Archives of Clinical Neuropsychology, 2024, **00**, 1–8
https://doi.org/10.1093/arclin/acae004
Original Empirical Article

Neurocognitive Concussion Test Performance for Student Athletes on the Autism Spectrum

Joseph Fontanals, Joseph P. McCleery, Philip Schatz*

Department of Psychology, Saint Joseph's University, Philadelphia, PA, USA

*Corresponding author at: Saint Joseph's University, Department of Psychology, 5600 City Avenue, Philadelphia, PA 19131, USA. Tel.: 610-660-1804.
E-mail address: pschatz@sju.edu (P. Schatz).

ABSTRACT

Objective: To examine baseline neurocognitive functioning among adolescent athletes on the autism spectrum based on self-reported level of academic performance.
Method: Participants in this cross-sectional, observational study were 6,441 adolescent athletes with a self-reported diagnosis of autism who completed pre-season neurocognitive testing using Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT); 4,742 reported a co-occurring learning disorder (LD), and 6,612 individuals without autism or LD were included as a control group. The majority (57%) self-reported Average Academic Performance, 39% Above Average, and 4% Below Average performance.
Results: Athletes with self-reported autism (with or without LD; 12.2%) were 2.74x (95% CI: 2.17–2.82) more likely to fall below cutoffs for ImPACT Embedded Invalidity Indicators (EVIs), with a significant interaction between self-reported Diagnosis and Academic Performance; individuals with co-occurring autism and LD who reported Below Average Academic Performance had the greatest likelihood of scoring below cutoffs (22%), followed by ASD without LD (14.8%) and Controls (14.6%) with Below Average Academic Performance. Analyses of variance (ANOVAs) revealed main effects of Diagnosis and Academic Performance on neurocognitive performance, with interactions on all ImPACT Composite Scores except Processing Speed.
Conclusion: Athletes with self-reported ASD are more likely to fall below ImPACT EVIs and score worse on ImPACT, with greater likelihood/-worse performance related to level of academic functioning. Academic performance should be considered when interpreting neurocognitive testing data, to best index neuropsychological functioning associated with concussion in this population. The current findings highlight the importance of individual participant baseline neuropsychological testing for individuals on the autism spectrum.

Keywords: Concussion; Autism spectrum disorder; Baseline Assessment

The assessment and management of sports-related concussion has received considerable attention in the past two decades, especially as applied to youth and child athletes. In the absence of a "gold standard" or neuromarker/biomarker for definitive diagnosis of concussion, consensus experts recommend a multi-modal clinical evaluation, including the use of symptom rating scales, balance and vestibular/ocular testing, and neurocognitive performance (Patricios et al., 2023). Baseline or pre-season/pre-participation neurocognitive test performance is often documented for use as a comparator against post-concussion performance. However, although post-concussion cognitive decline can be accurately identified using comparisons to normative data (Echemendia et al., 2012), such comparisons may improperly classify athletes who fall outside the "average range" (Schatz & Robertshaw, 2014). Moreover, individuals with neurodevelopmental disorders often score significantly lower than neurotypical individuals (Cook et al., 2023;) on neurocognitive testing. Further individuals with Attention Deficit Hyperactivity Disorder (ADHD), Learning Disorder (LD), and Autism Spectrum Disorder (ASD) are frequently omitted from normative reference data (Maietta et al., 2021) decreasing the utility of concussion assessment measures for the assessment and management of concussion in individuals with these disorders.

ASD is a neurodevelopmental disorder affecting an individual's social and behavioral abilities. ASD is typically life-long and develop before school age, although diagnosis may not occur until later in childhood or adolescence (Levy et al., 2010). Within the United States, the prevalence of ASD has increased over the past 20 years, from 1/150 children in 2000 to 1/36 children in 2020 (Center of Disease Control and Prevention, 2023). Globally, the rate of ASD has been documented at 1/100 children, with increased prevalence thought to be reflective of a combination of factors, including sociodemographic variance, increased awareness and public health response, and improvements progress in case identification (Zeidan et al., 2022). As individuals with ASD often present with motor deficits, increasing their risk for falls and other accidents (Miller et al., 2021), and given that nearly 91% of adolescents with ASD reported liking individual sports and exercise (Stanish et al., 2015), the potential for concussive injuries in this population is quite high.

