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The Effects of Attention-Deficit/Hyperactivity Disorder Symptoms on the Association between Head Impacts and Post-Season Neurocognitive and Behavioral Outcomes

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Abstract

Objective: Having attention-deficit/hyperactivity disorder (ADHD) is a risk factor for concussion that impacts concussion diagnosis and recovery. The relationship between ADHD and repetitive subconcussive head impacts on neurocognitive and behavioral outcomes is less well known. This study evaluated the role of ADHD as a moderator of the association between repetitive head impacts on neurocognitive test performance and behavioral concussion symptoms over the course of an athletic season. **Method:** Study participants included 284 male athletes aged 13–18 years who participated in high school football. Parents completed the Strengths and Weaknesses of ADHD Symptoms and Normal Behavior (SWAN) ratings about their teen athlete before the season began. Head impacts were measured using an accelerometer worn during all practices and games. Athletes and parents completed behavioral ratings of concussion symptoms and the Attention Network Task (ANT), Digital Trail Making Task (dTMT), and Cued Task Switching Task at pre- and post-season. **Results:** Mixed model analyses indicated that neither head impacts nor ADHD symptoms were associated with post-season athlete- or parent-reported concussion symptom ratings or neurocognitive task performance. Moreover, no relationships between head impact exposure and neurocognitive or behavioral outcomes emerged when severity of pre-season ADHD symptoms was included as a moderator. **Conclusion:** Athletes' pre-season ADHD symptoms do not appear to influence behavioral or neurocognitive outcomes following a single season of competitive football competition. Results are interpreted in light of several study limitations (e.g., single season, assessment of constructs) that may have impacted this study's pattern of largely null results.

Keywords: Attention, Cognition, Football, Athletes, Adolescent, Longitudinal study

In recent years, concussion and its impact on athletes has received considerable clinical, research, and media attention. However, the incidence of concussion is not decreasing despite increased concussion management legislation nationwide (Kerr et al., 2019; Schallmo, Weiner, & Hsu, 2017; Yang, Comstock, Yi, Harvey, & Xun, 2017). In response to growing concerns regarding head impacts in athletes, research has expanded to not only include concussion, but repetitive subconcussive head impacts as well. In a 4-year study of high school football players, the average player sustained 652 head impacts (>15 g) per season (Broglio et al., 2011). Neuroimaging studies have demonstrated functional and structural changes following repetitive head impacts, even in the absence of identified concussion or observable behavioral deficits (Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013; Bazarian, Zhu, Blyth, Borrino, & Zhong, 2012; Breedlove et al., 2012; Mainwaring, Pennock, Mylabathula, & Alavie, 2018). However, inconsistent and insufficient evidence in the literature has presented a challenge in understanding whether there are behavioral and

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neurocognitive performance changes associated with repetitive head impacts (Belanger, Vanderploeg, & McAllister, 2016; Mainwaring et al., 2018).

The lack of clarity surrounding the effects of subconcussive head impacts on behavioral performance is further compounded by individual factors that may influence outcomes. One such pre-injury factor is premorbid attention-deficit/hyperactivity disorder (ADHD). Having an ADHD diagnosis is associated with a higher likelihood of sustaining a concussion (Alosco, Fedor, & Gunstad, 2014; Biederman et al., 2015; Cook, Karr, & Iverson, 2021; Iverson, Atkins, Zafonte, & Berkner, 2016; Salinas et al., 2016). Furthermore, pre-morbid ADHD is a pre-injury factor that complicates concussion diagnosis and management (Harmon et al., 2013). Children with ADHD demonstrate premorbid deficits on many behavioral and neurocognitive outcomes traditionally associated with concussion, including impaired attention, concentration, working memory, and task-switching [American Psychiatric Association (APA), 2013; Harmon et al., 2013; Howell et al., 2013; Martel et al., 2007; Mayr et al., 2014; Rabinowitz & Levin, 2014; Sjowall et al., 2013]. Furthermore, ADHD and concussion share emotional and sleep-related features, such as irritability, emotional lability, and sleep disturbances (APA, 2013; Chiang et al., 2010; Graziano & Garcia, 2016; Harmon et al., 2013; McCrory et al., 2017). Lastly, the relationship between ADHD and concussion is further complicated by research demonstrating that children who suffer traumatic brain injuries are at risk for developing ADHD (Yang et al., 2016).

