Working memory capacity among collegiate student athletes: Effects of sport-related head contacts, concussions, and working memory demands

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Objective: To measure working memory capacity among a cohort of collegiate athletes and to compare results between athletes competing in head-contact-prone sports with those not subject to repeated head contacts. A secondary objective was to determine the effect of sport-related concussion on working memory capacity. Design: Ambidirectional cohort study. Setting: Athletics department at an American university. Participants: Student athletes competing in various sports. Interventions: None. Main outcome measurement: Automated operation span test scores. Results: Working memory capacity is not impaired in student athletes who participate in head-contact-prone sports or in student athletes with a history of diagnosed concussion, even those who are multiconcussed. Our results suggest that athletes competing in sports that impose significant working memory loading score higher on the automated operation span test than do other athletes. Conclusions: Further research is required to determine the value of measuring working memory capacity in acutely concussed, symptomatic athletes.

Keywords: Athlete; Working memory capacity; Neurocognitive tests; Brain injury; Concussion.

INTRODUCTION

Working memory capacity (WMC) is essential for important cognitive abilities including reasoning, comprehension and problem solving (Engle, 2002). Neuroimaging studies have shown that working memory (WM) is processed within the brain’s prefrontal cortex (Kane & Engle, 2002). Research demonstrates that development of WM in childhood is important for development of cognitive abilities (Alloway et al., 2005) while WMC declines may occur in at-risk individuals during the preclinical stages of Alzheimer’s disease (Rosen, Bergeson, Putnam, Harwell, & Sunderland, 2002). Although WMC is related to short-term memory capacity, WMC in addition reflects general “executive attention” ensuring that memory is maintained in spite of interference or distractions. This ability enables controlled attention capability in situations involving distraction during memory and cognitive control tasks (Engle, 2002).

We hypothesize that WM is important for athletic performance. The necessity for athletes to maintain task-relevant information during distracting events on the playing field is obvious, both for optimal performance and for physical safety. A recent review (Mayers, 2008) showed that recently concussed individuals (athletes and nonathletes) demonstrate cerebral dysfunction despite exhibiting normal WMC performance. For example, functional magnetic resonance imaging (fMRI) studies in concussed athletes have shown reduced task-related activation of the prefrontal cortex in symptomatic concussed
athletes while performing a probe-recognition task (Chen, Johnston, Collie, McCrorry, & Ptito, 2007; Chen et al., 2004). McAllister et al. (2001) found no impairment in back performance among non-athletic-related mild traumatic brain injury (mTBI) patients utilizing fMRI, especially with increasing processing loads. However, Smits et al. (2009) observed both decreased n-back performance and increased activation in relation to WM load in mTBI patients with “recruitment of brain areas outside the WM network in the prefrontal cortex (posterior parietal, parahippocampal gyrus and posterior cingulate gyrus areas) at high processing loads” (Smits et al., 2009, p. 2789). Finally, Jantzen, Anderson, Steinberg and Kelso (2004) administered the digit span to football players preseason and again within a week of suffering a concussion. They observed no change in digit span performance but larger increases of fMRI activity during task performance than that seen in nonconcussed athletes. Shuttleworth-Edwards and Whitefield (2007) have emphasized the individual and societal implications of subtle neurocognitive impairments (concentration, learning, and information processing) resulting from mTBI that may go unacknowledged but result in learning difficulties.

One possibility that emerges from this brief review is that the WMC tasks used in these studies were not sensitive to mTBI. In the current study, we have utilized a WMC measure that has been used extensively in the cognitive literature with published psychometric properties. Unsworth et al. recently developed an automated operation span (AOSPAN) test of WMC task capability (Unsworth, Heitz, Schrock, & Engle, 2005). Administered on a computer and mouse driven, AOSPAN (a) has high internal consistency (Cronbach’s alpha = .78) and test–retest reliability (r = .83), (b) is scored quickly and automatically, and (c) requires little investigator time or intervention. AOSPAN may be downloaded without charge through the Georgia Tech School of Psychology website (http://psychology.gatech.edu/rengelab, retrieved November 18, 2010). This instrument presents a subject with a series of simple mathematical problems that, when solved, generate a brief presentation of a letter on the computer screen. After a sequence of math problems resulting in a series of letters presented, the subject must correctly submit the viewed letters in order. In contrast to the digit span, AOSPAN is assumed to measure WMC because the test participant must alternate between the math and memory portions of the task. The score is the number of letters recalled in the correct order across all trials. Higher scores indicate better WMC.

