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Research Article

Cognitive function and recovery during the first 6 months following pediatric mild traumatic brain injury: An A-CAP study

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Abstract

Objectives: This prospective, longitudinal cohort study investigated cognitive functioning acutely and up to 6 months after pediatric mild traumatic brain injury (mTBI) relative to orthopedic injury (OI). **Methods:** Children age 8–17 years with acute (≤48 hours) mTBI or OI were consecutively recruited from five pediatric Emergency Departments. Acute Predicting and Preventing Postconcussive Problems in Pediatrics (5P) clinical risk scores were calculated. Children completed three CNS Vital Signs computerized cognitive battery subtests acutely (≤48 hours) and at 7 days, 3 months, and 6 months post-injury, and performance validity testing at all post-acute assessments. Generalized least squares models were fitted for Reaction Time, Visual Memory, and Executive Function standard scores. **Results:** For children ($N = 841$; 556 mTBI/285 OI; 12.45 ± 2.41 years; 57.91% male; 68.13% White) with valid performance validity and cognitive test scores, Reaction Time was lower after mTBI relative to OI for older (but not younger) children; differences declined in magnitude from acutely ($d = -1.11$) to 6 months ($d = -0.21$). Visual Memory was mildly lower across time after mTBI ($d = -0.20$). Odds of clinically impaired (standard score < 80) Reaction Time were higher acutely and post-acutely after mTBI for older children ($OR = 51.33$ to 8.01), but did not differ by group for Visual Memory or Executive Function. 5P clinical risk scores did not predict cognitive scores after mTBI. **Conclusions:** Pediatric mTBI negatively impacts cognition, especially for reaction time, ≤48 hours post-injury and among adolescents. Early cognitive dysfunction persists up to 6 months after mTBI in some children.

Keywords: Cognition; concussion; mild traumatic brain injury; orthopedic injury; pediatric traumatic injury; traumatic brain injury

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Statement of Research Significance

Research Question(s) or Topic(s): This prospective, longitudinal cohort study investigated cognitive functioning acutely and up to 6 months after pediatric mild traumatic brain injury (mTBI) as compared with mild orthopedic injury (OI). **Main Findings:** Cognitive domain standard scores were reduced after pediatric mTBI relative to OI, especially for Reaction Time ≤48 hours post-injury and among adolescents. Cognitive changes diminished over time during recovery. Odds of clinically impaired Reaction Time were 50-times and 8-times higher acutely and post-acutely after mild traumatic brain injury for adolescents, but did not differ for Visual Memory or Executive Function after mTBI. Clinical risk scores did not predict cognitive scores after mild traumatic brain injury. **Study Contributions:** Pediatric mTBI is associated with an early reduction and high risk of clinical impairment in reaction time that can persist up to 6 months post-injury for some children.

Introduction

Pediatric mild traumatic brain injury (mTBI) is a global public health concern, affecting millions of children annually (Cassidy et al., 2004; Nguyen et al., 2016; Thurman, 2016). In children, mTBI leads to cognitive symptoms that typically are most severe acutely and resolve to pre-injury levels within the first month of recovery (Zemek et al., 2016). However, a substantial minority (15–25%) of children experience persisting symptoms up to 6 months post-injury or longer (Chadwick et al., 2021; Ledoux

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et al., 2019; Mayer et al., 2020). Older children (i.e., adolescents) and females demonstrate particular risk for prolonged symptom recovery following mTBI (Ledoux et al., 2019; Mayer et al., 2020; Sicard et al., 2022, 2025; Zemek et al., 2016). In contrast to our understanding of subjective cognitive symptoms (based on child and parent-proxy report) after mTBI, the recovery trajectories, clinical significance, and moderators of objective cognitive functioning after pediatric mTBI are less well understood. This prospective longitudinal cohort study examined objective measures of cognitive function up to 6 months following pediatric mTBI to address important knowledge gaps.

Pediatric mTBI can negatively affect cognitive functioning, but results vary considerably across studies (Hou et al., 2023; Iverson et al., 2017). It appears to cause mild to moderate reductions acutely (i.e., ≤72 hours) and up to 1-month post-injury for most children (Babikian & Asarnow, 2009). However, cognitive scores are not always reduced after pediatric mTBI (Babikian et al., 2011; Maillard-Wermelinger et al., 2009; Studer et al., 2014). The effects of mTBI are not associated with alterations in general intellectual functioning and differ by cognitive domain (Ware et al., 2023). Fluid cognitive processes appear particularly impacted by mTBI, whereas crystalized processes are generally preserved (Chadwick et al., 2021; Ware et al., 2023). Reaction time, visual learning and memory, and executive functioning are among the most frequently affected fluid cognitive processes (Hou et al., 2023).