Most prior research examining ADHD as a moderator of head impact exposure on behavioral and neurocognitive outcomes has been done in the context of concussion. ADHD is not only associated with worse scores on neurocognitive tests and concussion symptom measures post-concussion (Biederman et al., 2015; Gardner, Yengo-Kahn, Bonfield, & Solomon, 2017; Iaccarino et al., 2018; Mautner, Sussman, Axtman, Al-Farsi, & Al-Adawi, 2015), but also at pre-season assessment (Elbin et al., 2013; Gardner et al., 2017; Nelson et al., 2016; Zuckerman, Lee, Odom, Solomon, & Sills, 2013). However, the literature is not consistent regarding the effect of ADHD on concussion outcomes. Indeed, research examining long-term effects of ADHD on concussion outcomes outside of the acute recovery period has not found significant associations, but has been limited by major methodological weaknesses (Cook, Iaccarino, Karr, & Iverson, 2020). Importantly, research examining ADHD as a modifier of neurocognitive performance or concussion symptoms has primarily examined ADHD dichotomously, using ADHD diagnostic status as a predictor of outcome. However, there is increasing evidence that ADHD should also be examined continuously regarding its association with head trauma (Iaccarino et al., 2018; Karic, Desrosiers, Mizrahi, & Zevallos, 2019). Specifically, Iaccarino et al. (2018) reported higher rates of post-concussion symptoms in an ADHD group compared to a control group. Given that 51% of athletes in the ADHD group were subthreshold for ADHD (defined in the study as having four or five symptoms in an ADHD symptom domain and/or ADHD symptom onset ≥12-years-old), the authors emphasized the clinical importance of subthreshold ADHD as an at-risk group with similar vulnerabilities as athletes with an ADHD diagnosis (Iaccarino et al., 2018).

Though the studies mentioned thus far highlight the importance of examining ADHD and head impacts as they relate to neurocognitive performance and head trauma symptoms, historically these variables have been assessed independently of one another. Only Rose et al. (2019) examined the influence of both ADHD and head impacts together on behavioral outcomes following a season of football, but is limited by the dichotomous classification of ADHD (Rose et al., 2019). In their study of football players aged 9–18, self-reported ADHD diagnoses and cumulative head impacts were examined as predictors of pre- to post-season change across cognitive, behavioral, and concussion symptom measures. Although cumulative head impacts was not predictive of pre- to post-season change scores in any outcome variable, history of ADHD was predictive of worsened change scores on several cognitive tests assessing attention and working memory. However, history of ADHD was not predictive of change scores on a concussion evaluation symptom checklist (Rose et al., 2019).

The present study aimed to examine ADHD symptoms as a continuous moderator of the association between repetitive head impacts, neurocognitive test performance, and concussion symptoms over the course of an athletic season in male high school football athletes. We hypothesized that increased numbers of head impacts over the course of an athletic season will lead to pre- to post-season worsening of neurocognitive test performance and measures of concussion symptoms. Furthermore, we hypothesized that ADHD symptom levels would moderate the association between head impacts and post-season scores on neurocognitive tests and concussion symptom measures, with increased ADHD symptom levels leading to a stronger effect of greater head impact exposure on post-season neurocognitive test performance and concussion symptom ratings.

METHODS

Participants and Recruitment

284 male high school football athletes aged 13 to 18 years-old and their parents/guardians consented/assented to participate in this study. Exclusionary criteria included lack of medical clearance to play sports, or having a history of neurological deficits, cerebral infarction, or severe head trauma (e.g., hydrocephalus, incidences of increased intracranial pressure, central vein thrombosis). 276 of the 284 athletes (*mean* age = 16.3, *SD* = 1.10) maintained participation in their sport over the course of the season. Demographic characteristics of the 276 included athletes are provided in Table 1. This study

Table 1. Characteristics of study sample ($n = 276$)

Characteristic	*M*	*SD*
Age	16.3	1.10
Seasons played of contact sports	14.37	7.64
	n	Percent
ADHD diagnosis		
Yes	38	13.82
No	237	86.18
ADHD medication status		
At both pre- and post-season	9	3.26
At post-season only	11	3.99
Reported TBI history		
Yes	95	34.42
No	181	65.58
Concussion sustained during season		
Yes	30	10.87
No	246	89.13

Note. *M*, mean; *SD*, standard deviation.

was conducted within the context of a clinical trial approved by an institutional review board and registered with clinicaltrials.gov (NCT# 04068883). All procedures were conducted in accordance with the Helsinki Declaration.

Procedure

Assessments of concussion symptoms, neurocognitive performance, ADHD symptoms, and key covariates (e.g., ADHD medication status, contact sport exposure, TBI history) were completed before the start of the regular season (pre-season). Concussion symptoms and neurocognitive performance were assessed again post-season. Post-season assessment was completed at the end of regular season and before any playoff games to ensure relatively equal numbers of practices and games across participants. During the athletic season, all athletes wore an accelerometer (CSx Systems Ltd, Auckland, New Zealand) secured below their left mastoid process that recorded head impact data during practices and games.

Measures

Questionnaires

Athlete ADHD symptoms. Athletes' ADHD symptoms were assessed at pre-season using the Strength and Weaknesses of ADHD-Symptoms and Normal-Behavior scale (SWAN; Swanson et al., 2001; Swanson et al., 2012). Parents completed 18 items asking them to compare their child to others of the same age (e.g., "How does this child pay attention to detail?"). Ratings were on a seven-point scale (1 = "far below average," 7 = "far above average"), with lower scores indicating higher symptom severity. The SWAN has consistent reliability with other consolidated and validated scales (Brites, Ferreira, Lima, & Ciasca, 2015). SWAN ratings were converted to a –3 ("far below average") to +3 ("far above average") scale and a mean score was computed.

