

The Effect of Prior Concussions on Cognitive Performance in Recreational College Athletes

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Abstract

Context: Sports-related concussions impact between 1.6 and 3.0 million athletes annually in the USA. Although the CDC has qualified sports-related concussion as an epidemic, there is a significant lack of data regarding the best way to assess the long-term effects of concussion, especially in recreational athletes.

Objective: To assess the relationship between concussion history and cognitive performance in a group of recreational athletes.

Design: Quantitative cross-sectional study.

Setting: University of South Carolina, Columbia SC, USA.

Participants: Healthy college athletes with no prior history of concussion (n=25) and college athletes with a prior history of at least one concussion (n=25).

Main Outcome Measures: Working memory (Paced Visual Serial Addition Test), response inhibition (Go/NoGo task) and decision-making (computer-based visual sorting task).

Results: Athletes with a prior history of concussion showed a trend toward lower accuracy on the working memory task, impaired performance in response inhibition and decision making tasks. Factor analysis of the dependent variables derived from a custom-built test battery identified five factors, when entered into a binary logistic model, correctly classified 80% of participants as either having a prior concussion or not. Results of a stepwise linear regression model revealed that the response inhibition factor was significantly correlated with the number of prior concussions.

Conclusions: Overall, the results indicated impaired cognitive performance in athletes with a prior history of concussion and show that some, but not all cognitive impairments may vary as a function of the number of prior concussions. These data provide further evidence of the negative consequences of concussion and highlight the vital need to increase research and development efforts aimed at creating apt precautionary measures and rehabilitative methods to minimize the effect of concussions in athletes.

Keywords: Concussion; Athlete; Cognition; Cumulative; Classification

Introduction

A concussion is a form of brain injury that is often caused by a forceful blow to the head or violent shaking of the head and upper body. In the United States, an estimated 1.6 to 3.0 million sport-related concussions occur every year [1]. A concussion can result in Loss of Consciousness (LOC), headache, dizziness, confusion, “feeling mentally foggy,” and “feeling slowed down” mentally [2,3]. Emerging literature often uses the terms mild Traumatic Brain Injury (mTBI) and concussion interchangeably; however, the repercussions of sports-related concussions can often be more severe than the term “mild” implies [2]. The serious nature of sports-related concussions, as well as increases in the number of concussions reported, has sparked debate

and controversy in both research and the media [4,5]. In particular, the lasting (chronic/lingering) effects of concussion, as well as the potentially additive effects of multiple concussions, have become central topics of discussion in concussion research.

While researchers generally agree that multiple concussions are linked to prolonged symptoms, longer recovery time, and an increased risk for future concussions, there is minimal previous research evaluating neurocognitive performance following multiple concussions, and much of the existing literature on the topic is equivocal in its findings [6]. In a baseline evaluation study conducted by Schatz et al. [3], athletes with a history of two or more prior concussions reported significantly higher ratings in the chronic symptom clusters regarding cognitive, physical, and sleep impairments than their counterparts with a history of one or no previous concussions. The symptom clusters included items such as “feeling

mentally ‘foggy’, “feeling slowed down” cognitively, headaches, dizziness, and balance problems [3]. In a separate study of collegiate athletes, participants with two or more concussions demonstrated significant verbal memory and reaction time deficits post-injury. A new study suggests, in addition to deficits in verbal memory and reaction time, athletes with three or more concussions exhibit higher levels of migraine-cognitive-fatigue symptoms post-injury [6]. Long-term outcomes of multiple prior concussions include deficits in executive functioning, the speed of information processing, and memory [3,7,8]. Interestingly, some literature argues there are no cumulative effects of concussion and that data on three or more concussions should be considered “preliminary, provocative, and suggestive” [8]. One of the goals of the present study was to contribute novel data to this ongoing debate.