Received: August 1, 2023. **Revised:** January 12, 2024. **Accepted:** January 15, 2024

Individuals with ASD commonly share comorbidity with other neurodevelopmental disorders (NDs), including intellectual disability, LD, and ADHD (Levy et al., 2010). The presence of such co-occurring disorders has potential to further complicate concussion assessment and diagnosis, given that students with ADHD and LD often score below average (e.g., on the left of the normative curve) on neurocognitive assessments, independent of an accompanied ASD diagnosis (Maietta et al., 2021). In a multi-state surveillance network, among autistic children with available intelligence quotient (IQ) test data, 35% scored in the intellectually disabled range (e.g., 70 or below), 23% scored in the Borderline range (e.g., between 71 and 85), and 42% scored in the Average to Above Average range (e.g., 85 or greater) (Maenner et al., 2021). It is important to note that these documented IQ ranges may not be reflective of children with ASD participating in organized athletics, and may reflect a noticeably more cognitively impaired group of students with ASD. In the classroom, even more intellectually capable children with ASD exhibited discrepancies between intellectual ability and academic achievement (Estes et al., 2011). Predictive factors of academic progress among students with ASD include sustained attention (McDougal et al., 2020), as well as cognitive flexibility and working memory (Dijkhuis et al., 2020). That said, academic achievement in students with ASD often falls along a continuum, ranging from significantly/functionally impaired students with special needs (Dalgaard et al., 2022) to students performing at or above the normal academic range (Whitby & Mancil, 2009). Given that previous research has documented lower neurocognitive test performance in student athletes with ASD (Cook et al., 2023; Maietta et al., 2021), the purpose of this study was to analyze and compare neurocognitive test performance among student athletes with and without ASD, whereas accounting for comorbid diagnosis of LD and levels of academic performance.

METHODS

Participants

Participants in this cross-sectional, observational study were student athletes, ages 12- to 22-years (mean age = 15.46, SD = 2.01) who completed a pre-season baseline assessment using the ImPACT test as part of their institution's concussion management program, between July 2018 and August 2022. Deidentified data were provided by the Chief Technology Officer from ImPACT Applications, who was blind to the purpose of the study. Exported data were restricted to test-takers who had completed their assessment in English, were from an organization in the United States, had not sustained a concussion in the past 6 months, and had no history of moderate to severe brain injury, seizures, or history of alcohol/drug addiction. The resulting sample was predominantly male (81.5% male vs. 19.5% female) and comprised of a total of 6441 individuals who responded "Yes" to the question "have you ever been diagnosed with Autism". Although research on neurocognitive test performance among student athletes with ASD is limited in the current literature, use of self-reported Autism diagnosis has been used by other researchers (Cook et al., 2023; Maietta et al., 2021). Baseline test data from an additional sample of 6612 individuals were exported from the ImPACT normative database (without ASD, LD or ADHD). As reflected in Table 1, the control group was of similar age as individuals with self-reported ASD (with or without LD; $p = .49$) and similar distribution of gender ($p = .17$), yielding a total sample of 13,053. ImPACT also contains a self-reported measure of student performance, and test-takers rate their level of academic performance on a 3-point ordinal scale: Below Average, Average, or Above Average. Overall, 3.7% of the sample self-reported a Below Average academic performance, 57.0% self-reported Average academic performance, and 39.3% Above Average academic performance. With respect to Developmental Diagnosis, 13.0% self-reported a diagnosis of ASD (without LD) and 36.3% self-reported both ASD and LD. Demographic information is presented in Table 1.

