JOURNAL OF NEUROTRAUMA 30:1469–1475 (September 1, 2013)

DOI: 10.1089/neu.2012.2720

Original Articles

Subjective, but not Objective, Lingering Effects of Multiple Past Concussions in Adolescents

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Abstract

The existing literature on lingering effects from concussions in children and adolescents is limited and mixed, and there are no clear answers for patients, clinicians, researchers, or policy makers. The purpose of this study was to examine whether there are lingering effects of past concussions in adolescent athletes. Participants in this study included 643 competitive Bantam and Midget hockey players (most elite 20% by division of play) between 13 and 17 years of age (mean age = 15.5, SD = 1.2). Concussion history at baseline assessment was retrospectively documented using a pre-season questionnaire (PSQ), which was completed at home by parents and players in advance of baseline testing. Players with English as a second language, self-reported attention or learning disorders, a concussion within 6 months of baseline, or suspected invalid test profiles were excluded from these analyses. Demographically adjusted standard scores for the five composites/domains and raw symptom ratings from the brief Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) computerized battery were analyzed. Adolescent athletes with one or two or more prior concussions did not have significantly worse neurocognitive functioning on ImPACT than did those with no previous concussions. There were significantly more symptoms reported in those with two or more prior concussions than in those with no or one prior concussion. Adolescents with multiple previous concussions had higher levels of baseline symptoms, but there were not group differences in neurocognitive functioning using this brief computerized battery.

Key words: baseline; concussion; cumulative; lingering; mild traumatic brain injury; pediatric

Introduction

Concussions in children and adolescents are not a trivial health issue, with approximately one out of six children sustaining a concussion before the age of 10 years.[1] The annual incidence of concussion is estimated to occur in ~600/100,000 people, with >60% of these injuries occurring in males, 20% occurring in sport, and the highest rates of incidence being in 15–24-year-olds.[2,3] It is estimated that 1 out of every 10 injuries sustained in United States high school athletics is a concussion.[4] In a 5 year longitudinal study, >700,000 concussions were estimated to have occurred in United States high school athletics, with 13% of these injuries being deemed as recurrent.[5] Cohort studies using validated injury surveillance in youth ice hockey report overall injury and concussion rates that range from 3 to 5 injuries/1000 player hours and from 0.8 to 1.5 concussions/1000 player hours (in leagues allowing body checking) and from 0.43 to 1.37 injuries/1000 player hours and from 0.2 to 0.4 concussions/1000 player hours in leagues that do not allow body checking (ages 9–17).[6–9] The number of injuries documented in amateur sport appear to have increased over time, with an 11 year epidemiological study of concussions in high school athletes demonstrating a fourfold increase in the number of concussions in both boys and girls.[10]

By definition, a concussion is a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces.[11] A concussion generally results in temporary neurophysiological disruption of cellular signalling,[12] along with time-limited cognitive changes and subjective problems including somatic and affective symptoms (e.g., headaches, dizziness, irritability). In high school athletes who sustain a sports-related concussion, significant group differences in neurocognitive functioning compared with non-concussed athletes generally dissipate within a few weeks post-injury despite the potential for ongoing elevated symptom reporting,[13–15] although longer recovery periods for neurocognition are also reported[16,17] and may be more evident with individual than with group analyses.[18,19] The majority of clinical symptoms

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associated with concussions resolve within 1–3 weeks, but a minority of people have symptoms that may persist beyond this time frame.[20,21] Varying lengths of time for expected recovery in a developing and maturing brain suggest that the management of concussive injuries should remain cautious in children and adolescents.[22]

Despite indications that the vast majority of people will recover from a single concussion, there is concern that sustaining multiple concussions over time will result in cumulative or lingering effects on brain functioning. To date, however, the existing literature on lingering effects from multiple concussions is mixed and remains inconclusive. In children, adolescents, and young adults, the cumulative effects of prior concussions range from no effect[23–26] to measureable neurocognitive effects.[17,27,28] When considering a recent meta-analysis of the adolescent and adult literature,[29] multiple prior concussions had a negligible/very small effect size on memory performance and a small effect size on measures of executive functioning, whereas other cognitive domains and symptom ratings were nonsignificant with negligible/very small effect sizes. In studies that only included children and/or adolescents, the results ranged from no lingering effects in children[23] to measureable residual effects of prior concussions in adolescents.[17] Overall, there is limited and weak supportive evidence that there are lingering effects on neurocognitive functioning from multiple concussions (i.e., two or more prior concussions in children and adolescents and three or more prior concussions in adults).