Athlete concussion symptoms. All 21 items from the Post-Concussion Symptom Inventory – 13–18 years and Post-Concussion Symptom Inventory – Parent version (PCSI-SR13, PCSI-P; Sady et al., 2014) were adapted for the present study to assess concussion symptoms. As the present study did not examine discrete events (e.g., a single head impact resulting in concussion) for which the original wording of the PCSI was designed, question stems were altered to assess symptoms over the same time period in which heads impacts were measured (i.e., the course of the sports season). Athletes and parents were asked to rate 21 symptoms on a seven-point scale ranging from 0 ("not a problem") to 6 ("severe problem") over the past 3 months (rather than current symptoms). Four factor scores were derived by summing items on each factor: Physical (8 items), Fatigue (3 items), Emotional (4 items), Cognitive (5 items) symptoms.

TBI history. Parents and athletes completed the Ohio State University TBI Identification Method questionnaire (Corrigan & Bogner, 2007) to assess the athlete's lifetime history of traumatic brain injury (TBI). If either the parent or athlete reported a possible, mild, moderate, or severe TBI, the athlete was considered positive for a history of TBI.

Contact sport exposure. Athletes completed a questionnaire indicating the number of seasons they participated in contact or collision sports (i.e., football, soccer, hockey, basketball, wrestling, and lacrosse). An exposure variable was created by summing the reported number of seasons played across all sports.

Head impact surveillance. In order to monitor head impact exposure over the course of the season, athletes wore a CSx accelerometer (CSx Systems Ltd, Auckland, New Zealand) to record the magnitude of each head impact sustained. Impacts were "hit-run" filtered for potential incidental recordings (e.g., dropping the accelerometer; Diekfuss et al., 2021; Dudley et al., 2020) and a 90 g-force threshold was applied. The number of repetitive head impacts greater than 90 g-force was used as an indicator of repetitive head impact exposure since the 90 g-force acceleratory threshold has been demonstrated to predict longitudinal changes in neurological function in football athletes (Gysland et al., 2012).

Neurocognitive tasks. The Attention Network Task (ANT; Rueda et al., 2004) is a computerized complex attention task designed to assess three components of attention: alerting, orienting, and executive/conflict. Each trial began with a central fixation cross, followed by a cue, and then a target stimulus. There were four warning cue conditions that each appeared in 25% of trials: (1) a center cue (asterisk in place of fixation cross); (2) a double cue (asterisks above and below fixation cross); (3) a spatial cue (single asterisk in

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position of upcoming stimulus); or (4) no cue. The stimulus array is a set of one to five arrows presented horizontally that appears either in the upper portion of the screen (50%) or lower portion of the screen (50%). The task included three types of stimuli: congruent trials (33%; central target arrow facing same direction as flanking arrows), incongruent trials (33%; central target arrow facing opposite direction as flanking arrows), and neutral trials (33%; no flanking arrows). This display remained on the screen until a response was detected, up until a maximum of 1700 milliseconds. Athletes were asked to indicate the direction the central arrow was pointing by pressing the left or right key on the mouse. After responding, they received auditory and visual feedback from the computer indicating whether their response was correct or not. Following a 24-trial practice block, athletes completed one experimental block of 96 trials. Accuracy, reaction times (RT), and attention network scores for alerting (median RT for no cue trials - median RT for double cue trials), orienting (median RT for central cue trials - median RT for spatial cue trials), and conflict (median RT for incongruent trials - median RT for congruent trials) were computed.

Athletes' visual attention was assessed using the Digital Trail Making Test (dTMT; Lezack et al., 2004). For the present study, we developed a custom application and graphical user interface using Unity (Unity Technologies; CA, USA) that was administered via a Samsung Galaxy Tab S 10.5 tablet (Samsung Group; Seoul, South Korea). Our custom dTMT application was designed to replicate the paper and pencil version (Lezack et al., 2004) while accommodating the constraints of the traditional versions (e.g., size of tablet vs. paper). In Part A, participants drew lines to connect the numbers 1–25 in ascending order. In Part B, participants drew lines to connect both numbers (1–12) and letters (A-L) in an ascending pattern with the added task of alternating between the numbers and letters. Timing began when the stylus contacted the tablet screen and stopped when the last circle was touched. Part A time was subtracted from Part B time to denote speed of executive functioning and cognitive flexibility.

