concept of perceptual attunement. This concept refers to when the actor has successfully "tuned-in" to the most relevant variables that optimize performance. The calibration and attunement process is refined by practice and experience during deliberate, goal-directed movement.[41, 43] In the absence of perturbations that disturb the system, the healthy actor (with enough practice and experience) can quickly regain previous levels of performance.

Goal-directed movement typically requires a distance to be covered, or a "gap" that needs to be closed.[48] While athletic actions occur in the spatiotemporal domain, spatial and temporal aspects can be isolated to provide a deeper understanding of how motor control occurs in the natural environment. Spatial aspects of behavioral movement usually rely on target location. Closing spatial gaps is central to behavioral movement- that is, moving one's body from the current position to the target, "goal" position in a controlled manner.[82] Imagine an American football linebacker tracking a ball-carrier from his initial stance to the place where a tackle will be attempted. The defensive player will estimate the time-to-closure of the gap (i.e., between himself and the ball-carrier) at the current closure rate and adjust rate of closure as needed to achieve the goal (e.g., make the tackle in a desirable location).[82] The rate of closure variable ties the spatial and temporal aspects together in athletic tasks.

The variable tau (τ), an estimate of time taken to "close the gap", is the premier example of temporal aspects of motor control.[48, 80] Tau has consistently described sensorimotor control of behaviors that occur in finite temporal sequence.[80, 82] This has remained true across species, from understanding how humans prospectively control braking of motor vehicles to avoid collision to how bats use echolocation to navigate.[80, 83] The body of evidence, occurring over the course of 30+ years, led to the hypothesis that movements with both a "start" and an "end" can be governed by "tau-guide", a general function that explains temporal control of movement.[82] Tau-guide takes the form $\tau_g(t) = 0.5(t - T^2/t)$ where T is total movement duration and t is time elapsed since movement initiation.[48, 82] Thus, tau-guide provides an elegant solution for the complex issue of how an athlete engages with dynamic environments.

2.3.4 Dynamical Systems Approach

Dynamic systems, like the human body, are inherently complex and difficult to characterize. That is, dynamic systems are made up of interacting components capable of influencing other components.[34] Dynamic systems are characterized by fundamental attributes, such as many independent and variable degrees of freedom, numerous levels of the system, nonlinear behavior, both stable and unstable patterns of adaptation, and the ability of subsystem components to influence behavior of other subsystems.[34] Viewing the human body through this paradigm is useful because it highlights the integrated contributions of numerous sub-systems in supporting a function. As Clarke and Crossland[19] stated: “In a highly complex system like the human mind or human body all the parts affect each other in an intricate way, and studying them individually often disrupts their usual interactions so much that an isolated unit may behave quite differently from the way that it would behave in its normal context.”

Dynamical systems theory stems from Nikolai Bernstein’s “degrees of freedom” problem.[6] Bernstein understood that the seminal motor control problem is understanding how humans are able to master and manipulate numerous degrees of freedom to achieve an intended output.[33, 126] Indeed, if every joint in the human body was reduced to a simple hinge joint, like the elbow, the body would consist of ~100 mechanical degrees of freedom![126] Bernstein realized that there must be a method for reducing the number of independent degrees of freedom to a more controllable figure.[6] Evidence stemming from Bernstein’s theories confirm his hypotheses. Novice performers of a skilled task tend to fix available degrees of freedom into rigid patterns, whereas more skilled performers can freeze or unfreeze available degrees of freedom to achieve the desired motor output, under constraints of the specific task.[100]

2.3.5 The Role of Constraints in a Dynamical System

Newell introduced the concept of "constraints", or variables that influence human movement behavior by acting as boundaries which limit motion of system subcomponents.[99] Newell[99] offered three categories by which to organize constraints: organismic (i.e., a person's characteristics), environmental (i.e., physical variables in nature), and task (e.g., specific rules of the activity). Constraints can also interact, such that, with practice and experience, patterns of neuromuscular coordination emerge and become optimized.[34] Ecological psychology principles fit neatly into this paradigm; specifically, the concepts of calibration and attunement to guiding goal-directed action. Constraints limit available degrees of freedom, reducing the complexity of dynamic athletic movement. In a constrained task-space, athletes can calibrate action capabilities and boundaries, as well as frame the down selection of optical variables that optimize task performance.

As studies of dynamical systems have evolved, researchers are beginning to view the complexity of a dynamic system as potentially advantageous.[33, 79] While dynamic systems are comprised of several independent sub-components, spontaneous patterns can emerge where sub-components interact in a self-organizing manner.[33] In this way, self-organization emerges as the system is pressured to change by internal and external constraints.[33] Or, viewing dynamic systems from a "constraints-led" approach, internal and external constraints reduce the number of degrees of freedom configurations available to the system.[34] Viewed this way, the complexity of the human body becomes an asset to be exploited, rather than a hindrance. Stable outcomes can be achieved with many different motor strategies, which emerge under different task constraints.[33]

2.3.6 Changing Task Constraints Through System Perturbation

While inherent variability may be an advantage for dynamic systems to achieve desired outcomes, the complexity of such systems makes it difficult to characterize experimentally. Because dynamic systems tend to self-organize into stable patterns, especially in a learned task, authors have attempted to understand dynamic systems by perturbing the system and observing the consequences.[33] These "perturbations" can be viewed as organismic constraints through which altered motor patterns emerge. Typically, the perturbations studied have involved inducing fatigue, through sleep disruption or exercise, or inducing anxiety.[7, 30-32, 115, 116] Researchers have also evaluated the effects of aging and/or neurodegenerative disease on adaptability of motor output, as well.[24, 45]

Daviaux et al.[32] have investigated the effects of sleep deprivation on the perception and actualization of action boundaries. Subjects were deprived of sleep for 24 hours and compared to controls with no sleep deprivation. Both groups were asked to estimate the maximal height at which they could step over a horizontal bar before and after the intervention. Additionally, both groups were asked to reach an actual maximum "crossable" height, to which they were blinded of the result. The sleep deprivation group underestimated the maximal height that was crossable, with no change in actual performance compared to baseline measurements. The authors concluded that prolonged wakefulness altered the perception of action capabilities.

Physiological fatigue can also impair visual perception of action capabilities. Bhalla and Proffitt[7] demonstrated that the gradation of a hill was judged as steeper when the subjects had exhausted themselves on a run immediately prior. Additionally, previous studies on wall-climbers have demonstrated decreased perception of maximal reach when perceived exertion is reported as higher.[115] Importantly, these changes occurred without actual decreases in maximal reach capabilities. Thus, fatigue acts as an organismic constraint which limits action capabilities in these cases.

Mental effort during a task could be viewed as an organismic constraint, as well, as sense of effort and mental fatigue are closely related.[118] Mental effort has not yet been measured within the context of dynamic systems, but a small body of research suggests that it might constrain performance during neurocognitive tasks. Hsu et al.[67] reported impaired visual working memory in "at-risk" for Attention-Deficit Hyperactivity Disorder (ADHD) subjects who experienced higher mental effort during the task. Specific to concussion, it is well known that increased mental effort can lead to increased concussion-related symptoms, especially in the acute phase of recovery.[74] Functional connectivity differed between a concussed group and a healthy group during a Constant Effort task, where the participants were asked to hold a predetermined effort level during a lengthy fMRI scan.[118] As sense of fatigue increased during the task, mental effort increased proportionately, indicating a complex relationship between concussion and sense of effort that may be related to inefficient neural networks.[118]

Experimentally-induced anxiety is another example of an organismic constraint that negatively affects perception and actualization of action capabilities. Pijpers et al.[116] used indoor wall-climbing traverses at high and low heights to manipulate anxiety and examine the effect on perceiving and realizing affordances. In a series of experiments, the authors found that anxiety reduced perceived and actual maximal reaching height. Additionally, when traversing back and forth at higher heights, anxious subjects used more holds to cross, which was consistent with the minimized maximal reaching heights achieved in the prior experiment. Daviaux et al.[30] and Graydon et al.[55] also induced anxiety in subjects with the aim of investigating any subsequent changes in action capabilities. Anxiety was achieved by restricting breathing during a seated reach-and-grasp task. In both cases, subjects whose anxiety had increased underestimated their action capabilities. These experiments clearly demonstrate that psychological constraints can alter action capabilities by adopting a more conservative motor pattern.

Organismic constraints can evolve gradually, as well, such as in neurodegenerative disease or even normal aging. Neurological degradation, via aging or pathology, has been shown to influence perception of action capabilities by impairing recalibration ability. Fernandez-Ruiz et al.[45] investigated the effects of donning prism glasses, which alter the visual field by several degrees, on ball-throwing accuracy towards a target between younger (mean age 20 years) and older subjects (mean age 64 years). When altering vision by wearing prism glasses, aged subjects adapted to the perturbation at a slower rate than younger subjects.[45] Contreras-Vidal et al.[24] investigated differences between subjects with Parkinson's disease and age-matched controls in a visual pointing task where the screen cursor output was distorted. Subjects with Parkinson's disease exhibited slower and reduced adaptation to the distorted feedback compared to age-matched controls.[24] Therefore, when considering these studies together, organismic constraints can be transient (e.g., anxiety and fatigue) or progressive (e.g., aging or neuropathology) but these constraints restrict the possibilities for action by negatively effecting perception of action capabilities and/or perceptuomotor recalibration.

2.4 Considering Concussion in the Context of the Ecological Psychology Paradigm

A concussive injury represents a disruption of the neurological system. The effects of the injury can be transient or long-lasting, depending on context of the injury, such as pre-existing medical history and injury severity.[94] Of primary concern in treatment and rehabilitation of concussion are identification of alterations in the organismic constraints which develop following the perturbation. Experimental manipulation has shown that many factors associated with concussion, such as sleep disruption, fatigue, and anxiety, interfere with the perception of action capabilities and/or temporarily alter action capabilities.[30-32, 115, 116] Further, subjects with improperly functioning nervous systems recalibrate to visual perturbations slower than healthy individuals; vision dysfunction is common following concussion.[24, 75]

A substantial body of evidence indicates that deficits in neuromotor control are related to concussion and present past resolution of "typical" concussion symptoms.[53, 63] It has been suggested that these deficits indicate concussed athletes may not be truly recovered from the injury.[63] Furthermore, several authors have suggested that subtle neuromotor deficits may underlie the increased risk of sustaining musculoskeletal injury following RTP.[35, 63, 85, 86] Within the context of dynamical systems theory and ecological psychology, concussion could increase behavioral risk after incomplete rehabilitation by not allowing adequate time for recalibration to altered system dynamics.

3.0 Methods

3.1 Experimental Design

Specific Aims 1-3 were components of a cross-sectional study (e.g., one measurement conducted up to 21 days post-injury). Specific Aim 4 utilized a sub-group of the recently concussed cohort, who completed a follow-up test at 22-50 days post-injury. This follow-up test was elective for the concussed group.

3.2 Participant Recruitment

Youth athletes aged 12-18 years were recruited for this study as they represent one of the most at-risk groups for sport-related concussion and its consequences. The concussed group were required to be 12-18 year old athletes who were diagnosed with a sport-related concussion per international consensus (McCrory et al., 2017) by a clinician.

3.3 Participant Characteristics

This study used a 2:1 experimental:control allocation of participants. Participants included 72 youth sport athletes- approximately 50% males, 50% females- who were evaluated and treated for a diagnosed sport-related concussion at the UPMC Sports Medicine Concussion Program.