Measures

Demographic data collected through ImPACT included binary Yes/No fields for test-takers to self-report diagnoses of ADHD, LD and ASD, as well as a self-rating of whether they are a Below Average, Average, or Above-Average student. The neurocognitive testing portion of the test yields four composite scores: Verbal Memory, Visual Memory, Motor Speed, and Reaction Time. ImPACT has been shown to have moderate-to-high levels of sensitivity and specificity (Czerniak et al., 2021; Schatz & Sandel, 2013), with mixed test–retest reliability data, ranging from low (Broglio et al., 2007; Resch et al., 2013) to moderate (Ferris et al., 2022) to high (Elbin et al., 2011; Nakayama et al., 2014; Schatz & Ferris, 2013) across a range of time intervals. Scores falling below embedded invalidity indicators (EVI) reflect baseline performance below the 5th percentile, and are identified with a "Baseline ++" classification; the specific criteria for identifying invalid test results are presented in Table 2 (Lovell, 2021).

Procedures

Student athletes were assigned to independent groups based on self-reported developmental diagnosis: ASD (without LD), ASD (with comorbid LD), and Control (neither ASD nor LD). In addition, student athletes were assigned to independent groups on the basis of self-reported academic performance: Below Average, Average, and Above Average.

Analyses

Chi-square analyses were conducted to identify the likelihood of obtaining an invalid baseline (Yes/No) on the basis of self-reported Developmental Diagnosis (Control, ASD without LD, ASD with LD) and on the basis of self-reported Academic Performance level (Below Average, Average, Above Average), with odds ratios (OR) using Cramer's V as a measure of effect size. Individual validity indicators were coded into dichotomous variables based on the pre-determined cutoffs in the ImPACT Manual, (Lovell, 2021) and outlined in Table 2. A log-linear analysis was conducted to identify the likelihood of obtaining an invalid baseline on the basis of both self-reported ASD and Academic Performance level. Finally, 3×3 Analyses of variance (ANOVAs) were conducted to identify the effects of Academic Performance (Below Average, Average, Above Average) and self-reported Developmental Diagnosis (Control, ASD without LD, ASD with LD) on neurocognitive test performance, using the 4 ImPACT composite scores and Total Symptom Scores as the dependent variables, with Scheffé post-hoc analysis.

Table 1. Demographic data

Variable	Developmental diagnosis		
	Control	ASD no LD	ASD with LD
Age	15.46(2.01)	15.15(1.95)	15.57(2.02)
Sex, %			
Male	81.50%	80.90%	80.10%
Female	18.50%	19.10%	19.90%
Academic Performance, %			
Above Average	46%	41.20%	29.20%
Average	53%	55.10%	63.20%
Below Average	1%	3.70%	7.60%
Composite Score			
Verbal Memory	84.44(10.72)	81.68(12.05)	79.31(12.62)
"Valid"	85.20(10.17)	83.27(10.89)	81.35(11.34)
"Invalid"	70.96(11.18)	64.77(13.92)	60.92(14.85)
Visual Memory	74.75(13.03)	70.28(14.67)	67.13(15.42)
"Valid"	75.53(12.60)	71.55(14.01)	69.09(14.64)
"Invalid"	60.85(12.66)	56.05(15.36)	50.11(14.32)
Processing Speed	35.66(7.15)	34.18(8.1)	31.42(8.38)
"Valid"	35.91(7.07)	34.76 (7.83)	32.06(8.22)
"Invalid"	31.18(7.14)	27.43(8.60)	24.46(8.93)
Reaction Time	0.65(0.10)	0.66(0.11)	0.68(0.11)
"Valid"	0.649(0.10)	0.654 (0.12)	0.682(0.13)
"Invalid"	0.692(0.10)	0.730(0.15)	0.773(0.27)
Symptom Score	4.04(5.65)	11.71(13.39)	12.65(14.94)
"Valid"	9.33(5.60)	11.59 (13.42)	12.27(14.53)
"Invalid"	4.93(6.46)	14.18(15.01)	12.90(15.28)