The Cued Task-Switching Task was designed to assess the ability to switch between competing tasks or stimuli (e.g., shape and color) response sets. Participants matched a stimulus presented in the upper center of the screen to one of two stimuli in the lower left and right corners of the screen. In task-homogeneous (i.e., single task) blocks or repeat blocks, participants match the upper stimulus to shape (Task A) or color (Task B). In task-heterogeneous (i.e. switch) blocks, participants switched between Tasks A and B in a pseudorandom fashion. Participants were instructed on which type of task they were to complete prior to each block. There were six blocks: Block 1 = Switch, Block 2 = Shape, Block 3 = Switch, Block 4 = Switch, Block 5 = Color, and Block 6 = Switch. Each block contained 12 trials. Each trial lasted approximately 3700 milliseconds. Post-season switching-cost (the difference in reaction time and error rate between repeat *trials* and switch *trials* within switch blocks) and mixing-cost (the difference in reaction time and error rate between repeat *blocks* and switch *blocks*) reaction times and error rates were computed.

Statistical Analyses

Athletes' pre- and post-season neurocognitive scores were assessed for outliers and removed from the analyses if any value across outcomes differed by more than three standard deviations from the group mean at that time point, resulting in the removal of four pre-season scores and one post-season score on the ANT.

Multivariate independent variable group comparison analyses were performed within a regression framework using Mplus Version 8.2. Analyses were run separately for PCSI scores (Model 1) and neurocognitive task performance indices (Model 2). Such a model accounts for all the interrelationships between all the variables, but of note, does not provide an overall test statistic. For each model, pre-season ratings or neurocognitive task scores were included in the model as a covariate. To account for nesting, a dummy-coded variable representing athletes' schools was included to account for school-related variance. In all models, the number of seasons played of contact sports, reported TBI history, and reported concussion occurrence during the season were included as covariates. In addition, ADHD medication status was controlled for with two dummy variables: one identifying children who were medicated at both pre- and post-season ($n = 6$), and another identifying children who were unmedicated at pre-season and medicated at post-season ($n = 7$). Predictor variables in all models included: (1) Parent-rated pre-season SWAN mean score; (2) number of 90 g+ head impacts; and a (3) SWAN score x number of head impacts interaction term. Post-season concussion symptom factor scores or post-season neurocognitive task scores served as dependent variables. Concussion symptom factor scores were not distributed normally since modal scores tended to be zero. Since model analyses operate under the assumptions of normality, we modeled this using censoring from below in Mplus.

Missing data were handled with maximum likelihood estimation in Mplus. All participants had pre-season data. However, we were missing post-season data for between 7–31 participants across measures (Tables 2 and 3). Those with missing post-season data were significantly older than those without missing post-season data for concussion symptom parent ratings [$t(274) = 2.75, p = .009$] and the Trails test [$t(274) = 3.72, p = .007$]. To control for multiple testing in our analyses, we used a false discovery rate (FDR) correction for the effects of ADHD symptoms, head impacts, and their interaction (Bejamini & Hochberg, 1995). All presented results for these variables report FDR-corrected p-values. All other effects (i.e., covariate main effects) were not FDR corrected.

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Table 2. Athlete- and parent-reported concussion symptom ratings

	Pre-season		Post-season		
	M	*SD*	*M*	*SD*	*t*
Athlete-reported	*n* = 276		*n* = 274		
Cognitive symptoms	2.54	4.10	2.96	4.90	1.61
Emotional symptoms	2.26	3.21	2.19	3.38	0.35
Fatigue symptoms	2.92	3.12	2.61	3.25	1.54
Physical symptoms	3.71	4.60	3.70	5.38	0.04
Total symptoms	11.12	12.08	10.99	13.89	0.19
Parent-reported	*n* = 258		*n* = 245		
Cognitive symptoms	1.06	2.56	1.05	2.50	0.07
Emotional symptoms	1.11	1.87	1.28	2.27	1.07
Fatigue symptoms	1.20	2.15	1.63	2.54	2.73[b]
Physical symptoms	1.60	2.33	2.12	3.83	2.34[a]
Total symptoms	4.84	6.58	5.92	8.80	1.96

Note: *M*, mean; *SD*, standard deviation.
[a] $p < .05$.
[b] $p < .01$.

Table 3. Athlete neurocognitive task scores

	Pre-season		Post-season		
	M	*SD*	*M*	*SD*	*t*
ANT	*n* = 276		*n* = 276		
Accuracy	0.95	0.08	0.96	0.04	2.46[a]
Mean RT	510.07	66.33	463.17	57.88	14.94[d]
SD RT	103.92	38.39	90.51	32.30	6.23[d]
Alerting network	16.87	32.99	27.73	28.04	4.29[d]
Orienting network	31.10	31.81	23.39	30.36	3.02[b]
Conflict network	90.37	49.58	68.54	32.58	7.61[d]
Trail making	*n* = 276		*n* = 269		
Time b – Time a	21.79	10.94	21.30	12.21	0.46
Task switching	*n* = 276		*n* = 276		
Mixing cost error rate	−0.07	0.08	−0.06	0.08	1.55
Mixing cost RT	119.67	74.55	100.81	67.43	3.44[c]
Switching cost error rate	−0.02	0.12	−0.02	0.12	0.05
Switching cost RT	−5.44	65.98	−5.09	65.12	0.03

Note. ANT, attention network task; trail making, digital trail making test; task switching, cued task switching task; RT, reaction time; *M*, mean; *SD*, standard deviation.
[a] $p < .05$.
[b] $p < .01$.
[c] $p < .001$.
[d] $p < .0001$.