Cognitive dysfunction typically lessens over time after pediatric mTBI (Brooks, Daya, et al., 2016; Chadwick et al., 2021; Crowe et al., 2016; Rieger et al., 2013; Sicard et al., 2021). However, no consensus exists regarding the typical time course of cognitive recovery. Conflicting research suggests that cognitive recovery may occur within 1 month, after 3 months, or as late as 2 years post-injury (Beauchamp et al., 2018; Chadwick et al., 2021; Cossette et al., 2016; Crowe et al., 2016; Lambregts et al., 2018; Rieger et al., 2013; Scherwath et al., 2011; Sicard et al., 2021). Substantial heterogeneity in brain development and the neural effects of mTBI could contribute to inconsistent findings. Inconsistent results also are likely to reflect methodological variation across studies (Hou et al., 2023; Iverson et al., 2017; Sicard et al., 2022). This includes varying sample characteristics (e.g., age ranges and sex ratios), comparison groups (e.g., uninjured typically developing children versus children with injuries not involving the head), cognitive assessment measures and tools (e.g., computerized versus paper–pencil; specific tests selected), assessment timing post-injury (e.g., within 72 hours versus 1 month post-injury), and study duration (6 months versus 2 years). Computerized testing appears to offer greater sensitivity to generally subtle and transient cognitive problems after mTBI, especially in reaction time and fluid cognitive processes (e.g., NIH Toolbox; Betz et al., 2024; Chadwick et al., 2021; Dufour et al., 2020) as compared with paper–pencil tests (Beauchamp et al., 2015). Finally, small sample sizes (e.g., Scherwath et al., 2011) could reduce power to detect subtle group differences or track change across time. Prospective, longitudinal research with adequate power for detecting subtle change over time is needed to better characterize the typical recovery trajectories of cognitive changes following pediatric mTBI.

Key demographic factors moderate subjective and objective cognitive symptom recovery following pediatric mTBI. For instance, both biological sex and age at injury moderate cognitive symptom recovery in children, whereby female sex and older age at injury are associated with prolonged recovery (Ledoux et al., 2019; Mayer et al., 2020). Both factors also predict objective cognitive functioning in children after traumatic injury and in uninjured typically developing children more generally (Babikian et al., 2013; Beauchamp et al., 2018; Chadwick et al., 2021; Rieger et al., 2013; Yeates et al., 2022). Limited evidence indicates that sex can moderate recovery of fluid cognitive processes (e.g., processing speed; Rieger et al., 2013) after pediatric mTBI, but this relationship has not replicated across studies (Yeates et al., 2022). Compared with sex, age at injury has been examined as a moderator of cognitive functioning in far fewer studies and does not appear to moderate cognitive functioning after mTBI (Babikian et al., 2013). Additional longitudinal research in larger samples with representative age ranges and balanced sex ratios is needed to understand whether key demographic factors moderate cognitive functioning after pediatric mTBI.

The clinical significance of cognitive changes is poorly characterized in pediatric mTBI. Many published studies do not report rates of clinical impairment based on standard thresholds, and studies that have reported on the clinical significance of cognitive reductions have used varying classification criteria (e.g., standard score ≤ 85 versus standard score ≤ 70; Beauchamp et al., 2018; Lambregts et al., 2018; Rieger et al., 2013; Scherwath et al., 2011). The American Academy of Clinical Neuropsychology (AACN) has established uniform labels for describing standardized cognitive scores (Guilmette et al., 2020). However, no pediatric mTBI study has examined rates of clinical impairment based on those standard classification thresholds. Addressing this knowledge gap has important implications for neuropsychological decision-making and could enhance clinical care of children with mTBI.