Studies of concussion effects in athletes have used a variety of methods. One approach is to perform baseline tests on all athletes and to compare these with retest scores of athletes who do or do not suffer a concussion during the season (e.g., Jantzen et al., 2004). These studies, however, typically have small sample sizes. A different approach, undertaken in the current study, was to investigate the possible relationship between a history of and/or propensity to athletic concussion and to relate this to current WMC function.

In view of the substantial incidence of athletic concussions (Klossner, 2008), the reported short-term attentional (van Donkelaar, Osternig, & Chou, 2006) and long-term (Guskiewicz et al., 2005) memory disorders described among concussed athletes and issues of resulting subtle neurocognitive disability (Shuttleworth-Edwards & Whitefield, 2007), we have utilized AOSPAN to compare WMC between the following groups:

1. Student athletes competing in head-contact-prone sports (football, soccer)—HC cohort.
2. Student athletes competing in non-head-contact-prone sports (baseball, softball, volleyball, swimming, and track)—NHC cohort.
3. Nonathlete students—NA cohort.

We addressed several questions in this study. First, athletes competing in sports involving frequent head contacts might be more likely to show diminished WMC. We compared the scores in the HC and NHC groups to answer this question. Second, to assess the possible effect of past sport-related head injuries upon current WMC, we collected information concerning history of diagnosed concussions from our study participants and compared concussed athletes (C) with nonconcussed athletes (NC). Third, previous research indicates that skilled, experienced athletes in certain sports exhibit superior memory abilities compared to those with lesser skill and experience (Starkes & Ericsson, 2003; but see also Furley & Memmert, 2010). While WMC is utilized during virtually all human activity, football and volleyball as played at the collegiate level demand a higher level of WM processing than most other sports. During football and volleyball competitions, coded verbal signals are “called” during each offensive and defensive sequence and may be changed instantaneously. A mistake in performing the proper movements or positioning in accordance with the called play results in failure of the team effort. Otherwise talented players with impaired WMC are less able to compete effectively. We grouped the athletes according to the WMC requirements of their sports and compared their AOSPAN scores.

**METHOD**

**Subjects**

Student athletes (n = 106) were recruited during team meetings, during which the purposes of the study were explained. They voluntarily reported to the campus computer center for group testing. Nonathlete students (n = 42) were tested as part of an unrelated study. Subjects signed an informed consent and recorded their age to the nearest year, gender, sport with years of participation, and history and year(s) of prior diagnosed concussion(s).

**Testing**

The self-administered AOSPAN test was completed utilizing preloaded desktop computers in a quiet room...
RESULTS

Initial analyses indicated that there were nonsignificant (all \( p > .31 \)) gender differences on AOSPAN scores among all groups (NA, NHC, and HC).

AOSPAN test scores by subgroups and teams are shown in Table 1. First, we compared the scores for our cohort with those reported from the validation study of 252 young adults (Unsworth et al., 2005). The NA (\( n = 42 \)) scores measured at our institution were virtually identical with those reported in that study. A one-sample \( t \) test demonstrated that our combined sample was not significantly different from the norms reported by Unsworth. Next, we compared test scores between our NA and athlete (\( n = 105 \)) samples and observed the difference between these two groups of college students to be nonsignificant, \( F (1, 145) = 0.04, MSE = 312.13, p = .84 \). We next compared AOSPAN scores between the head-contact-prone athletes and the non-head-contact-prone athletes. As shown in Table 1, there were no significant differences, \( F(1, 103) = 0.99, MSE = 327.80, p = .32 \).

Among our HC cohort, 5 of 13 soccer players (38%) had a history of diagnosed concussions (total of 10 episodes), and 16 of 50 football players (32%) had experienced concussion(s) (total of 22 episodes). Among the NHC sports cohort, 2 baseball players had a history of diagnosed concussion, both incurred while playing high-school football. We therefore had 23 athletes in the C cohort versus 82 in the NC cohort. Most of the reported concussive episodes had occurred 1–5 years prior to our study. As shown in Table 2, AOSPAN scores between C and NC athletes did not differ significantly, \( F(1, 103) = 1.05, MSE = 327.63, p = .31 \).