ASD, Autism Spectrum Disorder; LD, Learning Disorder Sex: [$\chi 2(2) = 3.53$, $p = .17$, $\varphi = 0.02$] Age: [$F(2,13{,}050) = 27.25$, $p < .001$, $\eta^2 = 0.004$]

Table 2. ImPACT validity indicators by developmental diagnosis group

Variable	Developmental Diagnosis			
	Control	ASD no LD	ASD with LD	p/V
Validity Indicator				
Impulse Control >30	0.5%	1.7%	2.8%	0.001/0.09
Below Average	3.1%	6.1%	5.0%	
Average	0.6%	2.4%	2.9%	
Above Average	0.3%	0.3%	2.0%	
Word Memory <69	0.3%	0.7%	2.1%	0.001/0.08
Below Average	0.0%	0.0%	7.5%	
Average	0.3%	0.6%	1.7%	
Above Average	0.3%	0.1%	1.4%	
Design Memory <50	2.5%	4.3%	6.6%	0.001/0.10
Below Average	6.3%	4.5%	11.1%	
Average	2.8%	5.3%	7.2%	
Above Average	2.0%	3.0%	3.9%	
Three Letters Correct <8	2.3%	6.0%	8.6%	0.001/0.13
Below Average	7.8%	10.6%	13.3%	
Average	2.9%	7.3%	9.5%	
Above Average	1.4%	3.7%	5.0%	

ImPACT, Immediate Post-Concussion Assessment and Cognitive Testing V=Cramer's V, as a measure of effect size Note: ranges for validity indicator scores are as follows: Impulse Control: (0–129; sum of X's and O's Total Incorrect (possible Range 0–120) and Color Match Total Commissions (possible Range 0–9)); Word Memory & Design Memory (0–100%), Three Letters Total Letters Correct (0–15)

Given that five dependent measures were included within each ANOVA, and the total number of analyses conducted (n = 20), a Bonferroni-corrected alpha level of $p < .0025$ was set for statistical significance.

RESULTS

Chi-square analysis identified a significantly greater likelihood of participants scoring below validity cutoffs based on self-reported Developmental Diagnosis (Control, ASD without LD, ASD with LD). Athletes with both self-reported ASD and self-reported LD were most likely to produce a score falling below the validity cutoffs (12.9%) compared to those with self-reported ASD without LD (10.1%) or control (5.3%), [$x^2(2) = 206.5$; $p < .001$; V = 0.12] (Table 3). Percentage of individuals falling above/-below individual EVIs is listed in Table 2. Chi-square analyses student athletes with ASD and LD were significantly more likely to surpass cutoffs than were student athletes with ASD and no

Table 3. Baseline score validity by developmental diagnosis and academic performance

Group	Below Average	Average	Above Average	Total	V
All Subjects[a]	19.9%	10.4%	5.2%	9.9%	0.12
Control (n = 6612)[b]	14.1%	6.4%	3.9%	5.3%	0.07
Total ASD (n = 6441)	20.8%	13.9%	7.1%	12.2%	0.12
ASD no LD (n = 1699)	14.3%	12.4%	6.6%	10.1%	0.10
ASD with LD (n = 4742)	21.9%	14.4%	7.4%	12.9%	0.12

[a]Across Academic Performance Groups: [$x^2(2) = 181.54$; $p < .001$, V = 0.12] [b]Between Control vs ASD (with or without LD): [$x^2(1) = 193.59$; $p < .001$;, V = 0.12] [b]Between Control vs ASD no LD vs ASD with LD: [$x^2(2) = 206.5$; $p < .001$; V = 0.11]

Table 4. Number of ImPACT validity indicators by developmental diagnosis and scholastic performance groups