This prospective longitudinal study sought to address existing knowledge gaps by examining cognitive functioning up to 6 months following pediatric mTBI relative to mild orthopedic injury (OI). Specifically, this study investigated objective cognitive outcomes up to 6 months post-injury to clarify the recovery course, severity (rate of clinical impairment; i.e., standard scores < 80), and demographic moderators of cognitive functioning after pediatric mTBI. Children with mild OI were included as a comparison group to account for both pre- and post-injury factors that are known to increase children's risk of injury and influence cognitive performance (Babikian & Asarnow, 2009; Yeates et al., 2017). Based on prior research, reduced standard scores and higher rates of clinical impairment (i.e., standard score < 80) in reaction time, executive functioning, and visual memory were expected acutely and post-acutely after mTBI as compared with OI, with gradual recovery occurring by 3 months post-injury (Crowe et al., 2016; Ledoux et al., 2019). Biological sex and age at injury were expected to moderate cognitive outcomes, with worse outcomes for females and older children with mTBI relative to OI (Chadwick et al., 2021; Hou et al., 2023; Iverson et al., 2017).

Methods

General procedures

Data were drawn from the Advancing Concussion Assessment in Pediatrics (A-CAP) study, a prospective, longitudinal, multisite, concurrent cohort observational study of pediatric mTBI and OI (Yeates et al., 2017). The A-CAP study protocol is published (Yeates et al., 2017). Briefly, the study consecutively recruited children (age 8 to 17 years) ≤48 hours of sustaining a mTBI or OI from the Emergency Department of five Canadian children's hospitals in the Pediatric Emergency Research Canada (PERC) network (Bialy et al., 2018). Enrolled children completed

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computerized cognitive testing during the acute Emergency Department visit and at three follow-up visits: post-acute (i.e., targeted for 7 days post-injury; range 1–32, Median = 8, IQR = 4 days) and 3 and 6 months post-injury. All study procedures were conducted in accordance with the Helsinki Declaration, and the ethical standards and Institutional Review Board approval at each study site. Parents and children respectively provided written informed consent and assent.

Participants

Detailed participant inclusion and exclusion criteria is published (Yeates et al., 2017). Briefly, children were included in the mTBI group if they presented with at least one of the following criteria, consistent with World Health Organization (WHO) definition of mTBI (Carroll et al., 2004): observed loss of consciousness, Glasgow Coma Scale score of 13 or 14, or at least one other acute sign or symptom. Children were included in the OI group if they presented with an upper or lower extremity injury associated with an Abbreviated Injury Scale score ≤ 4 (Committee on Injury Scaling, 1998). Children with OI who had a head or face injury, overt or suspected brain injury, or required surgery or sedation were excluded. Children with non-accidental injuries were excluded from both groups.

Measures

Demographic history

Parents completed a standard demographics questionnaire. Socioeconomic status was measured using the Material Deprivation Index (Pampalon et al., 2009, 2014). The Health and Behavior Inventory (Ayr et al., 2009) was used to assess post-concussive symptoms. Premorbid (pre-injury) symptom ratings were provided by parents at the post-acute visit, and post-injury symptom ratings were provided by both parents and children at each follow-up visit.

5P Clinical risk score

The Predicting and Preventing Postconcussive Problems in Pediatrics (5P) clinical risk score (Zemek et al., 2016) was calculated for each participant based on patient demographics and reported medical history, behavioral observation by Emergency Department medical and nursing staff, performance on an acute balance test, and acute self-reported symptoms. The 5P is validated to predict self-reported symptom recovery up to 4 weeks post-injury across multiple samples (Howell et al., 2018; Miller et al., 2023).

Cognitive function

At each study visit, children completed selected tests from the computerized CNS Vital Signs (Gualtieri & Johnson, 2006). Tests were selected that (i) best discriminate mTBI from comparison groups, including mild OI, (ii) are sensitive to changes across time during recovery, and (iii) can be administered acutely without worsening symptoms after mTBI in children (Brooks, Low, et al., 2016). Thus, the Stroop Test, Visual Memory Test, and Shifting Attention Test were selected and used to calculate age-normalized Reaction Time, Visual Memory and Executive Function domain standard scores. The selected tests and domain standard scores align with the factor structure of the full CNS Vital Signs battery (Brooks et al., 2019). Specifically, Reaction Time represents decision-making speed during an inhibitory control test and is the average of two Stroop Test reaction times (complex and stroop); Visual Memory is derived from the Visual Memory Test correct hits immediate, correct pass immediate, correct hits delayed, and correct passes delayed scores; and Executive Function represents cognitive efficiency and flexibility, and is derived from the Shifting Attention Test correct and errors scores (Brooks et al., 2019; Gualtieri & Johnson, 2006). Cognitive domain standard scores were confirmed during data cleaning and quality assurance; domain standard scores derived from subtests with reaction time scores of 0 were considered incomplete and were removed from the final dataset.