Based on the increasing concern of residual effects from concussions, coupled with the lack of research on the impact of concussions on a developing brain (i.e., many studies include a mix of older adolescents and young adults), it is important to investigate whether there are measureable effects from multiple past concussions in adolescents. The purpose of this study was to examine whether there are cumulative effects of prior concussions on neurocognitive functioning. Based on previous literature in children and adolescents (i.e., Moser et al.[17]) it is hypothesized that there will be lingering effects on neurocognitive functioning and symptom reporting in those adolescent athletes who report having sustained prior concussions, notably those with two or more past injuries.

Methods

Participants

Participants were recruited as part of a large cohort study with 44 hockey teams designed to evaluate outcomes following concussion in sport,[30–32] with the present study designed to focus on their baseline data. Inclusion criteria for baseline testing were: male or female players; written informed assent/consent to participate (player assent and consent from one parent or guardian); players registered with Hockey Calgary, Girls Hockey Calgary, or the Edge School in Calgary, Alberta, Canada; players registered with Hockey Edmonton or Edmonton Girls Hockey in Edmonton, Alberta, Canada; players participating in the Bantam (ages 13–14) or Midget (15–17 years) leagues only; players in the most elite 20% of divisions of play (AA, AAA); agreement of the player's head coach to participate in the study; and agreement of the team therapist to collect information about individual player participation and injury throughout the season as part of the larger cohort study. Players were excluded from baseline testing if they had sustained an injury or had a chronic illness that prevented full participation in hockey at the beginning of the 2011–2012 season (i.e., all players were cleared for return to play). The Conjoint Research Ethics Board at the University of Calgary granted approval for this study (Ethics ID E-24026).

Exclusion criteria for the present study consisted of those factors that could potentially adversely affect cognitive performance and/or alter symptom reporting, such as having English as a second language, attention or learning problems, or a recent concussion (i.e., defined as having had a concussion within the past 6 months).[33] The reason for these exclusion criteria was to minimize the influence of variables other than prior concussions on neurocognitive performance and symptom reporting. Exclusion criteria also included not completing baseline testing or test performance flagged as being potentially ''invalid'' (i.e., baseline ++) based on the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) program.

For this study on cumulative effects of concussions at baseline, 768 potential participants were recruited for baseline testing as part of the cohort study on concussion outcome. There were 25 players who consented to this study but did not participate in baseline testing; therefore, 743 players had baseline neurocognitive data on the ImPACT battery. Players were excluded from analyses in this study if they identified themselves as having English as a second language ($n=11$), had attention or learning problems ($n=26$), or indicated on the ImPACT injury surveillance questions that they had had a concussion within 6 months before the baseline testing ($n=29$). Additionally, those players with suspected invalid test profiles flagged by the ImPACT program were excluded ($n=34$) from analyses. The final sample size with baseline testing that was considered for further analyses on potential cumulative effects of previous concussions was 643.

Measures

All players completed the ImPACT battery at baseline as part of a larger study on outcome from concussion. ImPACT is a brief computerized screen of cognitive abilities (i.e., not designed to be a thorough neuropsychological assessment) that has been used previously in several studies investigating neurocognitive functioning following concussive injuries.[18,24,28,34–38] ImPACT includes six tests/modules (i.e., word discrimination, design memory, x's and o's, symbol match, color match, three letters) that yield five composite/domain scores (i.e., verbal memory, visual memory, visual-motor skills, reaction time, and impulse control). For the verbal memory, visual memory, visual-motor skills, and reaction time composite scores, demographically adjusted percentile scores (i.e., age and sex) are provided on the standard clinical report printout. Demographically adjusted percentile scores for the impulse control composite score were computed from the normative data tables available from the test publisher.