During data acquisition for this study, 3 athletes sustained concussions. A football player (Athlete 1) was tested 25 days after his injury having been symptomatic for 3 days and returned to play in 12. A soccer player (Athlete 2) was tested 2 days after her injury while still symptomatic with headache, "pressure in head," nausea, sleep disturbance, balance issues, and "feeling as if in a fog." She was symptomatic for 6 days and returned to play in 13. She was retested 6 weeks later and demonstrated a marked improvement. A second soccer player (No. 3) was tested and sustained a concussion 2 days later. She was retested 8 days postinjury at which time her symptoms had just resolved. Her score was unchanged. Test scores for these athletes are shown in Table 2. The results in this very small cohort of recently concussed athletes suggest that WM normalizes postconcussion and, in the case of Athlete 3, in close proximity with symptomatic recovery.

Six of our C cohort athletes were multiconcussed having sustained two or more diagnosed concussions from 12 years to 6 months prior to testing. Their AOSPAN test scores are shown in Table 3. These results are skewed by the single outlier whose score was the lowest among all of our subjects. In spite of her inclusion, the WMC mean score for this group was well above average.

Finally, as outlined in the Introduction, we examined a secondary hypothesis that WMC demands during

### TABLE 1

<table>
<thead>
<tr>
<th>Group</th>
<th>( n )</th>
<th>Gender (m/f)</th>
<th>AOSPAN M (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonathletes</td>
<td>42</td>
<td>11/31</td>
<td>38.4 (16.5)</td>
</tr>
<tr>
<td>Athletes</td>
<td>105</td>
<td>68/37</td>
<td>39.1 (18.1)</td>
</tr>
<tr>
<td>Head contact</td>
<td>62</td>
<td>50/12</td>
<td>40.5 (17.7)</td>
</tr>
<tr>
<td>No head contact</td>
<td>43</td>
<td>17/26</td>
<td>37.0 (18.7)</td>
</tr>
<tr>
<td>Concussion(^a)</td>
<td>23</td>
<td>17/6</td>
<td>42.5 (19.4)</td>
</tr>
<tr>
<td>No concussion(^b)</td>
<td>82</td>
<td>51/31</td>
<td>38.1 (17.7)</td>
</tr>
<tr>
<td>High WM demand(^c)</td>
<td>62</td>
<td>50/12</td>
<td>42.9 (15.9)</td>
</tr>
<tr>
<td>Low WM demand(^d)</td>
<td>43</td>
<td>17/26</td>
<td>33.6 (19.8)</td>
</tr>
<tr>
<td>Football(^a)^(^c)</td>
<td>50</td>
<td>50/0</td>
<td>42.0 (16.1)</td>
</tr>
<tr>
<td>Soccer(^a)^(^d)</td>
<td>12</td>
<td>0/12</td>
<td>34.4 (22.8)</td>
</tr>
<tr>
<td>Volleyball(^b)^(^c)</td>
<td>12</td>
<td>0/12</td>
<td>46.6 (14.8)</td>
</tr>
<tr>
<td>Baseball(^b)^(^d)</td>
<td>16</td>
<td>16/0</td>
<td>36.4 (22.4)</td>
</tr>
<tr>
<td>Softball(^b)^(^d)</td>
<td>9</td>
<td>0/9</td>
<td>32.6 (15.4)</td>
</tr>
<tr>
<td>Swimming(^b)^(^d)</td>
<td>5</td>
<td>0/5</td>
<td>21.4 (8.2)</td>
</tr>
<tr>
<td>Track(^b)^(^d)</td>
<td>1</td>
<td>1/0</td>
<td>48.0 (–)</td>
</tr>
</tbody>
</table>

Note. AOSPAN = automated operation span; WM = working memory; M = mean; m = male; f = female. 
\(^a\)Concussion. \(^b\)No concussion. \(^c\)High WM demand. \(^d\)Low WM demand.
game play would relate to the athletes’ AOSPAN scores. We therefore compared combined mean AOSPAN scores (42.9) from athletes competing in sports with high WM demands (62 football and volleyball players) with the rest of our 43 athletes competing in sports estimated to require lower WM demands (33.6). The difference was significant, $F(1, 103) = 7.14$, $MSE = 309.50$, $p < .01$. When compared with our low WM requirement NA cohort, the difference was in the predicted direction but not statistically significant, $F(1, 102) = 1.91$, $MSE = 260.24$, $p = .17$.