Number of EVIs	Developmental Diagnosis		
	Control	ASD no LD	ASD with LD
4 EVIs	—	—	—
Below Average	—	—	—
Average	—	—	—
Above Average	—	—	—
3 EVIs	—	0.1%	0.2%
Below Average	—	0.0%	0.8%
Average	—	0.1%	0.1%
Above Average	—	0.0%	0.1%
2 EVIs	0.3%	1.0%	1.8%
Below Average	3.1%	1.6%	4.2%
Average	0.3%	0.9%	1.2%
Above Average	0.2%	0.1%	0.9%
1 EVI	5.1%	9.4%	11.3%
Below Average	2.1%	12.7%	17.5%
Average	3.2%	11.1%	12.6%
Above Average	1.7%	6.9%	6.8%
0 EVIs	94.7%	89.5%	86.7%
Below Average	85.9%	85.7%	77.3%
Average	93.6%	87.2%	85.3%
Above Average	96.1%	93.0%	92.2%

V=Cramer's V, as a measure of effect size

LD, and Controls were less likely to surpass cutoff that student athletes with ASD (with or without LD). Similarly, student athletes with Below Average academic performance were significantly more likely to surpass cutoffs than were Average students, and Above Average students were significantly less likely to surpass cutoffs than Below Average and Average students. Of note, within the Control group, 5.1% of individuals "triggered" one EVI, and only 0.3% two or more EVIs. Within the ASD without LD group 9.7% "triggered" one EVI, 1.2% two EVIs, and 0.2% two or more EVIs. Within the ASD with LD group 12.4% "triggered" one EVI, 2.8% two EVIs, and 0.7% two or more EVIs [$x^2(8) = 413.2$; $p < .001$; V = 0.18].

Student athletes with self-reported ASD (with or without LD; 12.2%) were 2.74 times (95% CI: 2.17–2.82) more likely to fall below validity cutoffs [$x^2(1) = 193.59$, $p < .001$, V = 0.12] than individuals without ASD (5.3%; Table 3). Additionally, student athletes self-reporting Below Average performance were significantly more likely [$x^2(2) = 181.54$; $p < .001$, V = 0.12] to produce a score below the validity cutoffs (19.9%) than those with self-reported Average (10.4%) or Above Average (5.2%) performance (Table 3). Log-linear analysis revealed a significant interaction effect between self-reported Developmental Diagnosis and self-reported Academic Performance on the likelihood of scoring below validity cutoffs [$x^2(17) = 26{,}957.02$, $p < .001$]; individuals with both self-reported ASD and LD that self-reported Below Average Academic Performance had the greatest likelihood of scoring below validity cutoffs (22%) followed by self-reported ASD without LD with Below Average Academic Performance (14.8%) and Control with Below Average Academic Performance (14.6%) (Table 3). See Table 4 for the breakdown of the number of EVIs surpassed by Academic Performance and Developmental Diagnosis groups.

ANOVAs revealed that self-reported Developmental Diagnosis had a significant effect on Verbal Memory [$F(2, 13{,}044) = 26.14$, $p < .001$; $\eta^2 = 0.004$], Visual Memory [$F(2, 13{,}044) = 52.83$, $p < .001$; $\eta^2 = 0.01$], Motor Speed [$F(2, 13{,}044) = 50.41$, $p < .001$; $\eta^2 = 0.01$] and Reaction Time [$F(2, 13{,}044) = 34.06$, $p < .001$; $\eta^2 = 0.01$] (Table 5). In addition, ANOVAs revealed that self-reported Academic Performance had a significant effect on Verbal Memory [$F(2, 13{,}044) = 169.67$, $p < .001$; $\eta2 = 0.03$], Visual Memory[$F(2, 13{,}044) = 156.99$, $p < .001$; $\eta^2 = 0.02$], Motor Speed [$F(2, 13{,}044) = 513.38$, $p < .001$; $\eta^2 = 0.07$] and Reaction Time [$F(2, 13{,}044) = 177.61$, $p < .001$; $\eta^2 = 0.03$], with small effect sizes noted. Interaction effects between self-reported Developmental Diagnosis and self-reported Academic Performance

Table 5. Univariate comparisons for ImPACT composite and symptom scores by developmental diagnosis and academic performance groups, and valid/invalid baselines