In addition to the objective and rapid measurement of cognitive abilities, a subjective symptom reporting scale was administered as part of the ImPACT battery. The ImPACT post-concussion symptom rating scale contains 22 somatic, affective, and cognitive symptoms, with each symptom being rated from 0 (none) to 6 (severe). Two values can be computed for the symptom questionnaire: total symptom score (sum of all ratings for all symptoms) and the number of symptoms endorsed as being present (regardless of the severity). Both of these values were examined for this study.

Reporting of previous concussions was done using a pre-season questionnaire (PSQ). The PSQ is a previously validated measure that has been used in injury surveillance studies in youth ice hockey by this research group.[6,7,39] The PSQ was designed to pre-screen athletes for medical, mental health, or behavioral conditions. It is a paper and pencil questionnaire that collects participant information, including (but not limited to) demographics (i.e., age, sex, height, weight), current sport participation, and previous medical history (i.e., injury history, surgical history, diagnosed medical conditions). The questionnaire asks specifically about previous concussions (''Have you ever had a concussion or been 'knocked out' or had your 'bell rung'?''). All athletes and their parent and/or guardian completed the PSQ at home prior to coming into the laboratory for baseline testing, in order to document the number of prior injuries. Although self-reporting prior concussions right before completing the baseline testing has been used in previous studies,[18,24,28] the primary focus of this study was on the parent-/guardian-assisted report of concussion history.

Statistical analysis

Our study approached analyses of these data using three different statistical techniques (congruence of findings across various methods is important given the mixed literature): 1) correlations between the number of previous concussions and current functioning; 2) group comparisons of mean scores; and 3) group comparisons of the percentage who would be considered ''impaired'' (i.e., reflecting a pseudoclinical approach). Analyses were completed using SPSS Statistics 19.0. Correlations (Spearman's ρ) between concussion history, neurocognitive functioning, and symptom reporting were examined. Analyses of variance (ANOVAs) were used for ''group × age''and ''group × time since concussion'' comparisons. ImPACT composite scores (age- and gender-adjusted percentile scores) were uniformly transformed into age- and gender-adjusted T scores (mean = 50, SD = 10). A multivariate analysis of variance (MANOVA) was used for ''group × ImPACT composite score'' comparisons, with follow-up ANOVAs for each ''group × composite score'' analysis. Comparisons involving only two groups used Student's *t* test. Group comparisons for symptom scores were completed, using an analysis of covariance (ANCOVA) for ''group × symptoms,'' with age being entered as a covariate (because symptom scores are not adjusted for age). Cohen's *d* effect sizes were also computed to complement interpretation of results, with effect sizes being interpreted as negligible/very small ($d < 0.20$), small ($d = 0.20$–0.49), medium ($d = 0.50$–0.79), or large ($d \geq 0.80$). Comparisons of the frequency of ''impaired'' scores (defined *a priori* as performance 1.5 SD below the mean) across the groups were also examined using χ^2 tests for differences. Significance for analyses was set *a priori* at $p < 0.05$.

Results

The participants who completed baseline testing ranged in age from 13.0 to 17.9 years old, with a mean age of 15.5 years (SD = 1.2). The majority of participants were male ($n = 539$, 83.8%), right handed ($n = 554$, 86.2%), and in the Midget hockey league ($n = 438$, 68.1%). For those who had sustained a prior concussion, it had been a median of 22 months (range = 6-177) since the last injury had occurred.

Based on the PSQ information, groups were created for those with no ($n = 382$), one ($n = 190$), and two or more ($n = 44$) (two concussions, $n = 36$; three concussions, $n = 7$; four concussions, $n = 1$) previous concussions. There were 27 athletes (4.2%) with missing PSQ data; therefore, they were excluded from further analyses. The athletes with missing PSQ data (mean age = 16.2 years, SD = 1.0) were significantly older than those with PSQ data (mean age = 15.5 years, SD = 1.2; $F[1,741] = 9.57$, $p = 0.002$), but there were no significant differences with the cognitive scores or number of symptoms endorsed between those who did and those who did not complete the PSQ (all ps > 0.05). When comparing the groups who had had no, one, or two or more concussions, there was a significant group effect for age ($F[2, 613] = 4.931$, $p = 0.008$], with those who had had no prior concussions being significantly younger than those who had had one prior concussion ($p = 0.008$). There was a significant difference in the number of months since last concussion ($t[137] = 2.70$, $p = 0.008$], with more time having passed since the last concussion in those having had only one prior concussion compared with those who had had two or more prior concussions.