Note that the significant difference in AOSPAN scores between the high- and low-WM athletes did not result from selection bias or overall difference in cognitive ability. We compared the two WM-demand groups and found no differences in their SAT (Scholastic Aptitude Test) scores (Verbal/Quantitative/Total). SAT scores for the high-WM-demand group were 518/543/1,061 and for the low-WM-demand group were 520/541/1,061.

### DISCUSSION

We assessed whether or not WM might be impaired by athletic exposure to multiple head impacts as Shuttleworth-Edwards (Shuttleworth-Edwards & Radloff, 2008) and others (Collins et al., 1999; Matser, Kessels, Lezak, Jordan, & Troost, 1999; Thornton, Cox, Whitfield, & Fouladi, 2008) have suggested that subtle neurocognitive dysfunction occurs in rugby, football, and soccer athletes. We utilized AOSPAN because it was a validated and reliable test of WM, available for download without cost, could be self-administered and immediately scored by computer, was amenable to group testing, and required little investigator time and effort.

There were no significant test score differences between our HC and NHC and/or NA cohorts. We interpret this to indicate that no lasting impairment of WM results simply from participation in football or soccer. Although our HC athletes were young (mean age 19.7 years), they had played their sports for a mean ($SD$) of 10.2 (3.2) years. In addition, 21 of these 63 athletes (33%) had experienced a total of 33 diagnosed concussions so that their mTBI exposure is established.

One may ask why WM measured with a validated test instrument is apparently unaffected by mTBI? There are several possible explanations for our findings:

1. Most of our subjects were studied months to years after sustaining their brain injuries. This interval may have allowed for substantial healing and/or remodeling of injured neural tracts.
2. The subjects in our study cohort were volunteers. It is possible that athletes who perceived memory impairments elected not to participate fearing some consequence resulting from identification of their disorder.
3. The majority of our HC and concussed cohorts were football players. As noted above, this sport may select for individuals with enhanced WMC thereby masking any effect resulting from injury.
4. Our findings may reflect idiosyncratic characteristics relating to the particular cohort that we studied.

Although we theorized that AOSPAN might be useful for neurocognitive assessment for return to play following concussion, our study was not designed to address this issue since we were unable to test a large enough acutely concussed cohort. By chance, however, 3 of the athletes that we tested suffered concussive episodes during our data collection period. While these few outcomes do not permit firm conclusions, they do suggest that no long-term impairment of WM results from a single concussive episode (see Table 3). However, in accord with the results of other neurocognitive test instruments (e.g., ImPACT), we did find that AOSPAN was impaired in the one athlete who was still symptomatic when first tested (Athlete 2 in Table 2). After her symptoms resolved, she was restested 39 days later, and her score improved by 42 points. According to the norms established by Unsworth et al. (2005), this corresponds to an improvement of 2.4 standard deviations, changing her classification from low WMC to high WMC. This degree of change is unexpected since the published test–retest reliability of AOSPAN is $r = .83$. Therefore this is at least preliminary evidence that WMC, like other cognitive abilities, is temporarily impaired during the symptomatic period postconcussion. Future work with a larger cohort of concussed athletes will be required to determine whether AOSPAN can serve as a convenient and inexpensive tool to assess return-to-play readiness after injury.

Intact WMC with head contact sport participation or history of prior concussions is supported by the normal AOSPAN results measured in our small cohort of multiconcussed athletes although the distinctly low score in one subject might indicate individual susceptibility to impairment. This is speculative although a matter of concern. Although the multiconcussed group was small, similar findings utilizing the ImPACT concussion assessment instrument have been reported by Solomon and Haase (2008), Broglio, Ferrara, Piland, Anderson, and Collie (2006), and Iverson, Brooks, Lovell, and Collins (2006). Importantly, AOSPAN measures the specific psychological construct of executive attention (Engle, 2002) while ImPACT assesses multiple neurocognitive

### TABLE 3

<table>
<thead>
<tr>
<th>Sport</th>
<th>Gender</th>
<th>No. prior concussions</th>
<th>AOSPAN score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soccer</td>
<td>F</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Soccer</td>
<td>F</td>
<td>4</td>
<td>62</td>
</tr>
<tr>
<td>Football</td>
<td>M</td>
<td>3</td>
<td>38</td>
</tr>
<tr>
<td>Football</td>
<td>M</td>
<td>2</td>
<td>64</td>
</tr>
<tr>
<td>Football</td>
<td>M</td>
<td>3</td>
<td>62</td>
</tr>
<tr>
<td>Football</td>
<td>M</td>
<td>2</td>
<td>69</td>
</tr>
</tbody>
</table>