3.3.1 Inclusion Criteria

12-18 years of age, athlete currently participating in scholastic sports, diagnosed with sport-related concussion by a clinician, within 1-21 days of injury.

3.3.2 Exclusion Criteria

Previous diagnosis of neurological/vestibular disorder, previous diagnosed concussion within the past 6 months, >3 previous diagnosed concussions, history of brain surgery or moderate to severe TBI, and current psychiatric diagnosis.

3.4 Power Analysis

A 2:1 (experimental:control) sample size allocation was chosen due to the heterogenous presentation of concussion. Power analysis indicated that a total sample size of n=51, with n=34 in the concussed group and n=17 in the non-concussed group, would provide a power of at least 0.95, with an interaction effect size of 0.527 (estimated from previous research). Based on previous research experiences in this population to account for subject attrition and data loss, 72 subjects will be enrolled, with 48 subjects in the concussed group and 24 subjects in the non-concussed group.

3.5 Testing Procedures

3.5.1 Questionnaires

3.5.1.1 Medical History Questionnaire

Demographics including age, gender, concussion history, and relevant medical history (e.g., migraine, motion sensitivity) were obtained from athletes' electronic health records (EHR). All athletes were evaluated for a concussion per current consensus criteria[94] included: 1) clear mechanism of injury, 2) signs/symptoms at time of injury, 3) current symptoms and/or impairment not associated with another cause (e.g., illness, migraine, etc.).

3.5.1.2 Barratt Impulsiveness Scale (BIS)

BIS is a 34-item, self-report measure of impulsivity (Barratt, 1985). The scale includes questions about making quick cognitive decisions, acting without thinking, and lack of concern about the future. Patton et al.[109] demonstrated three second-order factors identified with the scale (i.e., Attentional, Motor and Non-planning). Each second-order factor has two sub-components, called first-order factors (i.e., Attentional: Attention and Cognitive Instability, Motor: Motor and Perseverance, and Non-planning: Self-Control and Cognitive Complexity). A total score is also included, which is the sum of the Attentional, Motor and Non-planning second order factors.

3.5.1.3 Personal Health Questionnaire-9 (PHQ-9)

The PHQ-9 is a brief, 9-item, self-report scale to identify symptoms of MDD. The PHQ-9 scores each of the 9 Diagnostic and Statistical Manual of Mental Disorders criteria for MDD by rating the degree to which the individual has been bothered by that item over the previous 2 weeks. Each item is scored on a 0-3 scale, where 0= “Not at All” and 3= “Nearly Every Day”. Example items include: “Little interest or pleasure in doing things?” and “Feeling down, depressed or hopeless?” PHQ-9 is a reliable (Cronbach alpha= 0.86-0.89) and valid measure (score >10 has a sensitivity of 88% and specificity of 88% for MDD).[77]

3.5.1.4 Generalized Anxiety Disorder (GAD-7)

The GAD-7 is a brief, 7-item, self-report scale to identify symptoms of GAD. Each item is answered by rating the degree to which the individual has been bothered by that item over the previous 2 weeks. Each item is scored on a 0-3 scale, where 0= “Not at All” and 3= “Nearly Every Day”. Example items include: “Feeling nervous, anxious or on edge” and “Not being able to stop or control worrying”. GAD-7 is a reliable (Cronbach alpha= 0.89) and valid clinical tool (score ≥7 has sensitivity of 73.3% and specificity of 67.3%).[123]

3.5.1.5 Physical Development Scale (PDS)

PDS is a reliable and valid self-administered survey tool (Petersen 1988) used to measure physical development status.[113] There are 8 questions for boys and 9 questions for girls. Both girls and boys are asked to estimate their growth in height, body hair, and skin changes on the following scale: “Has not yet started”, “Has barely started”, “Has definitely started”, “Seems completed”. These answers are scored from 1-4, respectively, where 4 indicates more completed physical maturity. Girls are asked a question about breast growth on the same scale, and a yes or no question whether menstruation has begun. Boys are asked to rate a deepening of their voice and hair growth on the 1-4 scale. Both boys and girls are asked to rate their development as earlier or later than most other boys/girls their age on a 5-point scale: “Much earlier”, “Somewhat earlier”, “About the same”, “Somewhat later”, and “Much later”. PDS was collected to evaluate any possible differences between individuals in physical development status.

3.5.1.6 Rating Scale of Mental Effort (RSME)

The RSME is a scale ranging from 0-150 with higher scores indicating greater mental effort.[14] This scale was administered after each computerized test described above to get a measure of mental effort required to complete each task.

3.5.2 Vestibular-Ocular Motor Screen (VOMS)

The VOMS is a brief clinical assessment of vestibular and ocular motor impairments and subsequent symptoms that may develop after sport-related concussion. The test battery includes 5 domains: smooth pursuit, horizontal and vertical saccades, near point of convergence distance, horizontal vestibular ocular reflex, and visual motion sensitivity. The outcome measures are based on symptom gain from pre-testing symptom status. Subjects are asked to rate their current level of headache, dizziness, nausea and fogginess on a 0-10 scale, where 0 reflects no symptoms and 10 reflects as symptomatic as the subject could imagine. Increased symptoms are totaled, compared to baseline scores, for analysis. The VOMS is a reliable and valid test, with procedures described in detail elsewhere[1].

3.5.3 Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT)

The ImPACT test is a computer based, neurocognitive assessment tool (version 4.5.729; ImPACT Applications, Pittsburgh, PA). The comprehensive battery contains three components including demographics, concussion symptoms (using the Post-Concussion Symptom Scale [PCSS]) and neurocognitive modules [26]. The ImPACT neurocognitive tests comprise four composite scores verbal and visual memory, motor processing speed, and reaction time [84].

3.5.4 Balloon Analogo Risk Test (BART)

BART is a computer assessment of risk-taking behavior.[3] A simulated balloon and balloon pump are presented on the computer screen along with a reset button labelled “Collect $”. A permanent display of total money earned is pictured throughout. Subjects are asked to use the computer mouse to click a balloon pump to inflate the balloon to a desired level. Subjects are told, “At some point, the balloon will explode, and this explosion could occur as early as the first pump or as late as the point at which the balloon would expand to fill the entire computer screen.” With each pump, a simulated dollar is earned. If a balloon reaches its random exploding point, all accrued simulated money is lost on that round. The subject can stop at any point during a trial, stop pumping the balloon and collect the money via the “Collect $” button. With either outcome, another balloon appeared on the screen and this process was repeated until the end of the 3-minute trial. Subjects are instructed to try to accrue as much simulated money as possible throughout the trial.

3.5.5 Perception-Action Coupling Task (PACT)

PACT uses matched pairs of ‘virtual’ balls and ‘virtual’ holes to assess the subject’s ability to accurately and quickly determine if a ball will fit inside a hole, when presented on an iPad screen [122]. Subjects are presented with a series of virtual balls, ranging in diameter from 10-60 mm, and a corresponding virtual hole, ranging in diameter from 18-44 mm. The ball-hole pairings are recorded as aperture ratios, ranging from 0.2-1.8. The objective of the task is to accurately and quickly judge if the ball will fit into the hole, or not. Subject are seated, with an iPad held in both hands and forearms resting on their thighs and the thumb of their preferred hand resting on the green (home) button on the iPad screen (Figure 2). Subjects are presented with randomly occurring series of virtual ball: virtual hole parings over a 15-minute period. Time between the presentation of the virtual ball: virtual hole parings is also random (ranging from 0.01-0.70 seconds). On presentation of a virtual ball: virtual hole paring, subjects react by moving their thumb from the home button to the blue joystick button. If they perceive the hole aperture (white circle) to be large enough to accommodate the ball (yellow circle) the subjects move the joystick forward towards the hole (e.g. the action of fitting the ball in the hole was afforded). If the subject perceives the hole to be too small compared to the size of the ball they move the joystick down, away from the ball (e.g., the action of fitting the ball in the hole was not afforded). The ball will move in correspondence with the movement of the joystick. After completing the move, subject return their thumb to the home button and await the appearance of the next pairing. This is repeated for a total of 15 minutes, after a 5-minute practice period under identical conditions and a brief rest. The PACT has been shown to be reliable across multiple testing sessions (ICC=0.78-0.94)[23]. The coefficient of variation for accuracy after a 15-minute practice period is 2.87%.[23]

Figure 2 shows a zoomed in version of the test on a tablet. Mean reaction (RXT), movement (MT), initiation (IT), response time (RT), correct response ratio, and percent accuracy are the main outcome measures of the PACT. All outcomes can be further analyzed based on the ratio of aperture size between the virtual balls and holes, which ranges from 0.2-1.8. An aperture ratio of 0.2 would indicate that the virtual ball was much *smaller* than the hole, whereas an aperture ratio of 1.8 would indicate that the virtual ball was much *larger* than the hole. Reaction time refers to the time period between presentation of the ball and hole on the screen to removing the finger from the green, "home" button. Movement time refers to the time period between the finger being removed from the home button and placed on the joystick. Initiation time refers to the time period between touching and then moving the joystick in the desired direction. Response time is the sum of reaction, movement, and initiation times.

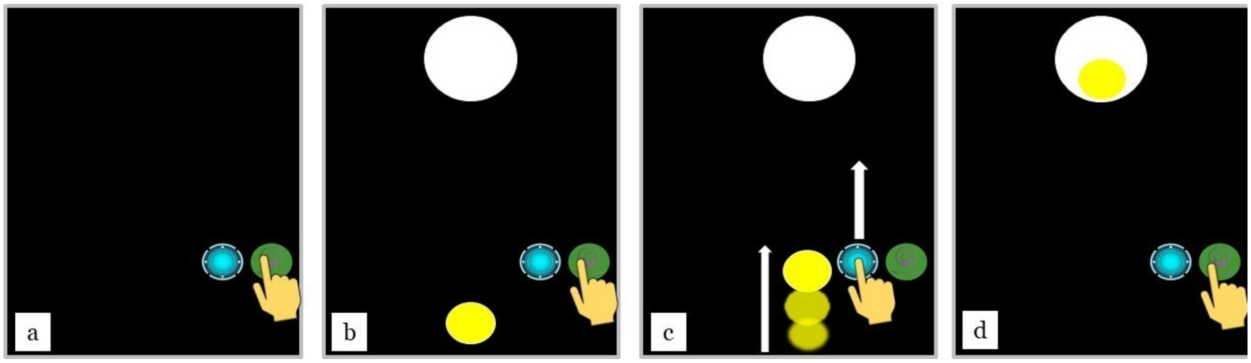


Figure 2 Temporal sequence of one PACT trial. a: Zoomed in image of iPad screen when initiating a PACT trial; subject's finger starts on the home (green) button. b: ball (yellow circle), hole (white circle) pairing is presented. c: subject quickly moves finger to the joystick (blue) and pushes forward, because the ball can fit inside the hole. d: ball reaches the hole and subject returns to the home button to initiate next trial.

3.6 Data Reduction

Outcomes from aperture ratios 0.2 and 1.8 were removed from analysis due to redundancy, consistent with previous work.(111) Lapses were recorded for each subject during the PACT, defined as an error in movement during a trial that did not register a response. Prior to analysis, outliers >2 standard deviations above the average number of lapses were identified graphically, with box-plots. These outliers were removed from analysis, as the large number of errors could bias test outcomes.