Performance on the five ImPACT composite scores and the symptom ratings are presented in Table 1. The number of previous concussions rated on the PSQ was significantly correlated with higher levels of symptom ratings ($\rho = 0.123$, $p = 0.002$) but not with cognitive abilities (verbal memory percentile, $\rho = -0.033$, $p = 0.417$; visual memory percentile, $\rho = -0.031$, $p = 0.442$; visual motor percentile, $\rho = -0.013$, $p = 0.752$; reaction time percentile, $\rho = -0.051$, $p = 0.202$; impulse control percentile, $\rho = -0.012$, $p = 0.770$). Additionally, there were not statistically significant correlations between cognitive abilities and symptom scores (all ps > 0.05).

Group comparison of the five ImPACT composite scores in those with no, one, or two or more previous concussions using MANOVA was not significant ($F[10, 1218] = 0.94$, $p = 0.494$, partial eta$^2 = 0.008$). (Although one group was significantly older, statistical analyses with ImPACT composite scores were not adjusted for age because the standardized scores are already adjusted for age.) Because of the non-significance of the MANOVA, follow-up analyses are presented as exploratory only. Follow-up ANOVAs were non-significant for verbal memory ($F[2,613] = 0.59$, $p = 0.556$), visual motor ($F[2,613] = 1.69$, $p = 0.186$], reaction time ($F[2,613] = 0.98$, $p = 0.378$], and impulse control ($F[2,613] = 0.65$, $p = 0.525$] composites. The follow-up ANOVA for visual memory approached significance ($F[2,613] = 3.01$, $p = 0.05$], but all follow-up group comparisons were non-significant ($p = 0.11$–0.77). Cohen's *d* effect sizes were negligible/very small for all comparisons between zero and one prior concussion ($d = 0.07$–0.18). Most comparisons between zero and two or more prior concussions revealed negligible/very small Cohen's *d* effect sizes ($d = 0.04$–0.19), with a small effect size ($d = 0.24$) on visual memory composite in favor of those who had had two or more prior concussions having *better* visual memory than those who had had no concussions. Again, most Cohen's *d* effect sizes for comparisons between one and two or more prior concussions were negligible/very small ($d = 0.01$–0.19), although there were small effect sizes for the visual memory ($d = 0.42$) and visual motor ($d = 0.28$) composites in favor of the latter group (i.e., those who had had two or more prior concussions had *better* visual memory and visual motor performance than those who had had one concussion). When considering ''impaired'' performance (percentile scores falling more than 1.5 standard deviations below the mean) in those athletes who had had no, one, or two or more prior concussions, there were no significant group differences in the percent of adolescents with low scores on the verbal memory ($\chi^2[2] = 0.067$, $p = 0.967$), visual memory ($\chi^2[2] = 0.640$, $p = 0.726$), visual motor speed ($\chi^2[2] = 5.20$, $p = 0.074$], reaction time ($\chi^2[2] = 3.93$, $p = 0.140$], or impulse control ($\chi^2[2] = 1.48$, $p = 0.477$) composites.