RESULTS

Descriptives

Descriptive statistics for all pre- and post-season measures are provided in Tables 2 and 3. The mean pre-season parent-reported SWAN score was 0.87 ($SD = 0.93$, $n = 256$). Athletes in the study sustained an average of 22.4 ($SD = 15.5$; min = 0, max = 92) head impacts greater than 90g over the course of the season (Figure 1). Regarding concussion symptom ratings, significant pre- to post-season worsening was observed for parent-reported Fatigue [$t(274) = 2.73$, $p = .007$] and Physical [$t(274) = 2.34$, $p = .03$] factor scores (Table 2). For neurocognitive tasks, significant pre-to post-season improvements were observed for the mixing cost reaction time metric of the Cued Task-Switching Task [$t(275) = 3.44$, $p = .0007$], as well as across all metrics of the ANT (Table 3).

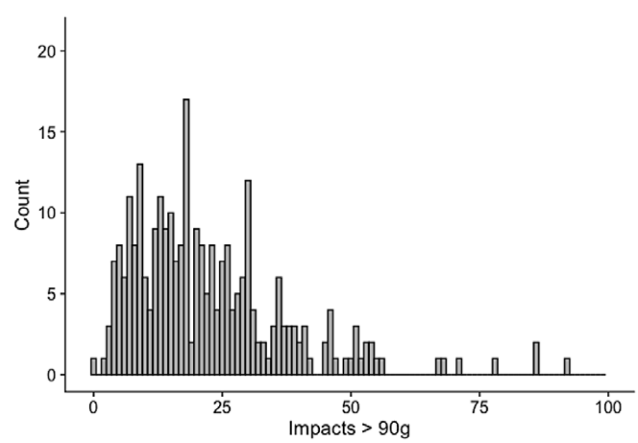

Fig. 1. Repetitive head impacts in athletes over a single football season.

Linear Mixed-Models

Multivariate analyses were conducted separately for each set of outcomes (see Tables 4 and 5). There were no significant main effects of head impacts, pre-season SWAN ratings, or their interaction on either athlete- or parent-rated post-season concussion symptom factor scores (Table 4). Similarly, there were no significant main effects of head impacts or pre-season SWAN ratings, nor their interaction, on post-season neurocognitive task variables (Table 5). Post-hoc power analysis with 5000 repetitions returned coefficients for the interaction for the PCSI outcomes between 0.051 and 0.064, and 0.058 and 0.068 for the neuropsychological outcomes, indicating at the current sample size, the effect is likely near zero.

There were a few significant effects of covariates in the expected directions. Specifically, a greater number of seasons played of contact sports was significantly associated with worse post-season scores on the PCSI fatigue factor. In addition, a change in ADHD medication status from being unmedicated at pre-season to medicated at post-season was significantly associated with improved performance on the conflict metric of the ANT and on the Trail Making Task. Additionally, a sustained concussion during the sports season was significantly associated with increased post-season parent-rated PCSI Physical symptoms. Of note, sustaining a concussion was associated with increased ANT alerting scores. Such an association is in the unexpected direction.

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Table 4. Mixed-models regression analyses of the effects of head impacts and mean SWAN scores on post-season concussion symptom factor scores (unstandardized betas)

	Medicated pre- and post-season	Medicated post-season only	# Seasons	TBI history	Concussion	Impacts	SWAN	SWAN x impacts
Athlete								
Cognitive	−0.650	1.967	0.074	1.277	1.501	0.045	0.325	0.020
Emotional	−0.148	−0.662	0.045	0.939	−0.688	0.023	0.201	0.014
Fatigue	−0.168	−0.708	0.067[c]	0.637	0.242	0.014	0.190	0.015
Physical	0.454	−0.546	0.060	0.711	1.527	0.031	0.579	0.009
Parent								
Cognitive	−0.448	−0.088	−0.007	0.582	1.625	−0.003	−0.423	0.003
Emotional	0.859	−0.590	−0.016	0.730	0.797	0.011	−0.242	−0.007
Fatigue	0.364	−0.641	−0.014	0.059	0.669	0.004	−0.021	−0.011
Physical	0.589	−0.744	0.022	0.394	3.612[a]	0.028	−0.123	−0.027

Note. SWAN, strength and weaknesses of ADHD-symptoms and normal behavior scale; cognitive, concussion symptom measure cognitive factor score; emotional, concussion symptom measure emotional factor score; fatigue, concussion symptom measure fatigue factor score; physical, concussion symptom measure physical factor score; medicated; reported ADHD medication status; Seasons, number of seasons having played contact sports; TBI history, reported history of any possible or confirmed traumatic brain injury; concussion, concussion sustained over the course of the Fall 2018 sports season; Impacts, number of repetitive head impacts over 90 g. Reported p-values for Impacts, SWAN, and SWAN x Impacts are the FDR-corrected p-values.
[a] $p < .05$.
[c] $p < .001$.