Mean ($SD$) 45.2 (26.4)

Note. AOSPAN = automated operation span. M = male; F = female.
domains including verbal and spatial recognition memory, visual working memory, verbal working memory, impulse inhibition, and visual motor speed. Although Shuttleworth-Edwards and Radloff (2008) have reported subtle sport-related dysfunction in visuomotor processing speed assessed with Digit Symbol and Trail Making tests, and Halterman at al. (2006) identified deficits in executive components of visuospatial attention a month following concussion, these affected areas may be “diluted” by normal results in the other multiple domains assessed by ImPACT and therefore may not be detected by this assessment instrument. Future research is necessary to pinpoint the most salient cognitive constructs that might identify cumulative neurocognitive impairment.

Such impairment, possibly involving other memory domains and genetic susceptibility, may occur (Terrell et al., 2008). This is suggested by our finding of significant self- and family-reported short-term memory impairment among several of our former concussed athletes and recent reports of memory impairment in retired professional football players (Guskiewicz et al., 2005). Our athletes’ mean age, 19.3 years, suggests the possibility that their competitive experience was too brief to produce detectable neurocognitive deficits. However, our HC cohort reported a mean (SD) of 10.3 (3.2) years of participation in their sports; this issue remains unresolved.

An interesting aspect in our data is the finding that the athletes’ AOSPAN scores varied as a function of the WM demands of their sport. Future research is necessary to confirm this result in a separate athlete cohort, especially to assist interpretation of its causality. One possibility is that only athletes with higher WMC can succeed and advance to collegiate-level competition in football and volleyball given the necessity for updating and inhibiting the multiple play calls in these sports. Another possible explanation is that repeated practice over years of competition “trains” the athletes resulting in higher WMC. In either case, further research should show whether higher WMC relates to better athletic performance. This idea is not irrelevant to current practice. All National Football League prospects are currently tested during annual draft combines utilizing the Wonderlic Personnel Test, an instrument for assessing aptitude for learning and problem solving. In addition, our finding that an athlete’s AOSPAN score may be a more sensitive indicator of cognitive performance than their SAT score is similar to studies reporting WMC measures to be better predictors of outcome than global measures such as IQ (Alloway & Alloway, 2010).

Our designation of football and volleyball as high-WM-demand sports relative to others may be disputed. We believe that the volume and frequency of modification of play calls in these sports justify our conclusion. Football and volleyball players must interpret hand signals and verbal codes instantly on every play. In contrast, although baseball and softball involve hand signals between catcher and pitcher and between coaches and base runners, these signals are relatively less frequent and less urgent and do not apply to all team members. In soccer, there may be set tactical play calls (e.g., corner kicks) but these are infrequent during a match. Another factor involves the number of plays to be recalled during a game, vastly more for football than in other sports. While this may appear to be a long-term memory demand, recent conceptualizations of WMC focus on the contribution of both immediate memory and recall through secondary memory (Unsworth & Engle, 2007).

Limitations of our study include the following:

1. We relied on voluntary participation while recruiting adequate numbers of subjects. This resulted in significant variations in the gender composition of the different groups. While it is known that aspects of neurocognitive test results may vary with gender, and females may develop more late complaints following concussion (Colvin et al., 2009; Covassin, Schatz, & Swani, 2007), we found no significant gender differences within any of our study groups.

2. To avoid intrusive questioning of our study participants, we did not request information concerning learning disabilities, street drug or alcohol abuse, or diagnosed psychiatric disorders that might influence WMC.

3. Sport-related concussions were self-reported by our athletes. While we know of no group factors that would systematically skew these reports, it is well documented that underreporting and underdiagnosis of concussions are common (Meehan & Bachur, 2009).

4. Our data were obtained from students and student athletes at a single institution. A multicenter approach would have been preferable but was not feasible.

CONCLUSIONS

WMC is not impaired in student athletes who participate in head-contact-prone sports. WMC is not impaired in student athletes with a history of diagnosed concussion, even those who are multiconcussed. Our results suggest that athletes competing in sports that impose significant WM loading score higher on the AOSPAN test than do other athletes. Whether this reflects a training effect or involves a selection process remains unknown.

REFERENCES