Mean total symptom score (sum of all ratings on the symptom questionnaire) for those who had had no previous concussions was 4.9 (SD = 7.0). On average, those who had had no previous concussions had 2.8 symptoms (SD = 3.3) present at any level of severity and only 26.7% of this group report having no symptoms at baseline (see Fig. 1 for proportions of groups with symptoms at baseline). When considering the total symptom scores for the PSQ-based groups, there was a significant group effect with age as a covariate ($F[2,612] = 11.99$, $p < 0.001$, partial eta$^2 = 0.038$]. Post-hoc analyses indicate that there was not a statistical difference between those who had had no previous concussions and those who had had one (mean = 5.8, SD = 7.3; $p = 0.534$, Cohen's $d = 0.13$) on total symptom scores. Those who had had two or more previous

Table 1. Cognitive Performance and Symptom Reporting in Adolescent Athletes with and without Prior Concussions

	Number of prior concussions		
	None	*One*	*Two or more*
n	382	190	44
Age (mean [SD])	15.4 (1.3)	15.7 (1.2)[a]	15.6 (1.1)
Age (range)	13–17	13–17	13–17
Months since last concussion (median [range])	–	22 (6–177)	15.5 (6–71)
ImPACT domains (mean T score [SD])			
Verbal memory composite T score	51.8 (10.5)	50.8 (10.0)	51.4 (10.5)
Visual memory composite T score	51.5 (10.5)	49.7 (11.3)	53.4 (8.5)
Visual motor composite T score	48.6 (9.6)	48.0 (10.1)	50.9 (7.8)
Reaction time composite T score	50.9 (9.6)	49.9 (9.4)	51.6 (7.0)
Impulse control composite T score	47.2 (9.5)	46.4 (9.3)	47.8 (9.3)
Total symptom score (raw sum total)	4.9 (7.0)	5.8 (7.3)	10.9 (12.5)[b]
Number of symptoms present (raw)	2.8 (3.3)	3.3 (3.6)	5.3 (5.1)[b]
ImPACT domains (percent of sample ≥ 1.5 SDs below mean)			
Verbal memory composite	6.0	5.8	6.8
Visual memory composite	7.9	7.9	4.5
Visual motor composite	7.3	10.0	0.0
Reaction time composite	8.1	8.4	0.0
Impulse control composite	10.7	14.2	11.4

Values for ImPACT domain scores are demographically-adjusted T scores (population mean, T = 50, population SD = 10). For ImPACT composite scores, higher scores reflect stronger/better performance relative to age and gender norms. ‘‘Total symptom score (sum total)’’ is a raw score based on summing all of the ratings of severity for each item (0-6), where higher values represent higher ratings of symptom severity. ‘‘Number of symptoms present’’ represents the number of symptoms, regardless of severity level of the symptom. Higher values represent more symptoms.

[a]Those who had had one previous concussion are significantly older than those who had not had a previous concussion.

[b]Those who had had two or more previous concussions have significantly higher symptom ratings than those who have not had a previous concussion or who have had only one.

ImPACT,Immediate Post-concussion Assessment and Cognitive Testing.