Table 5. Mixed-models regression analyses of the effects of head impacts and mean SWAN scores on post-season neurocognitive task scores (unstandardized betas)

Task	Medicated pre- and post-season	Medicated post-season only	# Seasons	TBI history	Concussion	Impacts	SWAN	SWAN x impacts
ANT: Mean RT	24.736	3.769	−0.439	−0.031	−7.735	0.080	−0.808	0.253
ANT: SDRT	0.795	12.045	−0.161	0.591	3.262	−0.073	−1.248	0.033
ANT: Alerting	2.200	−0.715	−0.029	−0.790	18.608[b]	0.154	0.384	0.181
ANT: Orienting	−16.917	−4.450	−0.069	−6.235	2.890	−0.106	−0.021	0.058
ANT: Conflict	−1.753	−26.778[b]	0.022	−1.880	−9.645	0.023	−3.549	0.037
ANT: Accuracy	−2.300	−3.219	0.005	−0.074	−1.784	0.024	0.213	0.007
Trails B-A	3.134	11.592[a]	−0.188	−1.011	−0.013	0.035	−0.366	0.061
TSW: MC Error Rate	3.098	−1.236	0.033	2.269	−2.692	−0.027	0.303	0.007
TSW: MC RT	−26.514	−34.236	0.389	−4.583	−2.300	0.016	−1.104	0.078
TSW: SC Error Rate	10.104	9.908	−0.095	2.431	−1.707	0.102	−0.905	0.024
TSW: SC RT	−13.040	39.567	−0.164	4.617	8.305	0.163	−5.192	−0.249

Note. RT, reaction time; SDRT, standard deviation reaction time; ANT, attention network task; TSW, task switching; MC, mixing cost; SC, switching cost. Reported p-values for Impacts, SWAN, and SWAN x Impacts are the FDR-corrected p-values.
[a] $p < .05$.
[b] $p < .01$.

DISCUSSION

This prospective longitudinal study examined the relationship between ADHD symptoms and behavioral and neurocognitive outcomes following a single season of head impact exposure. In the present study, neither head impacts, nor ADHD symptom levels, were associated with worsening of athlete- or parent-rated post-season concussion symptom ratings or neurocognitive task performance after a single season of high school boys' football.

Head Impacts

Results from this study indicated that the number of head impacts over 90g of force were not associated with any athlete- or parent-reported concussion symptom factor scores, nor any metrics of neurocognitive task performance at post-season. This is consistent with other studies examining the impact of head impacts on concussion symptoms and neuropsychological performance (e.g., memory, attention, and executive functioning) following short-term exposure

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(e.g., a single sports season) to repetitive subconcussive head impacts (Belanger et al., 2016; Mainwaring et al., 2018). However, it is possible that the limited effect of head impacts exposure on key outcomes may be attributable to our measurement of head impact exposure. While a 90 g threshold has been suggested to represent the force at which impact may potentially place athletes at neurological risk (Beckwith et al., 2013; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003), there is no consensus on a particular threshold of significant g-force as it relates to degradation of neurocognitive performance. It also is possible that it may require cumulative head impact burden over many seasons or assessment of longer-term outcomes to detect effects (Montenigro et al., 2017).

Another reason for the lack of association between head impact and behavioral and neurocognitive outcomes may be due to the measurement of these outcomes. With regards to post-concussion symptoms, importantly, these symptoms can be difficult to assess even when a diagnosed concussion has occurred. Post-concussion symptoms are only present in a subset of patients following a concussion, with prevalence varying widely based on a number of factors (e.g., pre-injury factors, patient characteristics, assessment methods, time since injury), and are nonspecific to concussion (Polinder et al., 2018). Furthermore, the 3-month timescale for which post-concussion symptoms were assessed may have also not been sensitive enough to reliably detect changes in these symptoms. With regards to neurocognitive tasks, tasks were selected based on their documented sensitivity to the subtle short-term neurocognitive effects of head impact exposure and concussion-related deficits in pediatric and adult samples (Howell et al., 2013; Karr, Areshenkoff, & Garcia-Barrera, 2014; Mayr et al., 2014; Moore et al., 2016; Moore et al., 2015). So how can the absence of neurocognitive changes be explained given the documented changes in neurophysiology (Abbas et al., 2015; Breedlove et al., 2012; Davenport et al., 2014; Nauman et al., 2015) and/or white matter integrity (Bahrami et al., 2016; Bazarian et al., 2014) that appear to be present following a season of contact sport? Perhaps the neurological changes are compensatory and result in unaltered task performance. In fact, Yuan et al. (2018) reported a post-season increase in functional neural activation in the absence of altered performance on a working memory task. Therefore, it is possible that our measures were not sufficiently demanding to override these compensatory mechanisms to detect subtle behavioral and neurocognitive changes.