Claiming to be the “most widely used and most scientifically validated computerized concussion management tool available,” ImpACT[®] (Immediate Post-Concussion Assessment and Cognitive Testing) is a neurocognitive test battery designed to assess verbal memory, visual memory, reaction time, and visual processing speed along with 22 other concussion symptoms [9,10]. While there are other computerized neuropsychological tools available for use, such as the Automated Neuropsychological Assessment Metrics (ANAM), CogState Sport[®], and HeadMinder, the ImpACT[®] protocol is the most well-known [11]. Despite its widespread use, the ImpACT[®] battery has been highly criticized for its low sensitivity and poor reliability [12]. It has also failed to meet the reliability and validity criteria for assisting in return-to-play decisions and failed to demonstrate clinical utility [11]. Even the research claiming the ImpACT[®] battery is a reliable measure for post-concussion assessment specifically adds a disclaimer stating that it “should not be used as a stand-alone measure” [13]. The shortcomings of individual concussion test batteries, along with broad research in the area of concussion, confirms that no single test or test battery is sufficient to justify routine clinical application [14]. This is consistent with the National Athletic Trainer Association’s position statement about concussions, in which they state that decisions about an athlete’s ability to return-to-play “should never be based solely on the use of anyone test,” also referring to single-administration test batteries [15]. In light of the aforementioned concerns regarding known concussion-assessment batteries, we decided to assess cognitive performance using two well-known TBI measures (Paced Auditory Serial Addition Test [PASAT] and a class C Go/NoGo task) along with a novel visual sorting task designed to measure participants’ ability to make rapid decisions based on a complex and dynamic visual scene.

Impairments in working memory are one of the most common symptoms of concussion [16]. Working memory, or the ability to temporarily hold information or data in memory while manipulating or using it in some way, is essential for countless activities of daily living such as entering a number into your smartphone or computing a tip at a restaurant, and is critical for many skills necessary to return to work or school post-injury [17]. Given the impact of concussions on working memory, it is important to utilize cognitive measures that can differentiate working memory performance in individuals who have sustained a brain injury. The Paced Auditory Serial Addition Test (PASAT) paradigm has sufficient evidence demonstrating differentiation of working memory performance for individuals sustaining a traumatic brain injury [18]. Thus, a similar task assessing working memory was included in the present study. Based on the demanding nature of the PASAT protocol, it has often been modified in research with traumatic brain injury populations to omit the effortful auditory processing component and foster increased effort,

cooperation, and motivation [17,18]. The present study chose to use one such modified version, the Paced Visual Serial Addition Test (PVSAT), to mediate the difficulty of the original paradigm as a piece of a three-part cognitive battery.

Post-TBI clinical reports often note impulsivity and issues with behavioral disinhibition in athletes. These features are indicative of a core deficit in what cognitive psychologists typically refer to as response inhibition, defined as the inability or failure to stop a response when required [19]. Response inhibition has been previously measured in traumatic brain injury populations using a Go/NoGo task, a stop-signal task, the Sustained Attention to Response Task (SART), and the Conners’ Continuous Performance Test (CPT) [20]. While the impact test, widely considered the gold standard for concussion assessment does not include an evaluation of response inhibition, there is some evidence suggesting that inclusion of a Go/NoGo paradigm, which requires participants to respond to most targets and inhibit their response on a small percentage of trials, can reveal significant impairments in traumatic brain injury participants when compared to controls [21]. Interestingly, it is possible to rehabilitate impairments in response inhibition via appropriate training techniques, and such an approach may prove useful in supplementing traditional cognitive rehabilitation methods in the development of a more targeted approach [20]. For the purposes of this study, a classic Go/NoGo response inhibition task based on the paradigm by Chikazoe et al. [22] was chosen.

The ability for patients to make competent decisions post-traumatic brain injury is crucial for returning their quality of life to pre-injury levels. Specifically, their decision-making capacity regarding treatment planning and medical options is particularly important for recovering functional independence and personal autonomy [23]. Previous evidence from decision-making tasks has indicated slower deliberation times and higher levels of impulsivity in traumatic brain injury groups when compared to control groups [24]. Additionally, working memory performance and basic executive functioning have been linked to decision-making capacity, which demonstrated the potential for connections between the tasks in the present cognitive battery [23]. The final component of our three-part test battery was designed to measure participants’ ability to make quick decisions in the context of a fast-paced, computer-based visual sorting task (see Methods). This task was developed specifically for this study and designed to maximize participant engagement.