Clinical impairment

The selected cutoff threshold for clinical impairment in this study was a cognitive domain standard score < 80 (i.e., <9th percentile rank; Below Average and Exceptionally Low scores based on Guilmette et al., 2020). This threshold was selected to optimize the base rate of low scores given the normal intra-individual variability and frequency of low scores in healthy, uninjured children (Binder et al., 2009; Brooks et al., 2009, 2010; Brooks, 2010), and is consistent with the test score labels based on standard scores for tests with normal distributions recommended by the AACN (Guilmette et al., 2020).

Performance validity

Children completed the Medical Symptom Validity Test (Green, 2004), a standalone performance validity test, at each follow-up visit to measure performance validity. The standard cutoff thresholds for valid performance from the manual were used. Performance validity can account for variance in cognitive testing for children with TBI (Chadwick et al., 2021; Kirkwood & Kirk, 2010). The CNS-VS embedded validity performance indicators were considered (Gualtieri & Johnson, 2006), but ultimately were not used as indicators of performance validity due to prior research suggesting they have low sensitivity (Brooks, Sherman, et al., 2014).

Statistical analyses

Statistical analyses were conducted using R version 4.2.2 (R Core Team, 2021). Groups were compared on demographic and acute injury characteristics using χ^2 for categorical variables and independent samples *t*-test for continuous variables (Yoshida & Bartel, 2022).

Generalized least squares (GLS) models with restricted maximum likelihood estimation were conducted using the *rms* package (Harrell Jr., 2023b) to compare groups and investigate age at injury and biological sex as moderators for cognitive domain standard scores across time (days) post-injury. Thus, participants with at least 1 cognitive domain standard scores and all covariates were included in final analyses. Separate models were conducted for the Reaction Time, Visual Memory, and Executive Function standard scores. Models included predictors group, time (linear and nonlinear), age at injury (centered), and biological sex, and all two- and three-way interactions between group, time (linear and nonlinear), and age or sex, and covariate socioeconomic status as fixed effects, with participant nested within site as random effects. Four-way interactions between group, time, age, and sex were not significant in preliminary analyses and were trimmed from final models to prevent overfitting and ensure interpretability. To test for the linear and nonlinear effects of time, restricted cubic splines with 4 knots were conducted using the *Hmisc* package (Harrell Jr., 2023a). Linear and non-linear effects of time were included in models because recovery is not expected to occur linearly acutely

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up to 6 months post-injury. Instead, recovery is expected to involve rapid recovery acutely and post-acutely, with gradual improvements 3 and 6 months post-injury. For random effects, a continuous first-order autoregressive correlation structure was used because participants and correlated residuals of participant-level change over time are nested within study site. Binomial generalized linear mixed-effect models were fitted to compare groups on rate of clinical impairment (i.e., defined as a cognitive domain standard score < 80) and to examine the moderating effects of time (linear and nonlinear), age, and sex using the same fixed and random effects as prior models.

Post hoc follow-up for significant interactions that involved group in the models for standard scores were conducted using the *emmeans* package (Lenth, 2023). Specifically, groups were compared at 0, 10, 90, and 180 days post-injury for interactions involving time (linear and nonlinear). For interactions involving age, groups were compared at younger (i.e., 5th percentile; 9.36 years) and older (i.e., 95th percentile; 15.90 years) ages at injury. Standardized effect size with 95% confidence interval (CI) was assessed for group comparisons. Specifically, for GLS models, Cohen's *d* was computed, with $|0.20| \leq d < |0.50|$, $|0.50| \leq d < |0.80|$, and $d \leq |0.80|$ signifying small, medium, and large effects, respectively (Cohen, 1988). For the binomial models, odds ratio (OR) was computed, with $1.5 \leq$ OR, $1.50 <$ OR ≤ 2.5, and $2.5 <$ OR ≤ 4 signifying small, medium, and large effects, respectively (Cohen, 1988).