3.7 Statistical Analysis

Normality of distribution for the dependent variables was assessed using Shapiro-Wilk tests. If the data violated normality assumptions, a log transformation was conducted and normality re-assessed. The p-value was set at 0.05, *a priori* for all analyses. Sex was included as a co-variate in all analyses. Analysis of co-Variance (ANCOVA) was compared to model performance after log transformation of non-normal variables. If significance did not change with log transformation, original ANCOVA values were reported. To evaluate between-group differences of PACT outcome measures at the acute recovery time-point (1-21 days post-injury; Specific Aim 1) a one-way ANCOVA will be used. To compare risk-taking and impulsivity between healthy controls and recently concussed 12-18 year old athletes, a one-way ANCOVA will be used (Specific Aim 2). To evaluate association of PACT outcome variables with outcomes from risk-taking, impulsivity, vestibular-ocular symptom gain, concussion symptoms, and neurocognitive measures, Pearson 2-sided correlations will be used (Specific Aim 3). To evaluate recovery trajectory of PACT outcome variables and measures of risk-taking and impulsivity, vestibular-ocular symptom gain, concussion symptoms, and neurocognitive outcome variables in a sub-group of recently concussed 12-18 year old athletes, a paired samples t-test was utilized (Specific Aim 4). Partial-eta squared (η^2) values were calculated for each outcome variable to measure magnitude of the difference between groups (i.e., effect size). All statistical measures were obtained using IBM SPSS Statistics for Windows, Version 23 (IBM Corp., Armonk, NY).

4.0 Results

4.1 Demographics

There was no interaction between sex and sport-related concussion (SRC) status. There were no significant differences between groups in age, height, or weight (Table 3). There were no differences between groups in physical development (Tables 4-5). NoHx included 10 boys and 10 girls, whereas Concussed included 33 boys and 14 girls. Concussed was tested ~10 days since the most recent SRC and reported ~1.5 total SRCs. Concussed self-reported significantly higher depression and anxiety symptoms compared to NoHx. The majority of Concussed were classified with a Vestibular primary profile (n=19), followed by Migraine (n=15), No Profile (n=7), Cognitive/Fatigue (n=4), and Ocular (n=3).

Table 3 Subject demographics and group differences

	NoHx (n=20)	**Concussed (n=47)**	***p***	**η^2**
Age (years)	14.68±0.41	15.17±0.28	0.33	0.02
Height (cm)	166.24±2.77	168.38±1.88	0.53	0.01
Weight (kg)	62.39±4.45	68.63±3.01	0.26	0.02
PHQ-9	1.74±0.74	4.05±0.48	0.01*	0.09
GAD-7	1.77±0.63	3.40±0.41	0.04*	0.07
Days Since Concussion		9.62±6.1		
Total Number of Concussions		1.47±0.79		

Table 4 Physical development scale group differences for girls

	NoHx (n=10)	**Concussed (n=14)**	***p***
Height	3.70±0.15	3.64±0.17	0.81
Body Hair	3.50±0.27	3.57±0.14	0.80
Skin	3.50±0.17	3.14±0.21	0.22
Breasts	3.40±0.27	3.2±0.19	0.56
Menstruation	1.90±0.10	1.93±0.07	0.81
Development	2.70±0.37	2.79±0.16	0.81

Table 5 Physical development scale group differences for boys

	NoHx (n=10)	**Concussed (n=33)**	***p***
Height	2.50±0.40	2.88±0.17	0.32
Body Hair	3.00±0.26	2.94±0.12	0.82
Skin	2.80±0.25	3.03±0.12	0.37
Voice	3.00±0.37	2.94±0.17	0.87
Facial Hair	2.20±0.33	2.64±0.17	0.22
Development	3.20±0.25	3.12±0.16	0.80

4.2 PACT Outcome Differences between Groups at Acute Recovery Stage (Specific Aim 1)

Concussed were significantly less accurate than NoHx and reported that PACT required higher mental effort to complete (Table 6). No differences were observed between groups in mean initiation, movement, reaction and response times (Appendix A). When analyzing accuracy by each aperture ratio, Concussed were significantly less accurate at 0.4, 0.8, 1.4 and 1.6 aperture ratios compared to NoHx, with the largest difference observed at 0.8 (Figure 3). There were no differences between groups for initiation, movement, reaction and response times when analyzed at each aperture ratio (Appendix A).

Table 6 Adjusted mean differences between groups in collated PACT outcomes

	NoHx	**Concussed**	***p***	**η^2**
Accuracy (%)	92.01±1.91	87.06±1.24	0.03*	0.07
Initiation Time (msecs)	0.44±0.02	0.42±0.02	0.54	0.01
Movement Time (msecs)	0.33±0.03	0.35±0.02	0.43	0.01
Reaction Time (msecs)	0.11±0.01	0.11±0.00	0.62	0.00
Response Time (msecs)	0.88±0.02	0.89±0.01	0.66	0.00
Rating Scale of Mental Effort	37.1±6.4	54.4±4.2	0.03*	0.07

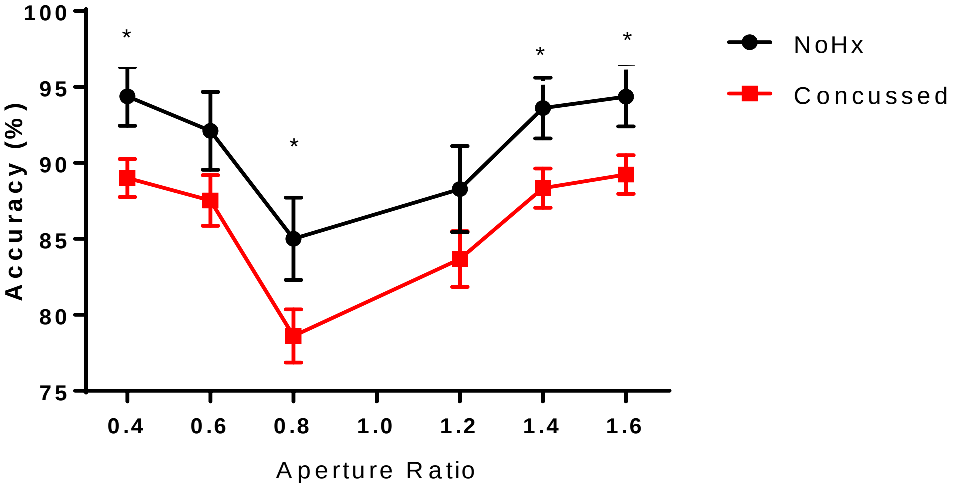


Figure 3 Action boundary accuracy differences by aperture ratio between NoHx and Concussed.* denotes statistical significance at p<0.05. Error bars represent standard error of the mean.

4.3 Differences between Groups in Risk-Taking and Feelings of Impulsivity (Specific Aim 2)

No differences between groups were observed in BART outcomes (Table 7). Concussed reported significantly greater mental effort required to complete the task (Table 7).

Table 7 Adjusted mean differences in BART outcomes

	NoHx	**Concussed**	***p***	**η^2**
Balloons Collected	17.92±0.71	17.97±0.46	0.95	0.00
Balloons Popped	12.08±0.71	12.03±0.46	0.95	0.00
Total Pumps	126.31±6.02	125.76±3.90	0.94	0.00
Mean Pump Reaction Time	764.76±76.58	861.263±49.57	0.30	0.02
Standard Deviation Pump Reaction Time	531.87±71.58	671.17±46.34	0.11	0.04
Total Money Collected	97.66±2.79	96.68±1.81	0.77	0.00
Rating Scale of Mental Effort	32.87±6.23	51.46±4.03	0.02*	0.09

Concussed reported more impulsive behaviors, specifically in regards to the Attention second-order factor and the Cognitive Instability first-order factor, as measured using the BIS (Table 8). Total impulsiveness, which is the sum of the second-order factors, was also significantly larger in Concussed.

Table 8 Adjusted mean differences in self-reported impulsivity

	NoHx	**Concussed**	***p***	**η^2**
Attention	13.16±0.72	15.08±0.47	0.03*	0.07
Attention	8.77±0.54	9.74±0.35	0.14	0.03
Cognitive Instability	0.49±0.35	5.35±0.22	0.02*	0.08
Motor	19.42±0.86	21.03±0.55	0.12	0.04
Motor	12.98±0.77	14.01±0.50	0.27	0.02
Perseverance	6.44±0.33	7.03±0.21	0.14	0.03
Non-planning	25.12±1.02	26.48±0.66	0.27	0.02
Self-Control	13.06±0.71	13.97±0.46	0.29	0.02
Cognitive Complexity	12.05±0.59	12.5±0.38	0.52	0.01
Total Score	57.70±1.97	62.60±1.27	0.04*	0.06

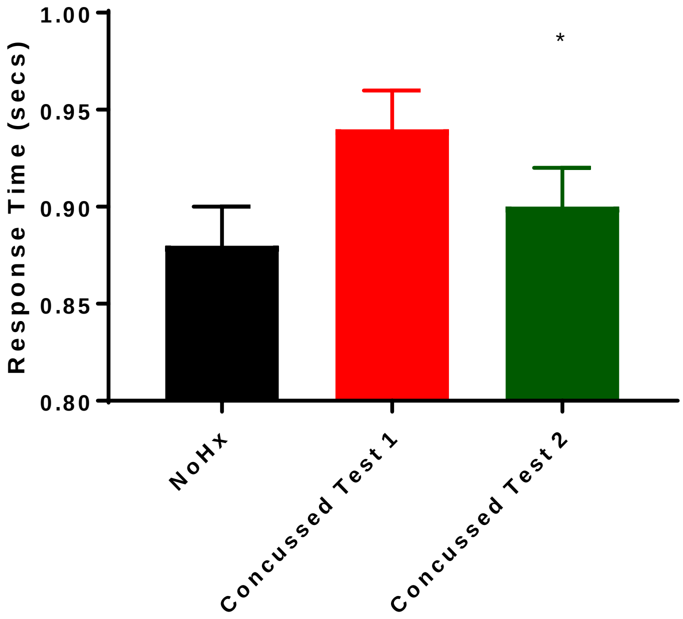
4.4 Associations between PACT Outcomes and Neurocognition, Risk-Taking, Impulsivity, and Vestibular-Ocular Symptoms (Specific Aim 3)

Several small to moderate correlations (r=0.2-0.5) were demonstrated between PACT outcomes and outcomes from neurocognition, risk-taking, impulsivity, and vestibular-ocular testing in the concussed group (Appendix B). Initiation time correlated with the Visual Memory domain in ImPACT ($p<0.05$; Appendix B). Reaction time negatively correlated with Visual Motor Speed and positively correlated with Reaction Time domains ($p<0.05$). Accuracy correlated with Visual Motor Speed, as well ($p<0.05$). No significant correlations were observed between risk-taking testing and PACT outcomes (Appendix B.1). Initiation time significantly correlated with the Non-planning and Self-control first-order impulsivity factors ($p<0.05$; Appendix B.2). Movement time negatively correlated with Perseverance and Self-Control ($p<0.05$; Appendix B.2). PACT Accuracy negatively correlated with symptom gain from baseline during Smooth Pursuits, Horizontal and Vertical Saccades ($p<0.05$; Appendix B.3).