Based on previous concussion and mild traumatic brain injury literature, it was hypothesized that participants with a history of concussion would show significant impairments in cognitive function and that the severity of these impairments would be directly related to the number of prior concussions. We tested this hypothesis by examining the performance of 50 athletes, 25 with no prior history of concussion and 25 with a prior history of concussion (13 of which had multiple concussions) on a cognitive task battery comprised of three computer-based tasks designed to measure cognitive function. In order to measure working memory, we used the Paced Visual Serial Addition Test (PVSAT), while Chikazoe’s Go/NoGo task was used to measure response inhibition, and a novel, the computer-based visual sorting task was used to assess decision-making abilities [22]. Although results from prior experiments examining the effect of concussion on cognitive performance are equivocal, it was predicted that athletes with a history of concussion would score lower on all three measures of cognitive function, and we also expected the severity of this impairment to be greatest in athletes with multiple prior concussions.

Methods

Participants

For the present study, 50 male, club athletes ($M=19.64$ years old, $SD=1.22$, range=18-23) were recruited from university club sports teams and assigned to one of two groups: 1) athletes with a self-reported history of any grade of concussion(s) ($n=25$); or 2) athletes without a history of concussion ($n=25$). Forty-seven of the participants self-reported that they were right-handed and three self-reported that they were left-handed. The breakdown of athletes by sport was as follows: rugby ($n=20$), ultimate frisbee ($n=7$), lacrosse ($n=5$), soccer ($n=5$), ice hockey ($n=4$), and other sports ($n=9$). The breakdown of athletes by sport and group was as follows: with previous concussions, rugby ($n=14$), lacrosse ($n=3$), soccer ($n=3$), ice hockey ($n=2$), ultimate frisbee ($n=1$), and other sports ($n=3$); without previous concussions, ultimate frisbee ($n=6$), rugby ($n=6$), lacrosse ($n=2$), soccer ($n=2$), ice hockey ($n=2$), and other sports ($n=6$). Within the concussion group, 15 (57.7%) participants reported a history of 1-2 concussions, while 11 (42.3%) reported a history of 3+ concussions. Exclusionary criteria included the presence of existing or prior learning disabilities diagnoses, ADHD, and other serious neurological issues. None of the participants reported failing any prior baseline concussion assessment administered during their sports career. Participants provided written informed consent before beginning the study. As an incentive, participants received \$10 monetary compensation for their time. To encourage participants to give their best effort on the cognitive assessment battery, the participant with the highest overall performance on each task received a \$25 gift card once data analysis was concluded.

Experimental procedure

Following the acquisition of informed consent, participants were seated in front of a computer in a supervised laboratory setting and asked to complete an online self-report survey and a computerized cognitive assessment battery. On the survey, participants have answered questions about their demographics (SES, age, etc.), history of sports experience, history of academic performance, and history of concussion (see Appendix for more). Following the survey, participants completed three cognitive tests. They first completed the working memory test followed by the response inhibition test in the decision-making test. Participants received a short break between tasks. The temporal sequence of events was designed to minimize fatigue, a commonly reported symptom of concussion, and prevent participant burnout. Total testing time for the survey and three cognitive tests was approximately xx minute.

Stimuli

The three cognitive tests were written using MATLAB (The Mathworks, Inc.) and the Psychophysics Toolbox [25-27]. To assess working memory, the first computer-based test completed by participants was a modified Paced Visual Serial Addition Test (PVSAT), a computer-based task designed to assess working memory. This paradigm combined previous modifications introduced to the Paced Auditory Serial Addition Test (PASAT) [17,18]. The digits ranged from 1-9 and appeared in a black font in the center of the all-white screen. Each stimulus was presented for 600 ms, and participants were given 1.5 seconds to respond (Figure 1A). Participants were asked to decide whether pairs of visually presented single-digit stimuli did

(Figure 1A (a)) or did not (Figure 1A (b)) sum to exactly 10. Prior to the experiment portion, a researcher verbally explained the instructions, and participants were given an opportunity to practice the task until they reported that they understood how to perform it. During the experimental portion, each participant completed a total of 120 trials across two blocks. Participants' mean response time, mean accuracy, and the number of perseverative errors (defined as reaction times faster than 100 ms) was recorded for further analysis.