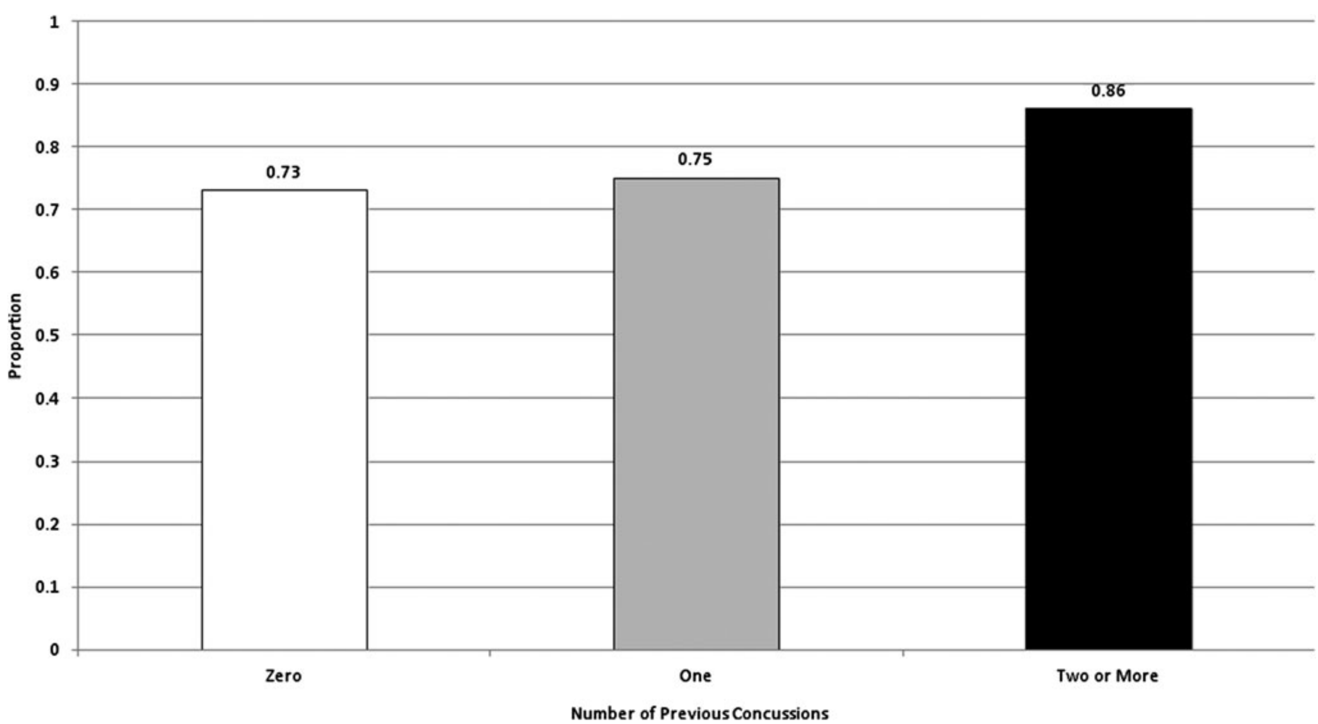

FIG. 1. The groups are based on the number of previous concussions identified using the pre-season questionnaire (PSQ). Values represent the proportion of adolescent athletes in each group who indicated that they had symptoms on the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) post-concussion symptom scale.

concussions (mean = 10.9, SD = 12.5) reported significantly higher total symptom scores than those who had had no concussions ($p < 0.001$, Cohen's $d = 0.79$) and those who had had one prior concussion ($p < 0.001$, Cohen's $d = 0.61$). Similar results were found when examining the number of symptoms experienced (at any level of severity), with a significant group effect when accounting for age ($F[2,612] = 9.18$, $p < .001$, partial eta^2 = 0.029]. Post-hoc analyses indicated differences between those who had had two or more prior concussions and those who had had no ($p < 0.001$, Cohen's $d = 0.71$) or one prior concussion ($p = 0.002$, Cohen's $d = 0.52$), but not between those who had had no and those who had had one prior concussion ($p = 0.478$, Cohen's $d = 13$).

Discussion

The purpose of this study was to examine whether there were differences in symptoms and neurocognitive functioning in adolescents who had sustained multiple prior concussions. It was hypothesized that those athletes who had had previous concussions would have worse neurocognitive abilities and higher levels of symptoms, particularly those who had had two or more past injuries. Indirectly, these findings may suggest whether there are lingering or cumulative effects from past concussions in adolescents. In this large sample of elite 13–17-year-old hockey players who completed baseline testing prior to starting the hockey season, there *was not* evidence that having one, two, or more previous concussions resulted in worse neurocognitive functioning as measured using the brief ImPACT computerized battery. There were, however, higher subjectively reported symptoms in those adolescents who had had two or more previous concussions.

Athletes who had had previous concussions did not have worse neurocognitive functioning in this study based on ImPACT test performance. This was based on 1) no significant correlations between number of concussions and neurocognitive functioning, 2) no significant group differences between those who had had no concussions and those who had had one, two, or more prior concussions on mean neurocognitive scores (any small effect sizes favored those with two or more prior concussions), and 3) no significant differences in the percent of athletes who had had no, one, or two or more concussions who had impaired test scores. Previous literature on residual neurocognitive effects in children and adolescents is very limited, and provides inconclusive evidence. Bijur et al.[23] reported that cognitive deficits from multiple injuries in children up to 10 years of age were related more to social factors (i.e., socioeconomic status, quality of housing, mother's age, and maternal malaise) than to the actual number of brain injuries or the age at which the injury occurred. Interestingly, there are also several studies with older adolescents/young adults that suggest an absence of substantial neurocognitive effects from multiple prior concussions.[24–26,29]