A post-hoc analysis was conducted to elucidate which concussion symptoms were most associated with deficits in PACT outcomes. Concussed was split into tertiles for ImPACT, BART, VOMS RSME scores, as well as BIS and GAD-7 total scores, and the upper 1/3 (U3) and lower 1/3 (L3) tertiles were compared to NoHx (Appendix C). The U3 of ImPACT RSME demonstrated ~13% poorer accuracy than NoHx at the 0.8 aperture ratio (Appendix C). The U3 of BART RSME had significantly longer overall movement time compared to NoHx ($p=0.010$) and the L3 BART RSME cohort ($p=0.022$; Appendix C.1). The U3 BART cohort also demonstrated significantly longer movement time at 0.4, 0.6, 0.8, 1.2, and 1.4 aperture ratios (Appendix C.2). The U3 VOMS RSME cohort demonstrated significantly shorter initiation time at the 0.6 aperture ratio than NoHx (p=0.048) and L3 VOMS RSME (p=0.021; Appendix C.3). The U3 BIS cohort demonstrated significantly shorter overall movement time than the L3 BIS cohort (p=0.008) with no differences in overall movement time from NoHx (p=0.052). The U3 BIS cohort demonstrated significantly shorter movement time than the L3 BIS cohort at aperture ratios 0.4 (p=0.006) and 0.6 (p=0.014), 0.8 (p=0.005), and 1.2 (p=0.008), with no differences in movement time from NoHx (Appendix C.4). The L3 BIS cohort demonstrated significantly longer movement time than NoHx at aperture ratios 0.8 (p=0.049) and 1.2 (p=0.038).

4.5 Recovery Trajectories of PACT, Risk-Taking, Impulsivity, and Typical Concussion Evaluations (Specific Aim 4)

A sub-sample (n=7) of Concussed returned for follow-up testing following clearance to return-to-play. This subset’s first testing session was 10.43±7.16 days since sport-related concussion, and the second testing session occurred at 35.14±8.67 days. At follow-up, Concussed significantly reduced response time and improved accuracy, with no difference in initiation, movement and reaction times (Figure 4). No significant changes were observed between testing sessions in BART outcomes. Both motor second order and motor first order factors had increased at follow-up (p=0.029, p=0.004) with no differences observed in other factors. Subjects reported less anxiety symptoms (p=0.017) at follow-up, with no significant changes in ImPACT scores or VOMS symptom gain between first visit and follow-up.



Response Time (secs)
1.00
0.95
0.90
0.85
0.80
*
NoHx
Concussed Test 1
Concussed Test 2

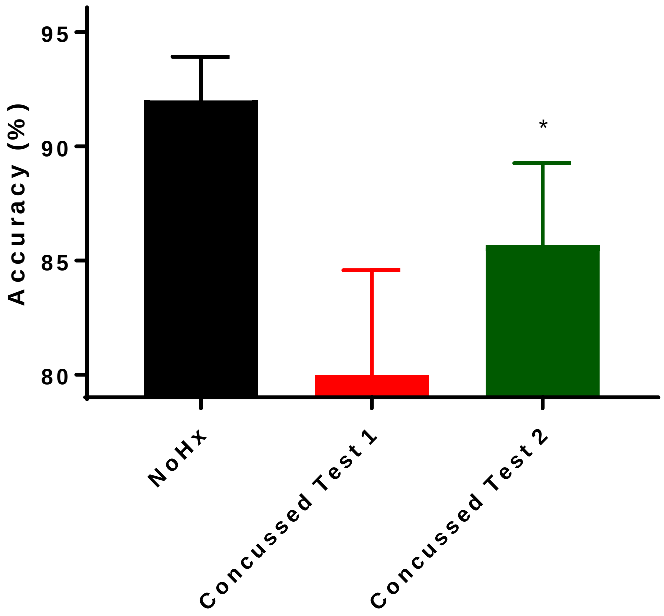


Figure 4 Differences at follow-up in response time (top) and action boundary perception accuracy (bottom)* denotes statistical significance between Concussed at initial test (Concussed Test 1) and follow-up (Concussed Test 2). Error bars represent standard deviation.

5.0 Discussion

5.1 Concussed Demonstrate Action Boundary Accuracy Deficits at Acute Recovery Stage (Specific Aim 1)

The major finding of the present study is that recently concussed adolescent athletes demonstrate a ~5% deficit in action boundary perception accuracy compared to NoHx (Table 6). Further, action boundary perception accuracy was significantly lower in Concussed at 0.4, 0.8, 1.4, and 1.6 aperture ratios, with the largest deficit observed at 0.8 (i.e., when the ball aperture is only slightly smaller than the hole aperture; Figure 3). Restated, Concussed performed significantly worse than NoHx at the aperture ratio closest to the action boundary. No differences were observed between Concussed and NoHx in actualization measures (e.g., initiation, movement, reaction and response times; Table 6), indicating no differences between groups in realizing an affordance once one has been perceived. Concussed also reported PACT testing as more mentally challenging than NoHx (Table 6). Overall, the results of this study aim indicate that, in this population, the perception-action coupling loop has been compromised by a reduction in perception accuracy following concussion, with no differences in action metrics.

The present study is the first to investigate perception-action coupling behavior in recently concussed adolescent athletes. One prior study investigated perception-action coupling behavior in collegiate athletes with sport-related concussion history.[37] Eagle et al.[37] reported significant deficits in action boundary perception accuracy, as well as movement, reaction and response time in athletes who had reported a concussion within the previous 2 years compared to healthy control athletes. The primary difference between that study and the present study is the population characteristics; the previous study included athletes ~22 years of age, while the mean age in the present study was ~15 years.[37] Further, concussed athletes in the previous study reported an average of 1.2 more prior concussions than the present sample, which could theoretically contribute to the deficits in actualization measures reported in that study.[37]

An additional difference is that concussed athletes in the prior study reported a much larger window of days since last concussion (263.8±228.9 days) whereas Concussed in the present study were still recovering from recent concussion (9.6±6.1 days).[37] It is possible that behavioral differences in affordance actualization may manifest over time following SRC, while deficits in accuracy are apparent in the acute recovery stage. Action boundary accuracy deficits, which are not rehabilitated, may contribute to an erosion of actualization behaviors after recalibration to these perceptual changes following SRC. It is also possible that multiple concussions may exacerbate the behavioral differences in actualization metrics, as concussed athletes in the prior study reported nearly 3 prior concussions, on average.[37] Longitudinal studies can provide crucial information regarding changing action boundary perceptual behaviors following SRC.

Another important consideration, when comparing differences in actualization outcomes between these two studies, is the role of physical development. While no differences in self-reported physical development were observed between Concussed and NoHx in the present study, the results indicate that, at least regarding the subject’s perception, puberty was not complete (Tables 4-5). While girls averaged between 3 (“Definitely started”) to 4 (“Seems completed”) in most categories, boys averaged between 2 (“Has barely started”) and 3 (“Definitely started”). This is worth noting because Concussed was 70% male. Physical development information is not available for the previous study, but one could assume that those subject’s bodies were more physically mature based on average age alone.[37] The differences between studies in physical development could reflect differences in nervous system maturity, as the brain is known to continue the maturation process into a person's mid-20s.[69, 125] The relative physical immaturity of the present sample, combined with less cumulative exposure to potentially concussive contact, could have affected affordance actualization and impacted the outcomes of the present study.

The results of the current study are important because athletes must be attuned to their own action boundaries, as they reflect the limit of one's opportunities to act. Misestimation of one's action boundaries in relation to situational information has been suggested to contribute to increased behavioral risk (i.e., increasing risk of musculoskeletal injury based on movement behaviors).[25, 117] For example, a runner in American football may perceive a closing gap between oncoming defenders as passable, if he is quick and agile enough to maneuver through it. However, an improperly attuned perceptual system may mislead the runner into incorrectly perceiving the passability of such a gap, potentially placing the runner in an injurious situation (Figure 1). The present study is the second to demonstrate a relationship between recently concussed athletes and poorer action boundary perception accuracy.[37] Moreover, in both studies, the largest magnitude difference between healthy athletes and Concussed occurred closest to the action boundary (i.e., at aperture ratio 0.8).[37] The highest skilled performers in athletics are typically those who can perceive and maneuver through the narrowest gaps (e.g., gaps closer to the action boundary). These deficits could theoretically be implicated in the increased risk of musculoskeletal injury following concussion. Returning to the previous example, if a typically elusive American football runner suffered an SRC with corresponding action boundary perception accuracy deficits, he or she may incorrectly perceive a closing gap as passable and endure a tackle they were not prepared for.

However, future longitudinal studies are necessary to elucidate if decreased action boundary perception accuracy is a consequence of concussion or a potential precursor.

5.2 Concussed Report Greater Feelings of Impulsivity with No Differences in Risk-Taking Behavior (Specific Aim 2)

Some researchers have hypothesized that increased risk for musculoskeletal injury following concussion may be related to increased feelings of impulsivity, or risk-taking, sensation-seeking personalities.[108] These athletes may be more likely to continually place themselves in harm's way during competition. Thus, the BART and BIS were included in the present study to quantify these behaviors and/or self-reported feelings in this sample. Regarding the BART, no differences were observed between groups, with the exception of Concussed rating greater mental effort for the test (Table 7). Literature is sparse on the role of personality traits, such as risk-taking propensity, and musculoskeletal/concussion injury risk in athletes.[63] Osborn et al.[104] reported on a prospective study in a professional ice hockey team, in which athletes were baseline tested with boredom susceptibility and sensation seeking surveys and injuries tracked for the following 18 weeks. Players whose scores were higher on each survey suffered more total injuries than those players who scored lower for boredom susceptibility and sensation seeking.[104] Specific to SRC, Beidler et al.[5] reported significantly higher risk-taking behaviors in collegiate athletes with 2 or more SRCs in their history, compared to athletes with no SRC history and athletes who reported only 1 SRC.

In the present study, Concussed scored significantly higher in Total Impulsiveness. Specific to the sub-domains of the BIS, Concussed scored significantly higher on Attentional Impulsiveness while also scoring higher on Cognitive Instability, which is a first-order factor within the Attention domain on the BIS (Table 8). A principal components analysis defined the Attention factor as "focusing on the task at hand", and Cognitive Instability as frequent "thought insertions and racing thoughts".[109] Beidler et al.[5] also reported greater impulsivity scores in their study of concussed collegiate athletes using the BIS. Kerr et al.[70] reported higher levels of impulsivity in former collegiate athletes with former concussions, as identified using the short-form version of the BIS via survey. Longitudinal studies are necessary in this population to understand if risk-taking behavior and impulsiveness are risk factors for concussion or if these personality traits are increased as a result of concussion.

Interestingly, attentional deficits, such as pre-existing attention-deficit/hyperactivity disorder (ADHD), have repeatedly been associated with increased risk for sport-related injury and general musculoskeletal injury risk.[20, 68, 95] Furthermore, adolescents with ADHD score significantly higher in the BIS compared to healthy controls, suggesting that children with ADHD struggle with feelings of impulsivity.[98] Baseline attentional deficits, such as those with pre-existing medical conditions like ADHD, may increase attentional deficits observed following concussion. Howell et al.[63] have suggested that attentional deficits underlie musculoskeletal injury risk following concussion, based on the above evidence combined with deficits observed during dual-task gait testing following concussion. However, those studies are often limited by study design, either cross-sectional or repeated measures after the concussion has occurred.[63] Additionally, the hypothesis offered by Howell et al.[63] is based on an indirect perception view of motor control; one the current authors reject in favor of direct perception theory. Attention deficits cannot be discounted, however, as attention is clearly necessary to perceive an affordance. Perhaps increased feelings of impulsiveness, such as those experienced by Concussed in this study, can negatively impact action boundary perception accuracy through incomplete attention. Future studies should evaluate the role baseline personality traits may play in concussion incidence and affordance perception.