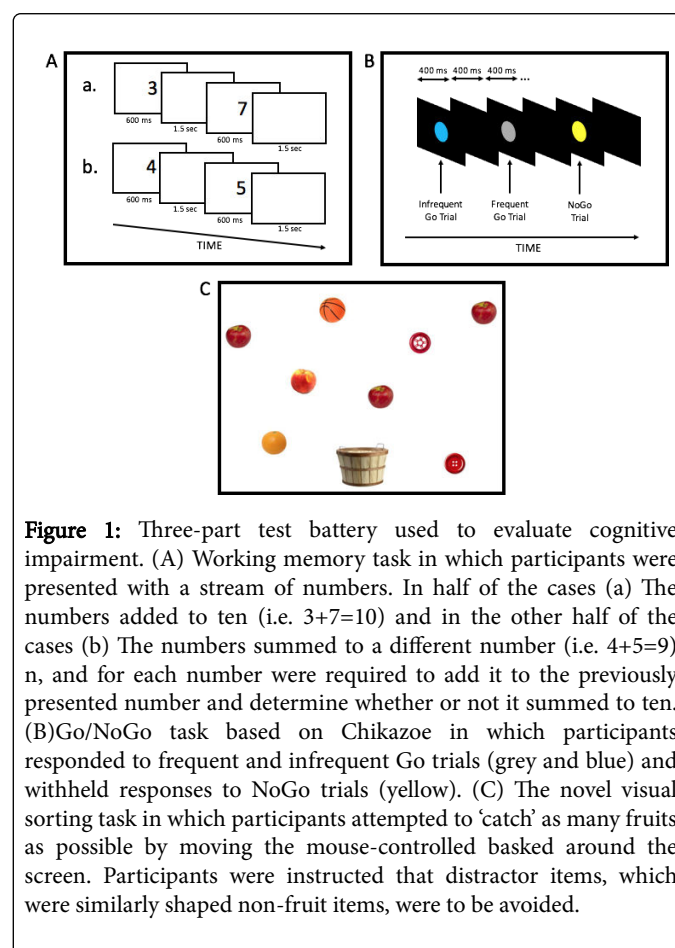


Figure 1: Three-part test battery used to evaluate cognitive impairment. (A) Working memory task in which participants were presented with a stream of numbers. In half of the cases (a) The numbers added to ten (i.e. $3+7=10$) and in the other half of the cases (b) The numbers summed to a different number (i.e. $4+5=9$), and for each number were required to add it to the previously presented number and determine whether or not it summed to ten. (B) Go/NoGo task based on Chikazoe in which participants responded to frequent and infrequent Go trials (grey and blue) and withheld responses to NoGo trials (yellow). (C) The novel visual sorting task in which participants attempted to 'catch' as many fruits as possible by moving the mouse-controlled basket around the screen. Participants were instructed that distractor items, which were similarly shaped non-fruit items, were to be avoided.

The second test was a response inhibition task designed to assess participants' impulsivity and the phenomenon of perseverations. The Go/NoGo task used in the current experiment was based on the task of Chikazoe et al. [22]. This task involved visually presentation of a colored circle on an all-white background. Participants responded by pressing the '1' button with their right index finger each time a "Go"/gray or "rare-Go"/yellow stimulus appeared (Figure 1B). Participants were instructed to withhold this response in the case of an infrequent "NoGo"/blue trial. Stimuli appeared for 400 ms each, with an interval of 500 ms, and participants had 1 second to respond. The gray/"Go" trials appeared in 75% of the trials, while the yellow/"rare-Go" and blue/"NoGo" trials each appeared in 12.5% of the trials. Following instructions and practice sufficient to ensure they understood the task, participants completed 200 trials of the Go/NoGo task, split evenly across two blocks. Mean accuracy, as well as the number of perseverative responses, and the number of failures to respond were recorded for later analysis.