One particularly noteworthy aspect of the neurocognitive tasks used in this study is both the presence and absence of possible practice effects. Practice effects resulting from repeated administration of neurocognitive or neuropsychological tests are a significant challenge in concussion assessment (Belanger & Vanderploeg, 2005; Farnsworth, Dargo, Ragan, & Kang, 2017; Parsons, Notebaert, Shields, & Guskiewicz, 2009). In the present study, both the ANT and Cued Task Switching tasks appeared to be susceptible to learned effects from repeated assessments, indicated by the significant improvements in task performance after completing the tasks a second time at the post-season visit. Pre- to post-season effect sizes on the ANT outcomes ranged from 0.16–0.75, while the effect size for mixing-cost reaction time on the Cued-Task Switching task was 0.27. Such effects are consistent with a meta-analytic review of post-concussion neuropsychological task performance, which highlighted significantly improved within-subject comparisons 7 days post-concussion for orientation, attention, and executive functioning abilities compared to baseline performance, despite no between-subject differences when compared with control participants (Belanger & Vanderploeg, 2005). However, analogous within-subject effect sizes from this review were larger (attention: 0.92; executive function: 1.10) than those observed in the present study. Of note, on the ANT, alerting scores increased between pre- to post-season suggesting that athletes became more efficient at using the cue for temporally alerting them of the target presence. Contrarily, orienting scores decreased between pre- to post-season suggesting that athletes may have learned to ignore or disengage from the non-informative central cue (Fan & Posner, 2004). However, no such practice effects were observed for the Trail Making test.

ADHD Symptoms

The results from this study also revealed a general pattern of pre-season difficulty with ADHD symptoms not being associated with athlete- or parent-reported post-season concussion symptom ratings. Such associations might be expected given that diagnosed ADHD has been associated with worse concussion symptom ratings both pre- and post-concussion (Biederman et al., 2015; Cook et al., 2020; Iaccarino et al., 2018; Orban et al., 2021). Additionally, there is substantial overlap between the cognitive, emotional, and fatigue symptoms present in concussion and ADHD (e.g., difficulty concentrating, emotional/sleep disturbances). A likely reason for the general absence of relationships between ADHD symptom levels and post-season concussion symptom ratings is the relative absence of any meaningful impairment captured by the SWAN ratings. This is likely due in large part to the representative nature of the study sample, as we did not actively recruit participants with ADHD. Only 24 out of 258 athletes (9.3%) had five or more ADHD symptoms (the current diagnostic threshold for individuals age 12 or older; APA, 2013) in either the Inattention (IN) or Hyperactivity-Impulsivity (HI) symptom domain rated as “slightly below average” or worse on the SWAN, a cutoff used in other studies utilizing SWAN data (Ramtekkar, Reiersen, Todorov, & Todd, 2010). Such a prevalence is lower than the prevalence of current ADHD among male adolescents ages 13–17 as reported by a recent national survey (Danielson et al., 2018). Thus, the SWAN scores in the present study overwhelmingly indicated the absence of ADHD symptoms, rather than a continuum of symptom presence, making it difficult to detect direct effects of ADHD symptomatology.

Moderating Effects of ADHD

Contrary to our hypotheses, the results from this study reveal a prevailing pattern that ADHD symptoms do not serve as a moderator between head impacts and any post-season athlete or parent-reported post-concussion symptom factor scores or neurocognitive performance. Perhaps this is to be expected given the absence of main effects of head impacts or pre-season ADHD symptoms on athlete- or parent-reported post-concussion symptom ratings and neurocognitive performance at post-season. While some studies examining the effects of ADHD on concussion symptoms in athletes have observed significant effects, these studies have examined concussion dichotomously (Biederman et al., 2015; Iaccarino et al., 2018). However, consistent with the present study, research examining repetitive head impacts has failed to observe significant effects of ADHD on concussion symptoms (Rose et al., 2019). Hence, the ability to detect main or moderating effects of ADHD symptoms might require more severe head impact exposure, either in terms of intensity (i.e., impacts sufficient to result in concussion) or cumulative burden (i.e., many seasons of contact sports).