5.3 PACT Outcomes are Associated with Select Neurocognitive, Impulsivity, and Vestibular-Ocular Domains in Concussed (Specific Aim 3)

An overarching goal of this study was to relate other testing parameters to the PACT, in order to provide better granularity about what characteristics may be associated with the PACT, and therefore action boundary perception, performance. Thus, neurocognitive, vestibular-ocular, and anxiety metrics were included because of an established relationship to impaired perception-action coupling in the literature, as well as strong evidence linking these symptoms with concussion.[73] Further, measures of impulsivity and risk-taking were included due to previous hypotheses of their potential role in sustaining concussion and/or musculoskeletal injury.[63] To provide a uniform measure to evaluate the difficulty of a specific test to the individual, RSME scales were completed following neurocognitive (ImPACT), vestibular-ocular (VOMS) and risk-taking (BART) tests. Specific outcomes for each test were correlated to PACT outcomes, and Concussed tertiles were created for post-hoc comparison to NoHx. The purpose of this post-hoc tertile analysis was to elucidate a deeper understanding of which individual characteristics may be affecting action boundary perception in this population.

5.3.1 Association between Neurocognitive Testing and PACT Outcomes

Only visual memory, visual motor speed, and reaction time domains in ImPACT testing correlated with PACT outcomes in the present study. Visual memory score positively correlated with PACT initiation time (Appendix B), meaning that Concussed whose visual memory score was higher demonstrated longer average initiation times. The visual memory ImPACT test produces a series of unique shapes that the athlete is asked to recall after a period of separate neurocognitive testing.[26] The results of the current study suggest that athletes who scored higher on visual memory took more time when presented with a new set of PACT apertures; gathering more perceptual information before moving the joystick. Elite athletes utilize a delayed strategy, in comparison to novice athletes, when judging the passability of gaps between oncoming defenders or if an incoming goal-kick is “stoppable” or not, as the goal keeper.[28, 131] Within the context of this study, this result may reflect a similar strategy to enhance PACT accuracy.

Higher scores on ImPACT visual motor speed (indicative of better performance) were negatively correlated with PACT reaction time but positively correlated with PACT accuracy (Appendix B). In other words, when Concussed removed their finger from the PACT home button quicker and responded to the aperture ratios more accurately, their visual motor speed composite score was higher. Further, ImPACT reaction time was positively correlated with PACT reaction time (Appendix B). These results are not surprising, as PACT performance is intimately related to integrity of the visual motor system. While these correlations may suggest a modest association between certain ImPACT and PACT outcomes, the scarcity of significance between outcomes in general and weakness of the significant correlations suggest that these evaluations measure different processes.

Post-hoc analysis was conducted where NoHx (n=20) was compared to lower (n=16) and upper (n=16) tertiles of RSME scores (Appendix C). ImPACT U3 demonstrated significantly lesser accuracy at aperture ratio 0.8 compared to NoHx, suggesting that Concussed who struggle with cognitive load are less accurate closer to the action boundary. Howell et al.[63] have hypothesized that incomplete attention, specifically during physical activity with concurrent cognitive load, may be related to increased injury risk following concussion. Impaired neurocognition following concussion may be related to increased musculoskeletal injury risk, as poorer perception near the action boundary has been postulated to increase behavioral injury risk.[25] It is important to note that this alternate hypothesis is based on Gibson's theory of direct perception, which is distinct from the hypothesis put forth by Howell et al.[51, 63] This is the first study to show that increased mental effort during neurocognitive tasks is related to poorer action boundary perception. It is well known that increased mental effort can lead to a transient increase in concussion-specific symptoms, especially in the acute phase of concussion recovery, however the body of evidence investigating the mental effort's effect on neurocognitive performance is lacking.[74, 118] Ramage et al.[118] reported altered functional connectivity in a Constant Effort task in fatigued subjects with recent concussion, compared to healthy controls. The authors concluded that functional network connections may become inefficient in the recovery period of concussion, increasing mental effort and propensity for fatigue.[118] The data in the present study suggest a complex relationship between mental effort during neurocognitive load and action boundary perception behavior in athletes with recent SRC.

5.3.2 Association between Risk-Taking Testing and PACT Outcomes

There were no significant correlations between BART and PACT outcomes (Appendix B.1). However, BART U3 (n=16) demonstrated significantly longer movement times per aperture ratio compared to NoHx and BART L3 (n=16) at aperture ratios 0.4, 0.6, and 0.8 (Appendix C.1). The absence of differences in BART outcomes between NoHx and Concussed, and lack of significant correlations between BART and PACT outcomes, may be explained by several factors. First, the BART utilized in this study is a 3-minute evaluation, whereas the PACT is a 15-minute evaluation with a 5-minute familiarization period prior. Thus, the absence of differences may be related to an inadequate sample size, both in terms of cohort and/or number of observations completed during the BART. An alternative explanation is that risk-taking is not a personality trait associated with PACT performance. This explanation does not seem likely due to the large differences between BART U3 and NoHx in PACT movement time (Appendix C.1). The results of this study suggest that Concussed who found a risk-taking task more arduous than others moved slower during an action boundary perception task. This preliminary evidence associates risk-taking personality traits with perception-action coupling, but more comprehensive evaluations of risk-taking behavior and personality traits is necessary to provide more granularity on its relationship with concussion.

5.3.3 Association between Impulsivity Traits and PACT Outcomes

Several BIS sub-factors significantly correlated with PACT initiation time or movement time in Concussed (Appendix B.2). Specifically, both non-planning and self-control factors were positively correlated with initiation time. Non-planning has been identified as a second-order factor, comprised of both self-control ("planning and thinking carefully") and cognitive complexity ("enjoying challenging mental tasks").[109] Thus, non-planning's significant relationship to initiation time is likely a function of the relationship between self-control and initiation time. In the current study, higher self-control impulsiveness was related to longer initiation time, which may be indicative of a more careful response strategy before moving the joystick. The first-order factors perseverance ("a consistent life-style) and self-control negatively correlated with PACT movement time (Appendix B.2). Higher impulsiveness scores for these factors (i.e., feelings of an inconsistent life-style and non-planning, impulsive decision making) were related to quicker PACT movement time. Higher impulsive feelings in concussed athletes may manifest behaviorally as quick, less careful movements.

Post-hoc analysis revealed a similar trend, as BIS U3 (n=14) consistently posted a quicker movement time than BIS L3 (n=17) and NoHx, but the difference between BIS U3 and NoHx was not statistically significant (Appendix C.2). Restated, Concussed with the highest feelings of impulsivity moved significantly faster than Concussed with the lowest feelings of impulsivity at each aperture ratio. However, BIS U3's movement times were not significantly faster than NoHx, and their movement times were much more variable in comparison to both NoHx and BIS L3. Moreover, BIS L3 produced significantly slower movement times than NoHx at aperture ratios 0.8, 1.2, and 1.4. One explanation for the absence of significant differences between BIS U3 and NoHx may be that NoHx was not subdivided into BIS tertiles, so that cohort likely contained a mix of athletes with high and low impulsiveness. The results of this study show that Concussed with higher feelings of impulsiveness move much quicker during an action boundary perception task compared to Concussed with lesser feelings of impulsiveness. The stark differences between

BIS U3 and BIS L3 may provide useful preliminary evidence for the role of personality traits, such as impulsiveness, in behavioral movement and, potentially, musculoskeletal injury risk.

5.3.4 Association between Vestibular-Ocular Testing and PACT Outcomes

The only vestibular-ocular symptoms significantly correlated with PACT were smooth pursuits and horizontal/vertical saccades, which were negatively correlated with PACT accuracy (Appendix B.3). These results could be considered surprising since these three VOMS sub-tests are primarily associated with the ocular system and only 6% of the current sample were diagnosed with primarily Ocular clinical profiles. However, ocular-related symptoms are a common symptom of concussion, regardless of primary profile assignment.[58] Further, each trial of the PACT requires a vertical eye movement to perceive the size of the hole aperture relative to the ball aperture, which would conceivably aggravate symptoms similar to vertical saccades. A slight horizontal eye movement may also be necessary during PACT trials, if the subject needs to look towards the home button and/or joystick. PACT accuracy may therefore be compromised by increasing ocular symptoms in recently concussed young athletes. Additionally, none of the sub-tests primarily associated with the vestibular-system, such as the vestibular-ocular reflex and visual motion sensitivity, were associated with PACT outcomes. However, the vestibular and ocular systems are intimately connected and each system cannot be completely isolated through these sub-tests.

Post-hoc analysis revealed significant differences between VOMS U3 (n=13) and both NoHx and VOMS L3 (n=17) in initiation time at aperture ratio 0.6 (Appendix C.3). Increased mental effort to complete VOMS may therefore reflect an increased symptom burden as a result of VOMS testing. Increased symptoms may cause the subjects to initiate joystick movement quicker as a strategy to limit the amount of times ocular movement is necessary. Unfortunately, in the present study, subjects only completed RSME scales to reflect the entire test, so mental effort cannot be parsed out to the primarily ocular versus primarily vestibular VOMS sub-tests.

5.3.5 Association between Anxiety and PACT Outcomes

There were no significant correlations between GAD-7 and PACT outcomes. Post-hoc analysis revealed movement time differences between GAD-7 U3 (n=20) and NoHx at aperture ratios 0.6 and 1.2 (Appendix C.4). Specifically, GAD-7 U3 demonstrated longer movement times in comparison to NoHx. Anxiety has repeatedly been shown to cause an underestimation in perception of action capabilities, but in the present study anxious feelings caused a behavioral difference in affordance actualization.[30, 31, 55] Anxiety has been suggested to impair processing efficiency during perceptual-motor tasks, and to reduce successful outcomes by a diversion of attention to more threatening stimuli within the environment.[116] This is a plausible mechanism for injury for athletes returning from concussion with primary mood profiles, as the symptoms are unlikely to be completely resolved by return-to-play.[120] A recovery period of sufficient length following concussion would be critical to allow proper recalibration and attunement to the environment, as these perceptual variables may have been altered by the presence of anxiety symptoms. Further research is necessary to investigate the role of pre-existing, as well as developed from concussion, anxiety or mood disorders and perceptuomotor control.

5.3.6 Summary

These preliminary data suggest multiple components of a Concussed athlete's symptoms and personality are related to PACT performance. Specifically, post-hoc analysis revealed characteristics like impulsivity, anxiety, and higher perceived mental effort during vestibular-ocular and risk-taking tests, may directly influence actualization of perceived affordances during PACT. Higher perceived mental effort during neurocognitive tasks was also associated with poorer action boundary accuracy nearer the actual action boundary. It is important to note the distribution at which these concussion specific symptoms (e.g., anxiety, vestibular-ocular and neurocognitive deficits, etc.) impact PACT outcomes, with little overlap between outcomes (Figure 5). These behavioral differences lend further support to the multifaceted nature of perception-action coupling, and the importance of viewing the athlete as a dynamic system.[33] Further characterization of the PACT and its relationship to typical concussion symptoms, while remaining its own distinct metric, are critical to understanding the role action boundary perception may play in future injury risk.