The final test assessed participants' decision-making skills and discrimination strategies using a novel, custom-built visual sorting task. Participants used a mouse to move an onscreen "basket" in order to "catch" falling apples while avoiding five other equally salient falling distractors (two fruits—a peach and an orange, and three unrelated objects—a basketball, a red wheel, and a red button) (Figure 1C). Each individual target item (both targets and distractors) moved vertically (downwards) at a rate of 12-16 pixels/frame (at 60 fps). As with the working memory task, participants were provided with comprehensive instructions, and practice sufficiently to ensure they understood the task prior to beginning the collection of data. Total accuracy, number of targets hit and target accuracy (calculated as the number of targets hit/the number of targets seen) were saved for later analysis.

Data analysis

Data were analyzed using IBM Statistical Package for Social Science Version 23.0 software program (IBM SPSS version 23). Reaction time and accuracy measures for each task were separated by condition and compared using independent t-tests and/or Pearson correlations.

Results

Working memory task

For the working memory task, it was predicted that the concussion group would perform significantly worse than the control group, evidenced by lower accuracies, slower reaction times, and a higher number of perseverations. While our initial data analysis revealed lower performance trends among the concussion group compared to the control group, the differences were not statistically different. Total accuracy for this task was calculated as the number of trials with correct responses out of the number of total trials, and the comparison of previously concussed participants ($M=82.53\%$, $SD=9.20\%$) to control participants ($M=86.13\%$, $SD=0.06\%$) was not statistically significant, $t(48)=1.60$, $p=0.06$. When comparing the two groups, the reaction times in the concussion group ($M=568$ ms, $SD=12$ ms) were also not significantly slower than those in the control group ($M=514$ ms, $SD=10$ ms), $t(48)=-1.68$, $p>0.05$. While not significant, the concussion group ($M=1.04$, $SD=2.03$) made somewhat more perseveration errors than the control group ($M=0.4$, $SD=0.91$), $t(48)=-1.29$, $p=0.08$.

In order to assess deficits in the automatic processing in the concussion group, the working memory trials were separated into automatic (numbers summed to 10) and non-automatic (numbers summed to a number other than 10) trials. Paired t-tests revealed that both the concussion, $t(24)=-6.38$, $p<0.001$, and control group, $t(24)=-6.45$, $p<0.001$, were significantly faster when responding to stimulus pairs that summed to 10 compared to stimulus pairs that did not sum to 10. Similarly, on trials where numeric stimuli did not sum to 10, the accuracy of the concussion group ($M=85.60\%$, $SD=9.78\%$) was significantly lower than the accuracy of the control group ($M=91.27\%$, $SD=4.84\%$), $t(49)=2.60$, $p<0.05$. This phenomenon did not occur on the trials where the stimuli did sum to 10, $t(49)=0.59$, $p=0.29$. With regards to RT, times on trials in which numeric stimuli summed to 10 were not significantly different in the control ($M=481$ ms, $SD=109$ ms) and concussion groups ($M=536$ ms, $SD=125$ ms), $t(48)=-1.63$, $p=0.55$. In general, athletes with a history of concussion did respond slower ($M=601$ ms, $SD=129$ ms) on trials in which the numbers did not sum to 10, than did athletes without a history of concussion ($M=537$ ms, $SD=116$ ms), $t(48)=-1.83$, $p<0.05$.

Go/NoGo task

Performance on the Go/NoGo task was expected to be worse in the concussion group as compared to the controls. The concussion group was expected to display lower overall accuracies, higher numbers of perseverative responses, and a higher number of responses to non-targets (NoGo trials). As with the working memory task, total accuracy was calculated using the number of trials with correct responses out of the number of total trials. As expected, the overall accuracy of previously concussed participants ($M=95.88\%$, $SD=2.85\%$) was not significantly lower than that of the control participants ($M=96.56\%$, $SD=3.28\%$), $t(48)=0.78$, $p=0.22$. We did not observe a significant difference between perseverations in the concussion group ($M=1.04$, $SD=3.38$) and the control group ($M=0.16$, $SD=0.47$), $t(48)=-1.29$, $p=0.10$. Participants in the concussion group were not less likely to respond to trials in which a response was required, $t(48)=-1.12$, $p=0.14$, and were not less able to inhibit their responses on NoGo trials than participants in the control group, $t(48)=-1.75$, $p=0.06$.