	Control			ASD no LD			ASD & LD		
Variable	Below Avg.	Average	Above Avg.	Below Avg.	Average	Above Avg.	Below Avg.	Average	Above Avg.
Verbal Memory	**78.28(11.08)**	**82.74(10.86)**	**86.53(10.13)***	**76.15(14.17)**	**79.44(12.94)**	**84.51(11.51)***	**73.62(15.16)**	**77.32(13.80)**	**81.54(13.56)***
"Valid"	79.33(10.88)	83.59(10.32)	87.12(9.62)	80.29(10.99)	81.80(10.93)	85.53(13.87)	78.91(11.45)	80.49(11.20)	83.73(11.21)
"Invalid"	71.89(10.75)	70.33(11.02)	72.08(11.50)	55.45(9.36)	64.02(14.41)	69.89(11.06)	58.27(14.15)	61.81(14.77)	59.93(15.73)
Visual Memory	**66.77(14.61)**	**72.92(12.99)**	**77.02(12.65)***	**66.12(17.53)**	**67.67(14.81)**	**73.45(14.21)****	**58.87(15.79)**	**65.09(15.74)**	**70.51(15.85)***
"Valid"	68.20(13.76)	73.77(12.58)	77.64(12.25)	70.04(14.62)	69.63(13.76)	74.24(13.87)	63.29(14.27)	67.96(14.38)	72.63(14.29)
"Invalid"	58.00(17.38)	60.46(12.41)	60.85(12.66)	46.55(18.37)	54.66(14.87)	62.17(14.46)	46.04(12.73)	50.99(14.45)	49.56(13.97)
Motor Speed	**29.27(7.56)**	**33.80(6.87)**	**37.93(6.75)***	**29.21(8.48)**	**32.06(8.11)**	**37.15(7.29)***	**25.53(8.20)**	**29.76(8.20)**	**34.95(8.44)***
"Valid"	29.70(7.99)	34.06(6.77)	38.09(6.71)	30.89(7.72)	33.02(7.66)	37.39(7.27)	27.02(7.89)	30.81(7.69)	35.78(7.83)
"Invalid"	25.58(7.12)	29.93(7.12)	33.90(6.57)	20.82(7.28)	25.78(8.62)	33.66(6.81)	21.21(7.54)	24.63(8.64)	26.74(9.76)
Reaction Time	**0.681(0.11)**	**0.665(0.10)**	**0.634(0.09)****	**0.692(0.13)**	**0.680(0.13)**	**0.634(0.11)****	**0.766(0.15)**	**0.704(0.15)**	**0.659(0.19)***
"Valid"	0.683(0.11)	0.663(0.10)	0.632(0.09)	0.678(0.12)	0.669(0.13)	0.632(0.12)	0.748(0.14)	0.692(0.13)	0.647(0.12)
"Invalid"	0.671(0.08)	0.698(0.11)	0.683(0.11)	0.766(0.14)	0.752(0.16)	0.654(0.10)	0.820(0.18)	0.761(0.20)	0.777(0.29)

*Below Average > Average > Above Average; **Below Average > Average, Above Average

	Control			ASD no LD			ASD & LD		
Variable	Below Avg.	Average	Above Avg.	Below Avg.	Average	Above Avg.	Below Avg.	Average	Above Avg.
Symptoms	**8.33(7.88)**	**4.33(5.82)**	**3.60(5.33)****	**15.89(15.75)**	**12.08(14.04)**	**10.96(11.26)***	**16.15(18.71)**	**8.76(12.13)**	**6.86(10.46)****
"Valid"	7.93(7.69)	4.26(5.77)	3.60(5.30)	14.62(15.96)	11.61(13.67)	11.03(12.29)	14.86(17.93)	8.22(11.42)	6.67(10.11)
"Invalid"	10.78(9.07)	5.38(6.40)	3.99(5.60)	22.27(13.49)	15.15(16.00)	9.98(11.77)	20.86(20.59)	12.86(15.99)	9.90(14.72)