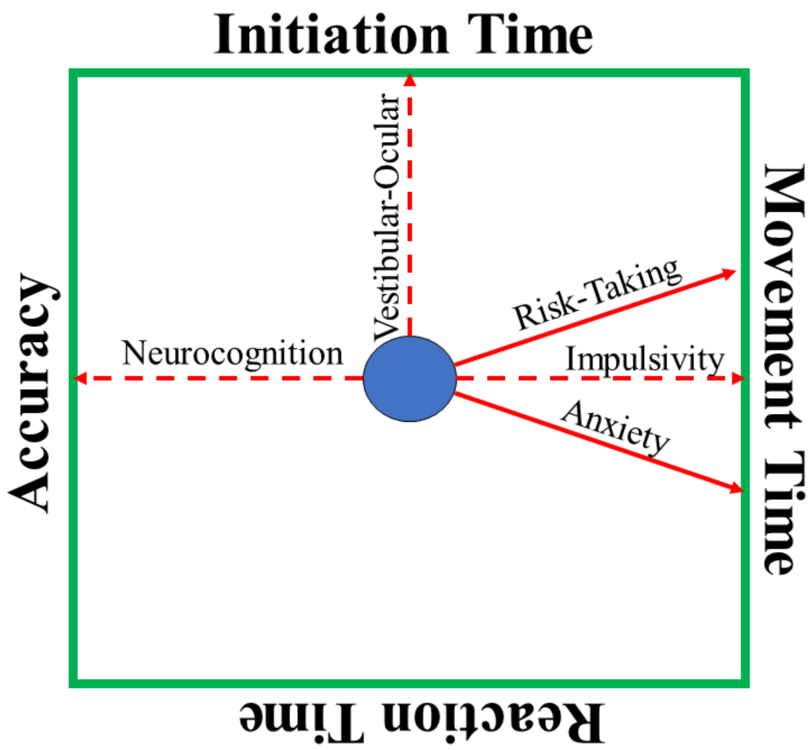


Figure 5 Graphical depiction of the association of PACT outcomes to concussion-related factors. Solid red lines indicate an increase in the PACT outcome (outside square), whereas dashed lines indicate a reduction in the PACT outcome.

5.4 PACT Outcomes Improve from Acute Phase to Post-Clearance (Specific Aim 4)

A subset of Concussed returned for follow up testing ~25 days after the initial test and following physician clearance for return-to-play. After clearance, Concussed had significantly reduced response time and improved accuracy (Figure 4), but both measures were still not equal to NoHx. This is the first study to demonstrate a recovery of action boundary perception performance following concussion. The study design precludes any definitive conclusion whether action boundary perception performance is a potential cause or result of concussion, but these data demonstrate an acute disruption of PACT performance in the early stage of concussion recovery with a rebound in performance following return-to-play. Baseline testing with sequential re-tests following injury would provide crucial information regarding cause and effect between perception-action coupling disruption and concussion. Still, this study provides preliminary evidence that action boundary perception improves during concussion recovery but is not equivalent to healthy controls after return-to-play.

Motor impulsiveness ("acting on the spur of the moment") increased from the first testing session to the post-test session.[109] As stated earlier, little data is available as to the role of impulsiveness and sustaining concussion, but an increased propensity to act impulsively would seem to be an intuitive risk-factor for injury during athletic competition.[63] Again, results of this study aim should be interpreted cautiously as the sample size only allowed for a preliminary investigation, but impulsiveness warrants further evaluation in concussion risk when considered in combination with the results of this study. Subjects also reported significantly less anxiety symptoms at follow-up. The normalization of anxiety symptoms may be related to the improvement in PACT performance in the present study, as anxiety has been shown to interrupt perception-action coupling by underestimating action capabilities.[31, 55, 116] Further, subjects who reported higher anxiety demonstrated prolonged movement times in the present study. Reducing movement times may have contributed to the reduction of overall response time at follow-up.

ImPACT and VOMS scores did improve over the follow-up period, but the change in scores was not statistically significant. ImPACT Verbal memory and impulse control recovered by the largest margin (p=0.06 and p=0.07, respectively). PCSS did not significantly improve but the average score dropped from 9 to 0.75. VOMS also did not significantly improve, but this cohort was apparently not suffering from vestibular issues at initial testing, as the average symptom gain from baseline for each sub-test was less than 1 (out of 10). Taken together, it appears neurocognition and vestibular-ocular function had improved, or at least maintained, since the initial injury. Future longitudinal studies can provide critical information about whether action boundary perception accuracy rebounds to baseline performance or if it remains suboptimal at return-to-play, based on current clearance criteria.

6.0 Conclusion

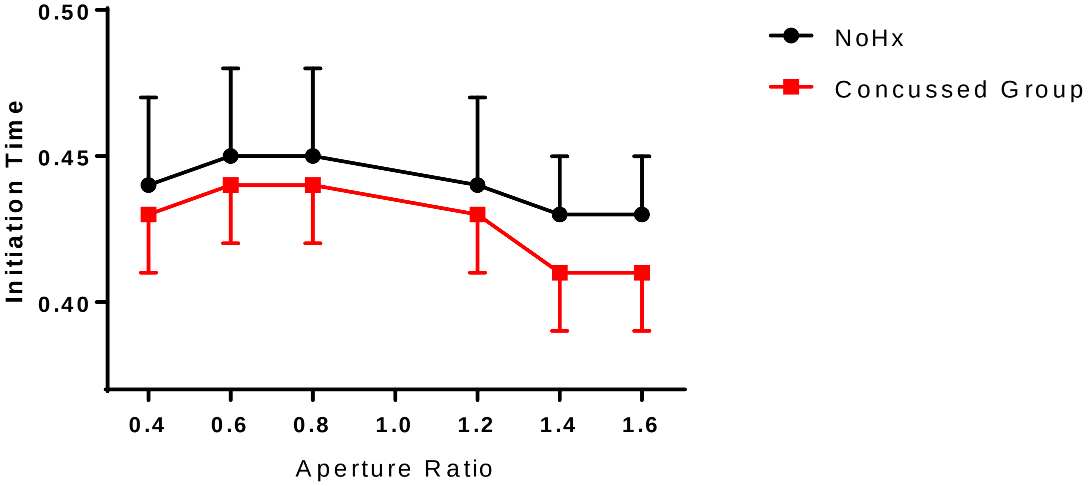
SRC is an ongoing, persistent problem, as up to 15% of athletes will experience a concussion during a single season.[58] While SRCs typically resolve spontaneously in a 2-4 week period, the body of evidence is growing that clinical recovery (e.g., recovery by current clinical standards) and complete neurophysiological recovery are not equivalent.[58] Deficits in motor control have continually been demonstrated in recently concussed athletes past symptom resolution and even return-to-play.[62-64] The seminal problem is that a vast majority of clinics do not have the tools to gather this information, due to high cost of the equipment and time to conduct the analyses.[63] Further, it is still unknown if these motor control deficits have injurious consequences after return-to-play, although one recent investigation linked dual-task gait deficits to future musculoskeletal injury risk in athletes.[62]

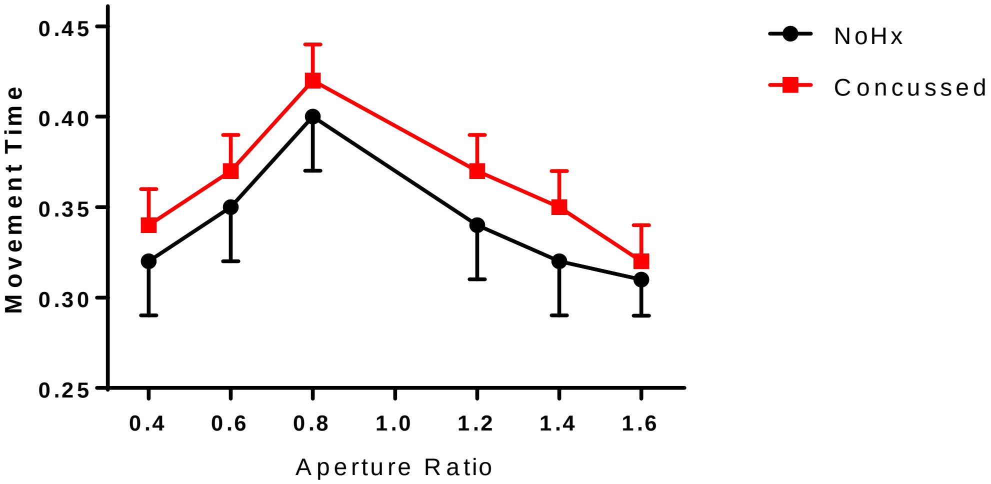
The current study is the second to demonstrate decreased action boundary perception accuracy in recently concussed athletes, using the PACT.[37] In a sub-sample of the current study, Concussed improved response time and accuracy but had not restored performance to an equivalent level with NoHx. Further, the previous study demonstrated significant deficits in accuracy and actualization metrics an average of 264 days since last concussion, well past return-to-play.[37] If deficits in PACT continue to be observed following normalization of typical concussion metrics, it could easily be incorporated into clinical testing procedures to get a broader overview of a concussed athlete's readiness to return-to-play. Prior to that step, longitudinal testing with a baseline measure and establishing any relationship to future concussion and/or musculoskeletal injury risk will be necessary. Still, the preliminary evidence shows that diminished PACT performance is related to recent SRC.

The results of the current study also show that further characterization of the PACT is warranted, as nuanced effects were revealed when Concussed individuals with higher symptoms than others were isolated into cohorts (e.g., upper anxiety tertile of Concussed). Perception-action coupling is a process that does not occur in isolation; anxiety, fatigue and ocular dysfunction are a few characteristics that are known to disrupt the process through delayed recalibration and/or attunement.[30-32] The current study also associated higher levels of cognitive effort and higher feelings of impulsiveness with altered action boundary perception behaviors. Following concussion, the individual's constellation of symptoms has, at least transiently, altered their perceptual system (which was calibrated and attuned to the environment as it existed "pre-concussion").[58] If perception-action coupling behaviors are not re-established prior to return-to-play, it could theoretically enhance injury risk via an inadequately calibrated/attuned perceptual system.[25, 127] Future research should evaluate if diminished PACT performance is a potential risk factor for concussion or result of concussion and quantify the relationship between PACT performance and injury risk. If hypotheses are confirmed, PACT could be an easily implementable clinical tool that significantly informs the concussion return-to-play decision making process.

If diminished action boundary perception is a consequence of concussion, the authors hypothesize that concussion may disrupt the recalibration/re-attunement process by introducing new constraints (i.e., anxiety, fatigue, or vestibular/ocular dysfunction) to the bodily system.[99] In addition, these issues may not be properly identified and addressed at the time of diagnosis, enhancing the likelihood that the athlete returns to play with lingering symptoms.[75, 120] Without adequate time to recalibrate and/or re-attune to the dynamics of their sporting environment, under their new constraints, the athlete could be subjecting themselves to increased risk of musculoskeletal injury by being “in the wrong place at the wrong time”. The authors do not mean to suggest that this hypothesis explains the complete phenomenon of increased musculoskeletal injury risk following concussion. Rather, the authors suggest those of specific clinical profiles (such as vestibular, ocular and mood as primary symptom drivers) may be more likely candidates based on the established relationship between these symptoms and perception-action coupling dysregulation.[30-32, 45] More research is necessary in order to understand which concussion clinical profiles are most related to dysregulated perception-action coupling.