Visual sorting task

It was predicted that the concussion group would demonstrate lower performance scores through lower total accuracies, fewer targets hit and lower target accuracies (calculated as the number of targets hit/the number of targets seen). In terms of overall accuracy, the concussion group ($M=72.52\%$, $SD=10.85\%$) did not differ from the control group ($M=74.04\%$, $SD=7.49\%$), $t(48)=0.88$, $p=0.19$. Target accuracy was not significantly different in the concussion ($M=68.53\%$, $SD=9.76\%$) and control ($M=71.01\%$, $SD=6.73\%$) groups, $t(48)=1.05$, $p=0.15$. A comparison of the number of targets hit failed to reveal statistically superior performance in the concussion group ($M=146.76$, $SD=24.51$) as compared to the control group ($M=156.04$, $SD=17.85$), $t(48)=1.53$, $p=0.07$. Further analysis revealed that control group participants were presented with a greater number of total stimuli during their testing session ($M=588.04$, $SD=17.39$) than were concussion group participants ($M=571.56$, $SD=15.66$), $t(48)=3.52$, $p<0.01$. This, in turn, led to the control group being shown more targets ($M=208.32$, $SD=6.56$) than the concussion group ($M=201.88$, $SD=5.45$), $t(48)=3.78$, $p<0.001$. While not intended as an index of cognitive performance, this measure may have captured a unique difference between the two groups, as the number of stimuli shown was directly dependent on the number of objects hit by participants.

Cognitive impairment-based concussion classification

Since there were some significant differences between the concussion and non-concussion groups, we decided to examine the ability of our cognitive battery to differentiate between individuals with and without a prior history of concussion by performing a binary logistic regression. Prior to conducting this analysis, an exploratory factor analysis (principal components analysis) was completed to check for clustering in the dependent variables. The following dependent variables were derived from the cognitive task battery and entered into the model: Working Memory Task (overall accuracy, reaction time, number of perseverative errors); Go/NoGo (overall accuracy, reaction time, number of perseverative errors, number of targets missed, number of erroneous presses); Visual Sorting Task (overall accuracy (targets hit/total number objects hit), target accuracy (targets hit/targets seen), the number of targets hit, the total number of stimuli shown and the total number of targets shown). Initial eigenvalues indicated that the first five factors explained 31%, 18%, 15%, 9%, 7% and 5% of the variance respectively (~80% total). The first factor

loaded on data derived from the Visual Sorting Task (overall accuracy, target accuracy, number of targets hit). The second factor loaded on the five Go/NoGo variables (with the exception of the total number of erroneous presses). The third factor loaded on the Visual Sorting Task variables of total stimuli and total targets are shown. The fourth factor loaded on the three Working Memory Task variables, as well as target accuracy in the Visual Sorting Task. Finally, the fifth eigenvalue loaded on the number of erroneous presses in the Go/NoGo task. After examining this model using both varimax and oblimin rotations, the varimax rotation was chosen since there was little difference between the two solutions.

In order to examine the ability of the results from our cognitive tests to classify an individual's prior history of concussion, we conducted a standard binary logistic regression was performed entering all variables (i.e. the five factors identified by the factor analysis described above) at the same time. This model was significant $X^2(5)=20.96$, $p<0.005$, and the model correctly classified 80% of participants. More specifically, it was able to correctly classify 21 out of 25 concussion participants (84% accuracy) and 19 out of 25 control participants (76% accuracy) were correctly classified.

The final analysis examined the relationship between the five factors identified in our factor analysis and the number of concussions an athlete had suffered. All five of the principle factors identified in the first steps (described above) were entered into a stepwise linear regression model designed to predict the number of prior concussions an athlete had suffered. This model was statistically significant, $F(1.23)=6.29$, $p<0.05$, suggesting a relationship between the previously identified factors and the number of concussions experienced by athletes with a history of concussion. Inspection of the results revealed that the model included Factor 2, and excluded Factors 1, 3, 4 and 5, suggesting that the number of prior concussions was primarily related to Factor 2 which, as noted above, was based on the five Go/NoGo variables (with the exception of the total number of erroneous presses). This model accounted for a significant portion of the variability ($r=0.46$, $p<0.05$) observed in the number of concussions in the subset of our concussed participants.