Limitations

This study has several limitations. First, we were unable to assess for common comorbid psychiatric conditions in adolescents, such as anxiety or depression. Such conditions, if present, would likely influence athlete- and parent-reported post-concussion symptom ratings given that several post-concussion symptoms are also present in these psychiatric conditions (e.g., irritability, sadness, nervousness, sleep disturbances). A second limitation was that we employed an *adapted* concussion symptom survey that has not undergone reliable testing or been validated (modification to the instructions). Despite our intention to better characterize symptoms over longer time periods (noted in the methods), this change may explain why the post-concussion symptom factor scores exhibited considerable variability both across and within athlete- and parent-reported scores. For example, athlete-reported change scores for the total symptom factor score (maximum possible score = 126) had a mean of –0.14 and a standard deviation of 11.94, indicating a wide range of both worsening and improving symptoms at post-season. Another limitation is that while post-concussion symptom factor scores varied widely, SWAN scores were not sufficiently varied. Though we chose the SWAN specifically because of its ability to capture a large range of variability in levels of functioning across different ADHD symptoms, there was a very limited range at the lower bound of the SWAN scores representing higher levels of impairment. Furthermore, 13.8% of football athletes in our sample reported a previous diagnosis of ADHD, which is a slightly lower prevalence than the reported life-time prevalence in same-aged males (Danielson et al., 2018). Though, to our knowledge, there is no literature examining differences in ADHD prevalence across sports, it is possible that adolescents with ADHD may be less likely to participate in football due to associated inattention and executive functioning
difficulties, and the high cognitive demands of football (e.g., remembering the playbook, learning defensive coverages). In addition to measurement-related limitations, there was also a substantial amount of missing parent data at both pre- and post-season. Regarding the study sample, the present study would have benefited from including a control group of non-contact sport athletes. Furthermore, the generalizability of this study is limited by only examining male athletes.

Future Directions

Future studies examining associations between repetitive head impacts, premorbid ADHD, and behavioral and neurocognitive outcomes may benefit from examining a broader range of concussion assessment measures such as motor/vestibular tasks or other neurocognitive constructs. For instance, it is possible that following repetitive head impacts, observable changes in more foundational behavioral and neurocognitive processes such as balance, postural sway, working memory, or processing speed may manifest before, or even without, observable changes in higher-order processes such as emotions or task switching. Thus, a more comprehensive examination of these outcomes may provide important information about different patterns of clinical outcomes across different quantities or severities of head impacts. Additionally, another important target of future research may be examining the effects of repetitive head impacts on ADHD symptoms, specifically in athletes with pre-morbid diagnosed ADHD. While assessing the influence of repetitive impacts on the full spectrum of ADHD symptoms may not reveal significant effects, athletes with preexisting clinically significant ADHD symptoms may nonetheless be at greater risk for negative outcomes. Furthermore, our understanding of ADHD and athlete head injuries would further benefit from examining associated features of ADHD that may place athletes with the disorder at greater risk for sustaining head impacts (e.g., inattention/distraction leading to accidental collision, an impulsive playing style).

CONCLUSION

Results indicate that athletes' relative high magnitude head impact exposure was not related to any behavioral or neurocognitive outcome after a single season of high school football. Furthermore, pre-season ADHD symptom levels examined continuously on the full symptom spectrum did not expose any unique relationships between head impact exposure and deficits in post-season outcomes, controlling for pre-season concussion symptom ratings and neurocognitive performance. Thus, athletes with increased ADHD symptoms did not appear to be at any additional risk for adverse outcomes relative to athletes with lower levels of ADHD symptoms. However, examining the effects of head impacts on ADHD symptoms in athletes with higher baseline ADHD symptom levels is necessary to enhance the generalizability of the present findings. Despite the promising results of limited negative effects of head impact exposure during a season of high-school football, concluding that a single season of head impact exposure does not impact functioning should be considered cautiously. Future research would benefit from more granular measures that are less susceptible to reporting error or practice effects, tap other domains of neurocognitive function (e.g., working memory), and also challenge the entire sensorimotor system (e.g., balance, cognitive and motor dual tasks) to further elucidate whether cumulative head impact exposure and ADHD symptom levels influences neurocognitive function.

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CONFLICTS OF INTEREST

Gregory D. Myer has consulted with Commercial entities, including Q30 Innovations to support applications to the US Food and Drug Administration but has no financial interest in the commercialization of the products. Dr. Myer's institution receives current and ongoing grant funding from National Institutes of Health/NIAMS Grants U01AR067997, R01 AR070474, R01AR055563, R01AR076153 and industry sponsored research funding related to brain injury prevention and assessment with Q30 Innovations, LLC, and ElMinda, Ltd. Dr. Myer receives author royalties from Human Kinetics and Wolters Kluwer. Dr. Myer is an inventor of biofeedback technologies (2017 Non Provisional Patent Pending- Augmented and Virtual reality for Sport Performance and Injury Prevention Application filed 11/10/2016 (62/420,119), Software Copyrighted.) designed to enhance rehabilitation and prevent injuries and has potential for future licensing royalties. No additional conflicts of interest exist.

ETHICAL STANDARDS

All study procedures were conducted in accordance with our institution's Institutional Review Board and the Helsinki Declaration.

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