In contrast to the absence of group differences with neurocognition in the present study, Moser et al.[17] reported that multiple prior concussions did have a measureable effect on neurocognitive abilities in adolescents. High school athletes with a history of two or more prior concussions had mean performance on paper and pencil attention measures that was not significantly different from that of athletes who had sustained a concussion within 1 week of being tested. These results would suggest *prima facie* that adolescents who had had two or more concussions were functioning at a level similar to that of acutely concussed athletes; however, on the same attention measure, those who had had multiple concussions also did not differ from those adolescents who had had no previous concussions or who had had only one. Moreover, the group who had had two or more previous concussions did not differ from those with who had had no, or only one previous concussion on measures of immediate memory, delayed memory, language, visuoconstruction, visuomotor speed, or visuomotor set switching. Therefore, although the Moser et al.[17] study presents some evidence of lingering neurocognitive effects from multiple prior concussions in adolescents, it is limited and not conclusive.

Although this study does not provide evidence of worse neurocognitive functioning on brief neurocognitive testing, those who had had multiple prior concussions reported higher levels of symptoms. Adolescents who reported sustaining one prior concussion did not report having a higher number of symptoms than did those who had not sustained a concussion. However, in adolescents who had had two or more past concussions, there were significant differences and medium effect sizes for symptom ratings when compared with those who had had no or only one prior concussion (note that symptom ratings do not correlate with neurocognitive functioning). It is unlikely that the differences in symptom reporting are related to age differences found across the groups, because results were significant even after accounting for the effect of age (i.e., adding age as a covariate). At an individual symptom level, significant group differences were found across the range of problems, including somatic, affective, and cognitive symptoms. The literature on multiple concussions and symptoms suggests that two or more prior concussions do not result in higher symptom ratings,[17, 24] but that three or more prior concussions generally result in higher levels of symptom reporting.[26,28,40] The present study supports the older adolescent/young adult literature on increased symptom reporting with multiple prior concussions, but suggests that adolescent athletes between 13 and 17 years of age who have sustained two or more prior concussions also have elevated symptom levels even when it has been at least 6 months since their last injury.

In the present study, retrospective reporting of concussions was completed using the PSQ, a previously validated measure that has been used in injury surveillance studies in youth ice hockey.[6,7,39] The PSQ was designed to be completed in advance of baseline testing and to include parent/guardian input, which is believed to provide a more reliable concussion history than self-report at the time of baseline testing. However, self-report of concussion history on ImPACT is a common method of injury surveillance that has been used previously when examining whether there are lingering effects of multiple past concussions.[18,24,28] Interestingly, in previous analyses with these same athletes stratified into no, one, two, or three or more previous concussions based on self-report on ImPACT at the time of baseline testing,[41] the results were the same as those of the present study with PSQ-stratified concussion history (i.e., no lingering effects found on neurocognitive scores, but higher levels of symptom reporting in those who had had more previous concussions). As such, the lingering neurocognitive effects of two or more, or even three or more concussions, have not been found in this sample of elite hockey players.

Limitations

There were some limitations with this study. First, the use of retrospective reporting of concussions has the potential to be problematic and influenced by normal human biases. For example, retrospective reporting of prior concussions that had occurred up to