Discussion

The purpose of the present study was to investigate the hypothesis that concussion impairs cognitive performance, and that the severity of this impairment would be directly related to the number of reported prior concussions. In order to address these questions, we examined performance on working memory, response inhibition and decision-making tasks were examined in a sample of 50 healthy college athletes, 25 of which did not have a history of concussion and 25 of which had a history of one or more concussions. Data analysis indicated that athletes with a history of concussion performed significantly worse on working memory, especially when required to process non-automatic stimuli and response inhibition tasks. Athletes with a history of concussion tended to perform worse than non-concussed athletes on a novel visual sorting task designed to assess decision-making ability. Based on the data obtained from the three-part cognitive battery, 80% of the participants were classified correctly. Finally, the number of concussions was inversely related to scores on cognitive measures related to impulse control. Taken together, results of this study suggest that concussions have a negative impact on cognitive performance and that some aspects of cognitive impairment scale with the number of concussions an athlete has suffered.

Working memory task

Based on prior research in individuals with mTBI [28-34], it was predicted that athletes with a history of concussion would be less accurate, slower to respond and make a larger number of perseverative errors on the working memory task when compared to the control group. While the differences were not statistically significant, athletes with a prior history of concussion were slightly less accurate, made a marginally higher number of perseverative errors and evinced somewhat slower overall reaction times than their non-concussed controls. Interestingly, athletes with a history of concussion responded more slowly and made more errors on trials in which numerical stimuli did not sum to 10 (i.e. the effect was not present for trials in which the numerical stimuli summed to 10). Arguably, trials in which target numbers summed to 10 (e.g. 6,4) could have been processed differently than trials in which target numbers summed to less common numbers like 9 (e.g. 7,2) or 11 (e.g. 4,7). It is possible that the participants had more experience summing numbers to 10, and that this task was done more 'automatically,' and with less difficulty, than adding numbers with different totals. This is supported by the finding that participants from both groups responded faster to trials in which numbers summed to 10. One possible explanation for the results is that whereas automatic processing is relatively preserved in concussed participants, 'non-automatic processing' more clearly demonstrates impairments after a concussion as compared to automatic processing.

Indeed, there is evidence to support the idea that automatic processing is impaired, at least directly following a concussion. For example, many athletes report symptoms of confusion and "feeling foggy" after a concussion and cite the necessity for higher levels of cognitive effort to perform tasks that are normally easily accomplished [2,3]. Other research suggests that some of the negative effects of concussion are modulated by task complexity [35,36]. The impact of concussions on non-automatic processing could manifest in difficulties with tasks of daily living, including doing laundry, driving, and buying groceries. If the deficits were shown to be cumulative, they could inhibit people with a history of multiple concussions from properly functioning in their jobs, homes, and relationships.

Go/NoGo task performance

Based on prior research indicating that cognitive control and response inhibition are impaired in concussed athletes [33,34,37-39], it was predicted that the concussion group would exhibit a higher number of responses to non-targets (the "NoGo" trials), lower overall accuracies, and a higher number of perseverative or anticipatory responses (i.e. responses under 100 ms). While previously concussed athletes demonstrated lower overall accuracy, a higher number of perseverative responses, and a higher frequency of responding incorrectly to non-targets and failing to respond to targets than the control group, these trends did not reach statistical significance.

While between-group comparisons were not significant for any of the dependent variables derived from the Go/NoGo task, an exploratory factor analysis identified a single factor that was primarily based on these dependent variables, and this factor was significantly correlated with the number of prior concussions experienced by individuals in the concussion group. This finding suggests that the ability of a given measure to predict whether someone has or has not had a prior concussion (i.e. concussion history) is not necessarily the same as its ability to predict the number of prior concussions an

individual has suffered. Researchers should keep this in mind when evaluating the potential of novel cognitive assessments.