Finally, GLS models with restricted maximum likelihood estimation were used within the mTBI sample to investigate whether the 5P clinical risk score predicted cognitive functioning across time. Only the mild TBI group was examined because risk score calculation was confounded with group. Age and sex were removed from models because they contribute to 5P clinical risk score calculation, but the model structure was otherwise the same as prior models. For the 5P clinical risk score analyses, follow-up tests for significant interactions were compared at the cutoff thresholds for low (5P = 3) and high risk (5P = 9) established in the original validation study (Zemek et al., 2016).

Results

Sample

The A-CAP study enrolled 967 children (633 mTBI/334 OI) out of 3,051 eligible children. Of those, 121 children (12.20%; 71 mTBI/50 OI) only completed study enrollment in the Emergency Department and did not complete any subsequent visits, and were therefore missing data on premorbid symptoms and excluded from analysis. A total of 827 (85.52%; 549 mTBI/278 OI), 722 (74.66%; 477 mTBI/245 OI), and 691 (71.46%; 453 mTBI/238 OI) children returned for the post-acute, 3 months, and 6 months visits. The study attrition rates of 14.48%, 25.34%, and 28.54% for post-acute, 3 months, and 6 months visits did not differ by study site or group, $p \geq .246$ (Ware, Yeates, Tang, et al., 2022; Yeates et al., 2017), and are similar to those of other published pediatric mTBI studies (e.g., Chadwick et al., 2021; Taylor et al., 2015). The children who completed ≥1 study visit after enrollment ($n = 846$; 87.49%; 559 mTBI/287 OI) did not differ from those who only completed study enrollment in the Emergency Department in terms of age at injury, sex, or socioeconomic status, $p \geq .177$.

Children who returned to complete the post-acute visit completed a 3T MRI scan without sedation. Radiological review was conducted by qualified examiners who were blind to group membership. Trauma-related findings (i.e., hyperintensity) were noted in only 2 children (0.2%; 1 mTBI/1 OI). The child (14-year-old female) with trauma-related findings in the mild OI group was excluded from further analysis. An additional 4 children (0.41%; 3 mTBI/1 OI) were excluded for missing cognitive assessment data.

The final sample included 841 children (86.97%; 556 mTBI/285 OI) who had ≥1 valid cognitive domain standard score at one or more study visit and scored above standard cutoffs on standalone performance validity testing; none of the children in the final sample performed below standard thresholds on performance validity testing at any timepoint. Children included in the final sample did not differ from those who only completed study enrollment in the Emergency Department or had missing cognitive data in terms of group, study site, age, sex, or socioeconomic status, $p \geq .188$.

Groups in the final sample (Table 1) did not differ in age at injury, sex, parental education, race, socioeconomic status, whether the injury occurred during sport/recreation, or incidental brain findings (i.e., not considered to be trauma-related; e.g., cyst, posterior fossa malformation, and vascular malformation). However, groups differed in mechanism of injury, and pre- and post-injury symptom ratings were higher in the mTBI group relative to the OI group.

Cognitive domain standard scores

After excluding incomplete cognitive domain standard scores using pairwise deletion (i.e., 34 Reaction Time/32 Visual Memory/3 Executive Function), the final dataset included 2,818 assessments (2,785 Reaction Time/2,788 Visual Memory/2,772 Executive Function) across cognitive domains and study visits. Number of assessments included in final analyses and descriptive statistics for standard scores and rate of scores below the clinical impairment cutoff (i.e., standard score < 80) are reported for the cognitive domains for each group and study visit in Table 2.

Final models included premorbid PCS ratings (based on parent report) as a covariate to account for group differences in this variable. Mechanism of injury differs inherently between groups and was therefore not included as a covariate in final models. Final model statistical results for the cognitive domain scores are reported in Table 3 and shown in Figure 1.

Reaction Time

Time and age moderated group effects for Reaction Time standard scores, after adjusting for sex, socioeconomic status, and premorbid PCS. Scores were lower after mild TBI relative to OI for older children, with differences that were large acutely, Cohen's *d* (95% CI) = −1.11 (−1.42, −0.80), medium post-acutely, −0.70 (−0.98, −0.43), and small at 3 months, −0.29 (−0.61, −0.02), and 6 months, −0.21 (−0.56, 0.14); in contrast, the mild TBI and OI groups did not differ for younger children.

Visual Memory

Visual Memory standard scores were significantly lower after mTBI relative to OI, but with a small effect size, $d = -0.20$ (−0.37, −0.04), and differences did not vary by time, age, or sex, after adjusting for sex, socioeconomic status, and premorbid PCS.