177 months before baseline testing was completed, as noted in the present study, could potentially have resulted in some inaccuracies. Second, the results of the current study might not translate to other sports (e.g., football, soccer, lacrosse) or to non-athletes, especially because these were elite level hockey players. Third, the present study is cross sectional, whereas a more powerful and convincing study design might be longitudinal in nature, in which athletes are followed over several years to document injuries and repeat testing (and to track those who stop playing sports because of injuries). In fact, this is even more important to consider because we are indirectly attributing the group differences in elevated symptoms to a history of concussions. Elevated symptom reporting *may not be* the direct result of the past concussions. A more thorough longitudinal design might allow us to ascertain if the group differences found with symptom reporting were truly the direct result of prior concussions (or any other factors). Fourth, this study employed a rapid computerized screen of neurocognitive abilities and did not employ other methods of measuring neurocognitive functioning, such as more comprehensive paper and pencil testing included from a battery of neuropsychological tests. Also, it did not include other methods of examination that may have the potential to identify lingering neurological effects from prior multiple concussions, such as functional magnetic resonance imaging (fMRI) to detect hemodynamic changes associated with neuronal activity.[42] Using fMRI, researchers have found that athletes with persistent post-concussion symptoms displayed hypoactivation and altered connectivity in the mid-dorsolateral prefrontal cortex, even though cognitive task performances were similar to those of controls.[43–46] This suggests that regional brain activation during the fMRI task may have the potential to be more sensitive to cumulative concussive injuries than actual test performance. As such, the conclusions are limited to an absence of neurocognitive effects based on the rapidly administered ImPACT battery. Additionally, this study did not include informant-based ratings of symptoms from parents or guardians, which may differ from the athletes' self-reporting of symptoms.

Conclusion

Overall, the results of this study do not support neurocognitive differences (based on the brief screen of abilities provided using the ImPACT battery) in adolescents who have sustained one, two, or more prior concussions. This study does, however, suggest that adolescents who have sustained two or more previous sport-related concussions will have more self-reported symptoms (e.g., headaches, balance problems, dizziness, fatigue, trouble falling asleep, sleeping less than usual, irritability, nervousness, numbness or tingling, feeling slowed down, difficulty concentrating, difficulty remembering, and visual problems), even when they are >6 months post-injury. Whether the previous concussions are truly causal of the higher levels of symptom reporting needs to be further studied. Interestingly, the number of symptoms reported did not correlate with neurocognitive abilities, which suggests that the lingering effects of perceived/subjective problems are not objectively measured using this method of rapidly screening neurocognitive abilities. Higher levels of symptoms in those with previous injuries are important to consider when assessing the potential acute effects of a recent concussion and monitoring recovery in an adolescent, as well as when considering the increased risk of sustaining another concussion.[47] Further research into the cumulative effects of concussions on developing brains is needed, particularly with emphases on large samples, younger ages, gender differences, more comprehensive neuropsychological assessments, and multiple investigative techniques.

Acknowledgments

The authors thank the following people for their help with data collection (in alphabetical order): Tracy Blake, Andrea Jubinville, Nicole Lemke, Maria Romiti, and Kathryn Schneider. The authors thank Emily Tam for assistance with data management, and Dr. Helen Carlson for her help with data management, entering the demographically adjusted normative scores for this entire sample, and formatting the manuscript. The authors also thank Hockey Calgary, Girls Hockey Calgary, Hockey Edmonton, Edmonton Girls Hockey, the Edge School (Calgary), the team designates, research assistants, coaches, families, and the players who participated in this study. Computerized cognitive testing in this study was funded in Calgary by the McCarthy Tetrault award (administered by the Alberta Children's Hospital Research Institute for Child & Maternal Health) to Dr. Brooks (computers, test credits) and in Edmonton by funding provided to and in-kind support by ImPACT to Dr. Mrazik. The Sport Injury Prevention Research Centre is one of the International Research Centres for Prevention of Injury and Protection of Athlete Health supported by the International Olympic Committee. Drs. Meeuwisse and Emery acknowledge funding from Alberta Innovates Health Solutions (AIHS), Canadian Institutes of Health Research (CIHR), and the Alberta Children's Hospital Research Institute for Child & Maternal Health (ACHRI; Professorship in pediatric rehabilitation for Dr. Emery).

Author Disclosure Statements

None of the authors have a financial interest in the ImPACT battery. Dr. Brooks receives funding from a test publisher (Psychological Assessment Resources, Inc.), book royalties from Oxford University Press, and in-kind test credits for research from another computerized test publisher (CNS Vital Signs). In-kind support from ImPACT was provided to Dr. Mrazik for the assessments conducted in Edmonton.

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