Appendix A PACT Actualization Outcome Measures by Aperture Ratio





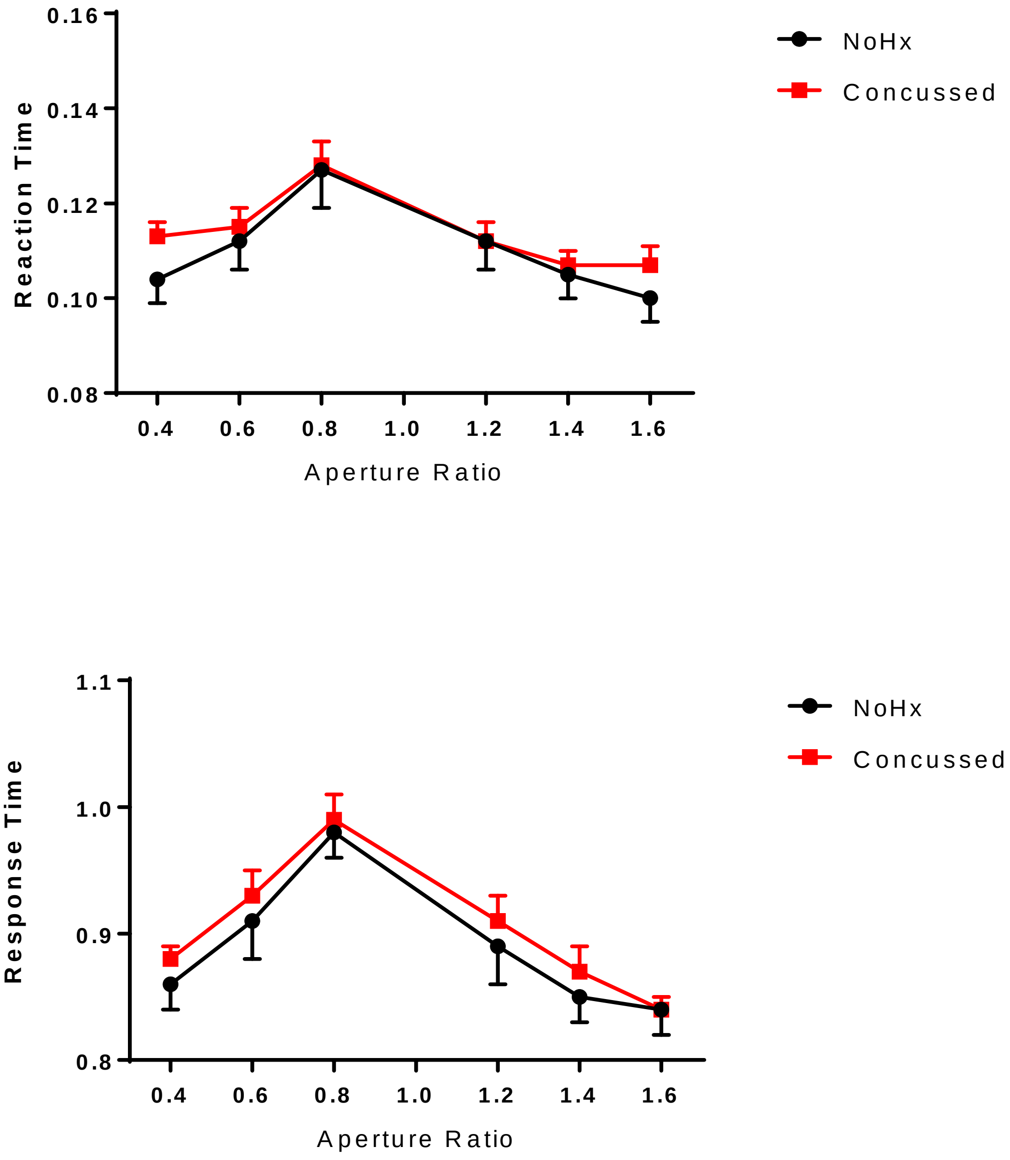
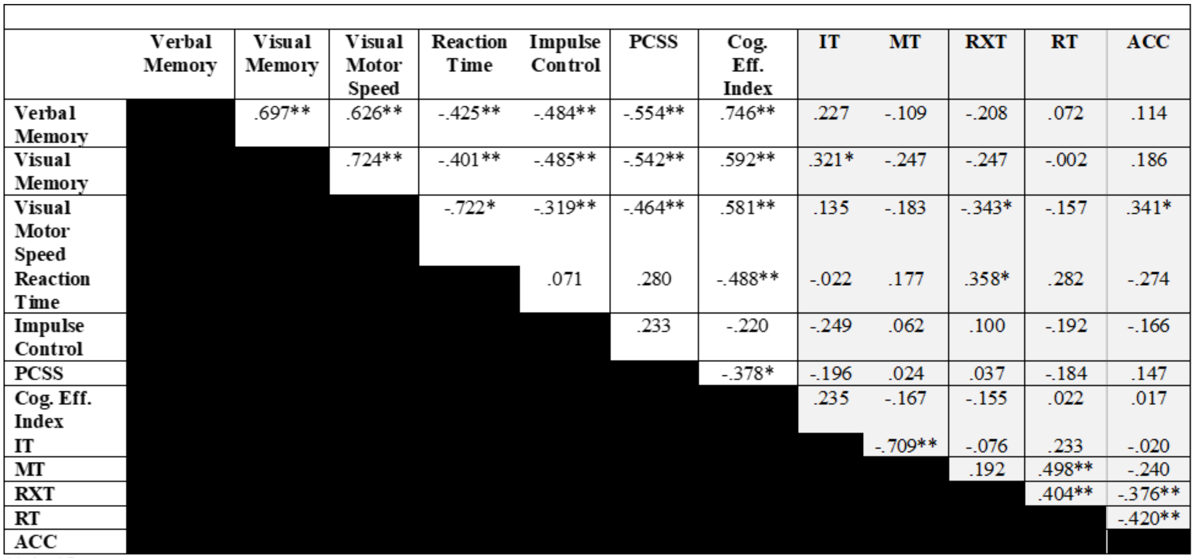


Figure 6 PACT Actualization Outcomes by Aperture Ratio. Error bars represent standard error of the mean.

Appendix B Correlation Matrices

Table 9 Bivariate correlation matrix for ImPACT and PACT outcomes



	Verbal Memory	Visual Memory	Visual Motor Speed	Reaction Time	Impulse Control	PCSS	Cog. Eff. Index	IT	MT	RXT	RT	ACC
Verbal Memory		.697**	.626**	-.425**	-.484**	-.554**	.746**	.227	-.109	-.208	.072	.114
Visual Memory			.724**	-.401**	-.485**	-.542**	.592**	.321*	-.247	-.247	-.002	.186
Visual Motor Speed				-.722*	-.319**	-.464**	.581**	.135	-.183	-.343*	-.157	.341*
Reaction Time					.071	.280	-.488**	-.022	.177	.358*	.282	-.274
Impulse Control						.233	-.220	-.249	.062	.100	-.192	-.166
PCSS							-.378*	-.196	.024	.037	-.184	.147
Cog. Eff. Index								.235	-.167	-.155	.022	.017
IT									-.709**	-.076	.233	-.020
MT										.192	.498**	-.240
RXT											.404**	-.376**
RT												-.420**
ACC												

**significant at p<0.001

*significant at p<0.05

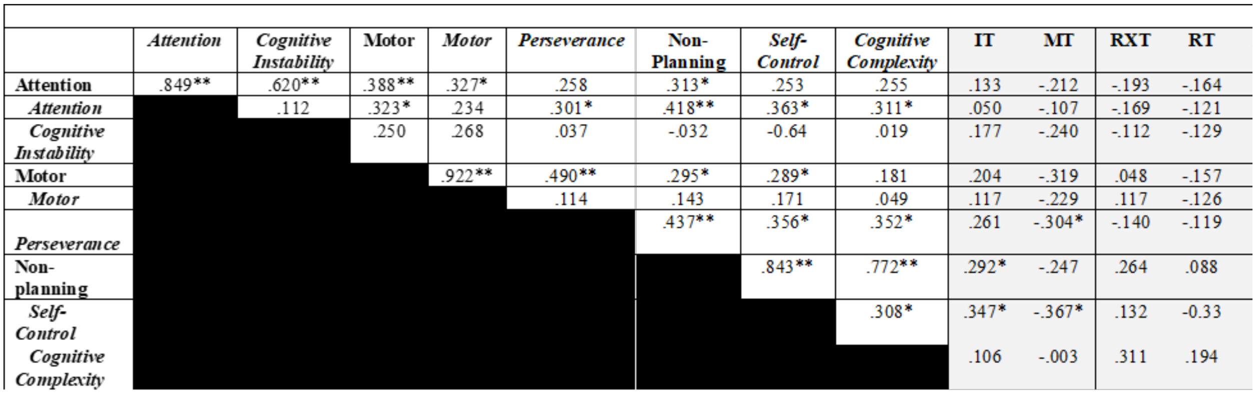
Table 10 Bivariate correlation matrix for BART and PACT outcomes

	Balloons Collected	Balloons Popped	Total Pumps	Mean Reaction Time	Std, Reaction Time	Total $ Collected	IT	MT	RXT	RT	ACC
Balloons Collected		-1.0**	-.922**	.449**	.525**	.246	.139	-.175	.057	-.047	-.116
Balloons Popped			.922**	-.449**	-.525**	-.246	-.139	.175	-.057	.047	.116
Total Pumps				-.507**	-.525**	.106	-.118	.244	-.058	.158	.085
Mean Reaction Time					.679**	-.099	.124	-.186	-.009	-.095	.064
Std. Reaction Time						-.153	.149	-.077	.033	.083	-236
Total $ Collected							.125	.077	-.010	.239	.034

**significant at p<0.001

*significant at p<0.05

Table 11 Bivariate correlation matrix for BIS and PACT outcomes

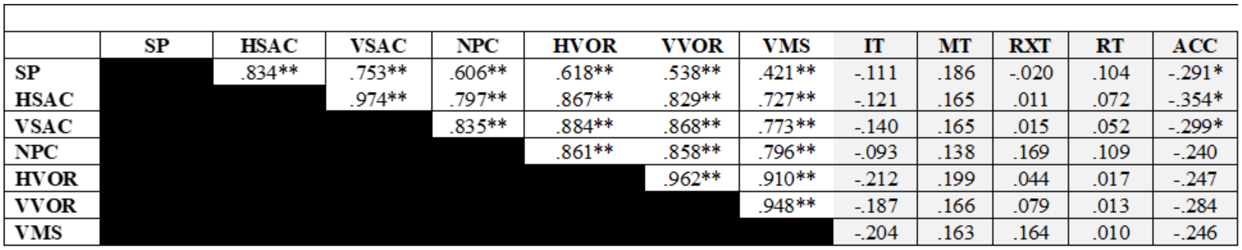


	Attention	*Cognitive Instability*	Motor	*Motor*	*Perseverance*	Non-Planning	*Self-Control*	*Cognitive Complexity*	IT	MT	RXT	RT
Attention	.849**	.620**	.388**	.327*	.258	.313*	.253	.255	.133	-.212	-.193	-.164
Attention		.112	.323*	.234	.301*	.418**	.363*	.311*	.050	-.107	-.169	-.121
Cognitive Instability			.250	.268	.037	-.032	-0.64	.019	.177	-.240	-.112	-.129
Motor				.922**	.490**	.295*	.289*	.181	.204	-.319	.048	-.157
Motor					.114	.143	.171	.049	.117	-.229	.117	-.126
Perseverance						.437**	.356*	.352*	.261	-.304*	-.140	-.119
Non-planning							.843**	.772**	.292*	-.247	.264	.088
Self-Control								.308*	.347*	-.367*	.132	-0.33
Cognitive Complexity									.106	-.003	.311	.194