Visual sorting task performance

Based on reports of impaired decision-making in concussed populations [33,39-43], it was expected that the concussion group to likewise show impairments in our novel computer-based visual sorting task. While there was a trend toward worse decision-making in the concussed group, results of the analyses failed to reach statistical significance. Specifically, there were trends toward lower overall accuracy, lower target accuracy, and a lower overall number of targets hit in the concussed group. Further analysis indicated a significant difference in the number of targets seen by the concussion group compared to the control group. Due to the nature of the program, as more targets were hit, it caused them to vanish, rather than letting them disappear off the bottom of the screen and prompted the program to present new target stimuli. The majority of concussion assessments contain a fixed number of stimuli, and this number does not vary as a function of the testee's response speed. Our data suggest that such programs may be missing out on important data and that programs designed to present more stimuli for faster responders could be used to differentiate between individuals with and without a history of concussion. Further research might explore this possibility.

Cognitive battery-based classification of concussed athletes

While the majority of prior concussion classification research has focused on the ability to identify concussions in the acute stage based on classic post-concussive anomalies [44-47], fewer studies have examined the ability of cognitive tests to accurately classify individual history of concussion. Factor analysis of the data obtained from our custom cognitive battery identified five major factors (eigenvalues > 1). Consideration of these five factors facilitated a model to identify individual athletes with and without a history of concussion with a high degree of sensitivity and specificity. Using five factors derived from the dependent variables measured during our 40-minute cognitive battery, 80% of the participants in this study were correctly classified. It is worth noting that our primary data analysis revealed a few highly significant differences between concussed and non-concussed groups. Although none of the predictor variables, used alone, were able to correctly classify participants with great accuracy, it is somewhat surprising that the combination of predictors resulted in an accurate classification model. These findings suggest that individual results from cognitive batteries designed to assess acute effects of a concussion may not be as useful as combined scores such as those derived from factor analysis of many different variables. These results are in line with the general consensus that multidimensional approaches to concussion assessment are better able to correctly identify individuals with a history of concussion than are single tests [48,49], and additionally suggest that this approach is preferable for the identification of concussion.

Cognitive effects of multiple concussions

Based on prior data demonstrating inferior performance in college athletes that had suffered two or more concussions as compared to athletes that had experienced a single concussion [3,6], it was predicted that cognitive performance in the current study would vary as a function of the self-reported number of prior concussions. Results indicated an association between one of the factors identified with a factor analysis and a number of prior concussions. Specifically, we

report that participants with a higher number of prior concussions tended to perform worse on a cluster of tests dealing with response inhibition, i.e. dependent variables measured in the Go/NoGo task.

This finding is particularly interesting in light of available evidence suggesting a relationship between frontal trauma and impulse control in general. For example, one study reported that performance on a modified flanker task designed to measure cognitive control was worse in individuals with a history of concussion and the magnitude of this impairment was positively correlated with a number of prior concussions [50]. While another study did not find a significant relationship between a number of concussions and cognitive performance using a multidimensional approach, this failure may be due to their choice of statistical analysis [51]. Specifically, they chose to conduct ANOVAs for each outcome variable rather than first conducting a factor analysis on all of their data to establish predictive clusters of data. In general, the results of this study are consistent with prior findings and demonstrate a coupling between cognitive performance and the number of prior concussions in an otherwise healthy population of collegiate athletes [52,53].

Limitations and Future Directions

An obvious weakness of the present study is its relatively small sample size, and visible trends within the present sample may well have reached significance with a larger sample. Another potential weakness is that concussion history was based solely on self-report data. Therefore, the number and severity (grade) of concussions, the time between injuries, and elapsed time before returning to play could not be verified or properly analyzed. These first two limitations could have reduced statistical power and lead to an inability to detect true differences between concussed and non-concussed athletes. Finally, as all participants performed the tests in the same order, and fatigue may have become an issue during the latter tests, we cannot rule out the possibility that differences in stamina between the two groups could be responsible for some of the observed differences. Future studies should recruit larger sample sizes and counterbalance conditions to counteract potential testing effects. As more pilot studies indicate the devastating effects of a concussion(s) on cognitive performance, they will pave the way for more in-depth research in the field.

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