*Below Average > Average > Above Average; **Below Average > Average, Above Average were noted on Visual Memory [$F(4, 13{,}044) = 2.77$, $p < .05$; $\eta^2 = 0.001$], Motor Speed [$F(4, 13{,}044) = 2.94$, $p < .05$; $\eta^2 = 0.002$] and Reaction Time [$F(4, 13{,}044) = 5.49$, $p < .001$; $\eta^2 = 0.002$], with small effect sizes noted. Post-hoc analyses for self-reported Developmental Diagnosis group revealed that the Control group performed the best followed by self-reported ASD without LD and then self-reported ASD with LD. Post-hoc analyses for self-reported Academic Performance group revealed that the Above Average group performed the best followed by Average and then Below Average. ImPACT performance by Developmental Diagnosis, Academic Performance, and Baseline Validity is presented in Table 5.

DISCUSSION

The aim of the current study was to examine the relationships of self-reported autism diagnosis, co-occurring learning disability, and academic performance on neurocognitive concussion testing performance in adolescents. This study expands on the limited research investigating the impact of a self-reported ASD diagnosis on neurocognitive test performance. Results indicated a greater likelihood of neurocognitive scores falling below validity cutoffs for individuals with self-reported ASD, with or without comorbid LD. The current study replicates the findings of both Cook and colleagues (2023) and Maietta and colleagues (2021) documenting poorer performance on neurocognitive testing for individuals with ASD. More specifically, the rates of "invalid" baselines in the current sample of athletes with self-reported ASD (with LD) are identical to athletes with self-reported ASD (with LD) reported by Maietta and colleagues (12.9% vs. 12.9%) (Maietta et al., 2021). Given the similarity in sampling (e.g., age, sex) and methodology (e.g., criteria for group assignment), the current study serves to replicate their findings in a different sample. In addition, the current study expands upon the existing literature (Cook et al., 2023; Maietta et al., 2021) by including academic performance as a variable of interest. In particular, the current study revealed (a) a greater likelihood of falling below validity cutoffs based on self-reported Academic Performance level, (b) an interaction between self-reported Academic Performance and self-reported Developmental Diagnosis with respect to likelihood of falling below validity cutoffs, (c) poorer neurocognitive performance for individuals with Below Average academic performance, and (d) interaction effects among self-reported Academic Performance and self-reported Developmental Diagnosis for three of four ImPACT composite scores. Together, the current findings provide important new information on the roles that autism diagnosis itself, co-occurring learning disability, and academic performance level each contribute to clinically significant variability in neuropsychological concussion testing performance.

Past concussion literature has addressed assessment validity in cases of sandbagging (Schatz & Glatts, 2013); however, alternate causes for an "invalid" outcome (such as developmental diagnosis) create the need for an adjustment to the criteria by which we identify cases which fall below invalidity cutoffs which were established largely based on normative samples. Although neurotypical athletes who fall below invalidity cutoffs generally perform above these cutoffs on re-assessment (Schatz et al., 2014) an athlete with ASD may continue to produce scores which fall within the "invalid" range upon re-assessment despite providing their best effort.

In the absence of baseline data, post-injury scores are often compared to normative reference data. However, given that individuals with ASD are not represented in normative samples (Maietta et al., 2021), within-subject comparison of post-injury to baseline performance data are warranted, in particular, for this population. This is especially true for individuals with comorbid LD and ASD, given the higher likelihood of scoring below invalidity cutoffs. Given the nature of the ImPACT test, this increased likelihood may reflect deficits in comprehension, sustained attention, and working memory in those with comorbid ASD and LD (Dijkhuis et al., 2020; McDougal et al., 2020). It is important to note that the identification/classification of "invalid" performance, or "individuals falling below cutoffs", was made solely using ImPACT EVIs. Research has shown that use of external/free-standing symptom validity measures (such as the Medical Symptom Validity Test) show "poor correspondence" to EVIs, and EVIs may not be "equally appropriate" for athletes with ND (Nelson et al., 2015). As such, although ImPACT EVIs may identify individuals falling below cutoffs reflective of the 5th percentile, such performance may not be reflective of intentional underperformance.