**significant at p<0.001

*significant at p<0.05

Table 12 Bivariate correlation matrix for VOMS and PACT outcomes



	SP	HSAC	VSAC	NPC	HVOR	VVOR	VMS	IT	MT	RXT	RT	ACC
SP		.834**	.753**	.606**	.618**	.538**	.421**	-.111	.186	-.020	.104	-.291*
HSAC			.974**	.797**	.867**	.829**	.727**	-.121	.165	.011	.072	-.354*
VSAC				.835**	.884**	.868**	.773**	-.140	.165	.015	.052	-.299*
NPC					.861**	.858**	.796**	-.093	.138	.169	.109	-.240
HVOR						.962**	.910**	-.212	.199	.044	.017	-.247
VVOR							.948**	-.187	.166	.079	.013	-.284
VMS								-.204	.163	.164	.010	-.246

**significant at p<0.001

*significant at p<0.05

Appendix C Post-Hoc Analysis

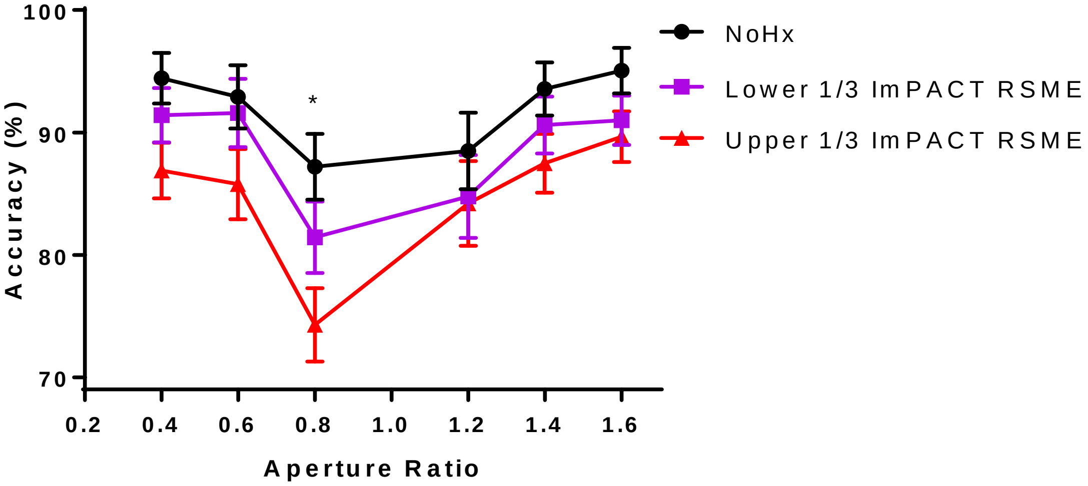


Figure 7 Upper and Lower Tertile Comparison to NoHx in PACT Accuracy by Aperture Ratio. *indicative of statistically significant difference ($p<0.05$) between Upper 1/3 tertile and NoHx. Error bars represent standard error of the mean.

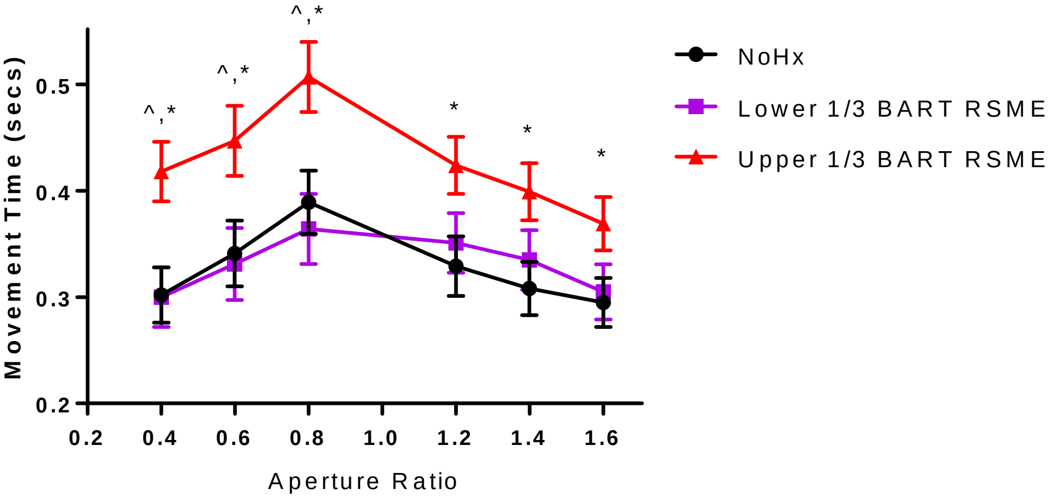


Figure 8 Upper and Lower BART Tertiles Comparison to NoHx in Movement Time by Aperture Ratio. * indicative of statistically significant difference ($p<0.05$) between Upper 1/3 tertile and NoHx
^ indicative of statistically significant difference ($p<0.05$) between Upper 1/3 tertile and Lower 1/3 tertile. Error bars represent standard error of the mean.

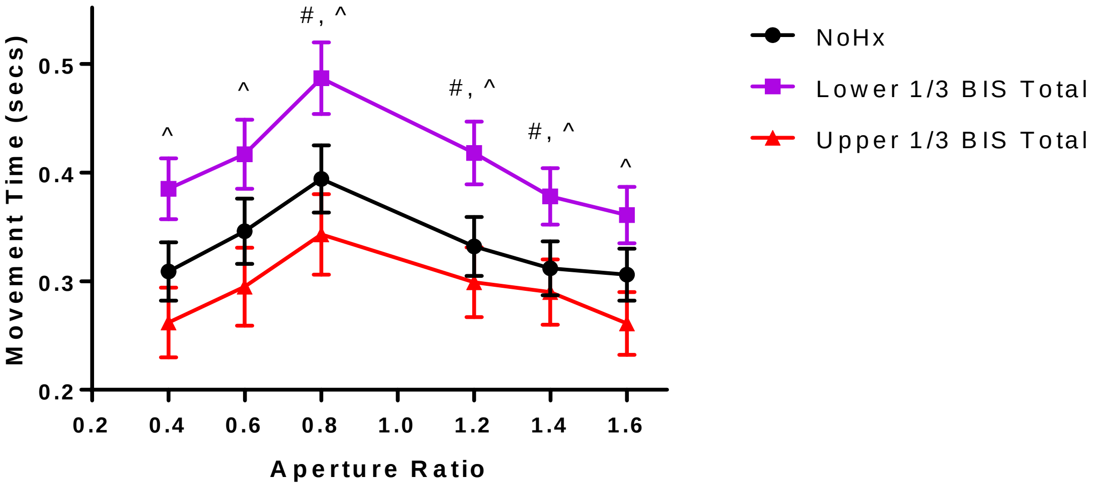


Figure 9 Upper and Lower BIS Tertiles Comparison to NoHx in Initiation Time by Aperture Ratio. $^{\#}$ **indicative of statistically significant difference (p<0.05) between Lower 1/3 tertile and NoHx**
^ indicative of statistically significant difference (p<0.05) between Upper 1/3 tertile and Lower 1/3 tertile. Error bars represent standard error of the mean.

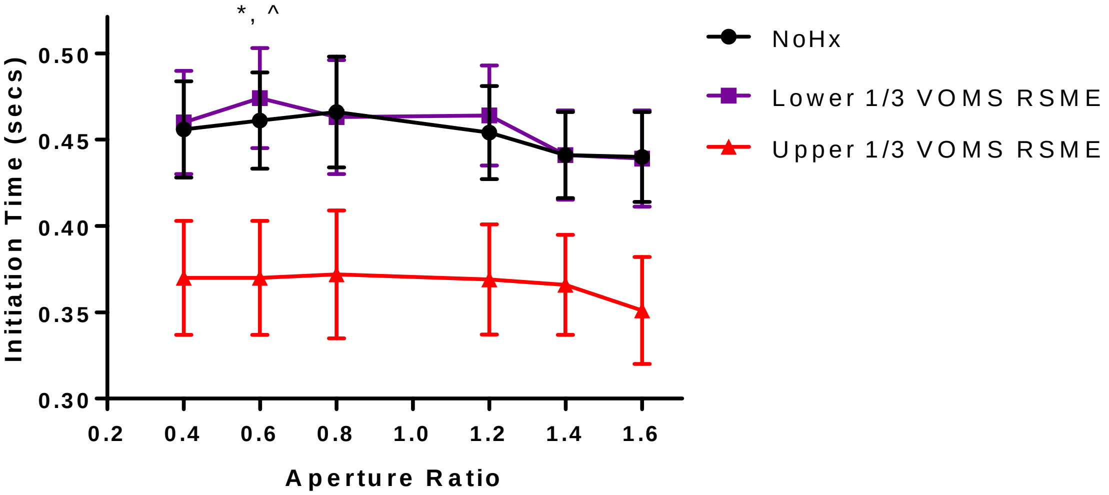


Figure 10 Upper and Lower VOMS Tertiles Comparison to NoHx in Movement Time by Aperture Ratio. * **indicative of statistically significant difference (p<0.05) between Upper 1/3 tertile and NoHx**
^ indicative of statistically significant difference (p<0.05) between Upper 1/3 tertile and Lower 1/3 tertile. Error bars represent standard error of the mean.

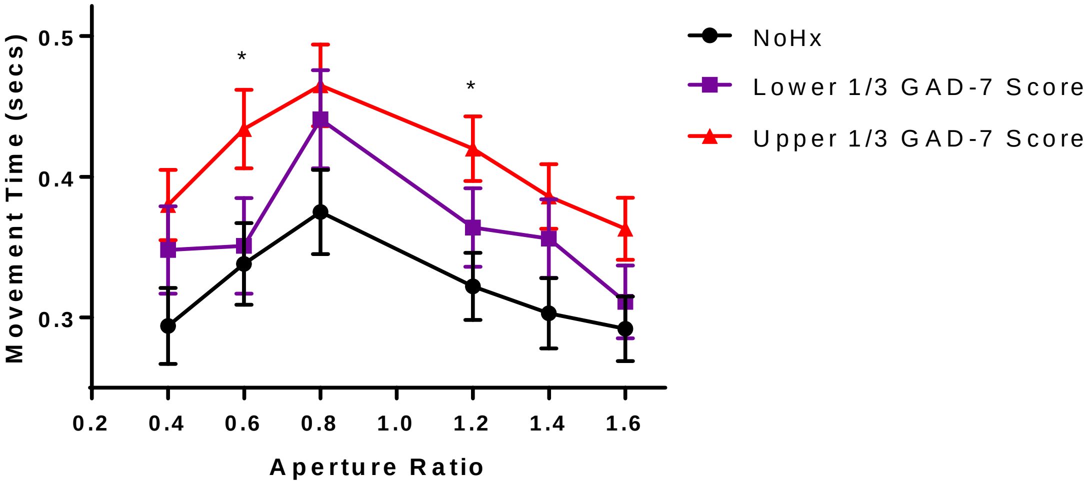


Figure 11 Upper and Lower GAD-7 Tertiles Comparison to NoHx in Movement Time by Aperture Ratio. * **indicative of statistically significant difference ($p<0.05$) between Upper 1/3 tertile and NoHx. Error bars represent standard error of the mean.**

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