Research on the importance and benefits of physical activity and sport in the ASD population shows improvement in motor skills, macular strength, endurance, and social skills (Healy et al., 2018). However, with the promotion and implementation of sports and physical activity in the ASD population comes an increased need for effective and reliable concussion testing procedures to be present and available. Given the findings of the current study and other recent studies (Cook et al., 2023; Maietta et al., 2021), there is a clear need for either an alternative assessment or a modified form of the current ImPACT that is specific to this population. In particular, it is critically important for both research and clinical/medical practice that the field establish normative data as well as appropriate data analysis and interpretation practices and procedures for individuals with ASD on neurocognitive tests such as ImPACT, and similar widely used neurocognitive/neuropsychological tests measuring similar constructs.

This study is not without its limitations. First, both developmental diagnosis and academic performance were self-reported. Of the entire sample, approximately 5% reported below-average academic performance which is likely not reflective of actual classifications in academic settings. Moving forward, an objective scale for measuring academic performance may provide more reliable data on classification of academic performance. Next, although self-diagnosis of ASD is common in adults (Lewis, 2016), it is recommended that self-reported ASD-related symptoms be explored and verified (Lewis, 2017). Given the timeline of the study (e.g., 2018–2022), the overlap with COVID (2020 onset), and the commensurate social isolation (Holm-Hadulla et al., 2023), increases in stress and psychiatric symptomology have been documented (Bertollo et al., 2023). Given that access to social media applications increased during this time frame (Drouin et al., 2020), and ASD-related information on sites such as TikTok was found to be "misaligned with current knowledge" (Aragon-Guevara et al., 2023), self-reported diagnosis of ASD in this sample may not be entirely accurate. Another limitation is inclusion of only student-athletes. ASD is a diverse disorder, ranging from mildly-impaired to entirely non-verbal. Being a student-athlete requires a certain level of cognitive, intellectual, social, and emotional functioning. So, when examining this population, those who are less capable, less interested, and/or less willing to participate in athletics are not represented in the current study findings. As stated earlier, individuals with ASD often experience deficits in motor function and are likely to fall more often than those of the normative population (Miller et al., 2021). Given that falls can occur within athletic competition and/or in everyday life outside of athletics, examining more diverse samples of individuals with ASD will be critically important for providing greater insight into the effects of neurotrauma and ensuring effective and appropriate assessment of concussion data across the full autism spectrum. Despite these limitations, this study expands the current research in this area by investigating the effects of developmental diagnosis on neurocognitive performance whereas controlling for comorbid diagnoses of LD academic performance as well.

In summary, the current study examined the relationship of self-reported autism diagnosis, co-occurring learning disability, and self-reported academic performance levels on neurocognitive concussion testing performance in adolescents. Consistent with the findings of two other recent studies, the adolescents with self-reported ASD in our study had a greater likelihood of neurocognitive test scores below cutoffs for invalidity. Having examined the impacts of both co-occurring self-reported learning disability and self-reported academic performance on this population's neurocognitive testing performance, we further uncovered evidence that both co-occurring learning disability and below average academic performance contributed to lower scores in this population. The current findings highlight the importance of consideration of self-reported developmental diagnoses on neurocognitive testing performance, the critical importance of baseline testing for individual participants with self-reported ASD as a comparison for post-concussion testing interpretation, and the need for the field to establish normative data sets and data analysis and data interpretation practices and procedures for individuals with ASD and related developmental conditions.

AUTHOR CONTRIBUTIONS

Joseph Fontanals (Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing), Joseph McCleery (Conceptualization, Methodology, Supervision, Writing – review & editing), Philip Schatz (Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing).

FUNDING

No funding was received for this study.

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