Executive Function

Group and its associated interactions were not significantly associated with Executive Function standard scores, which increased over time. Age and sex were not significant moderators, after adjusting for socioeconomic status and premorbid PCS.

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Table 1. Group sociodemographic and injury characteristics

Variable		Group mTBI (n = 556)	Group OI (n = 285)	p
Study site, *n* (%)				**<.001**
	Calgary	134 (24.10)	62 (21.75)	
	Edmonton	107 (19.24)	56 (19.65)	
	Montreal	60 (10.79)	24 (8.42)	
	Ottawa	139 (25.00)	47 (16.49)	
	Vancouver	116 (20.86)	96 (33.68)	
Valid cognitive scores, *n* (%)				.674
	1 Visit	26 (4.68)	9 (3.16)	
	2 Visits	82 (14.75)	44 (15.44)	
	3 Visits	150 (26.98)	72 (25.26)	
	4 Visits	298 (53.60)	160 (56.14)	
Age at injury, *Mean* (*SD*) years		12.38 (2.51)	12.61 (2.20)	.190
Sex, *n* (%) male		330 (59.35)	157 (55.09)	.266
Parental education, *n* (%)				.800
	No certificate, diploma, or degree	14 (2.52)	6 (2.11)	
	High school diploma or equivalent	65 (11.69)	33 (11.58)	
	Trades certificate or diploma	47 (8.45)	21 (7.37)	
	College diploma (2-year)	105 (18.88)	58 (20.35)	
	Bachelor's degree (4-year)	199 (35.79)	88 (30.88)	
	Master's degree	69 (12.41)	39 (13.68)	
	Doctoral degree (PhD or similar)	14 (2.52)	9 (3.16)	
	Medical degree	7 (1.26)	5 (1.75)	
	Unknown	36 (6.47)	26 (9.12)	
Race, *n* (%)				.298
	Asian	50 (8.99)	22 (7.72)	
	Black	21 (3.78)	7 (2.46)	
	Hispanic	12 (2.16)	12 (4.21)	
	Indigenous	11 (1.98)	3 (1.05)	
	Mixed	69 (12.41)	38 (13.33)	
	Unknown	12 (2.16)	11 (3.86)	
	White	381 (68.53)	192 (67.37)	
Socioeconomic status, *mean* (*SD*)[a]		34.59 (26.90)	34.16 (26.91)	.829
Mechanism of injury, *n* (%)				**<.001**
	Fall	181 (32.55)	118 (41.40)	
	Struck object	130 (23.38)	49 (17.19)	
	Struck person	82 (14.77)	27 (9.47)	
	Bicycle related	8 (1.44)	11 (3.86)	
	Motor vehicle collision	5 (0.90)	0 (0.00)	
	Other	6 (1.08)	19 (6.67)	
	Unknown	144 (25.90)	61 (21.41)	
Injury setting, *n* (%) sport/recreational		345 (62.05)	187 (65.61)	.073
Post-concussive symptoms, *mean* (*SD*)[b]				
	Premorbid (parent)[c]	11.86 (9.86)	9.47 (8.77)	**.001**
	Post-acute (parent)	18.24 (11.71)	7.92 (8.04)	**<.001**
	Post-acute (child)	23.16 (12.78)	8.72 (8.27)	**<.001**
	1-month post-injury (parent)	12.23 (10.26)	7.11 (7.97)	**<.001**
	1-month post-injury (child)	13.39 (12.11)	7.82 (7.97)	**<.001**
	3-months post-injury (parent)	11.20 (9.91)	8.38 (8.50)	**<.001**
	3-months post-injury (child)	12.40 (12.22)	9.18 (9.74)	**<.001**
	6-month post-injury (parent)	10.67 (9.74)	8.56 (8.71)	**.006**
	6-month post-injury (child)	12.09 (11.94)	9.71 (9.78)	**.008**
5P clinical risk score, *mean* (*SD*)		6.14 (1.94)	–	–
Incidental MRI finding, *n* (%)[d]		25 (4.50)	20 (7.02)	.169

Note. **Bolded** signifies $p < .05$.
[a]Pampalon Material Deprivation Index percentile (Pampalon et al., 2009, 2014).
[b]Health and Behavior Inventory total score (Ayr et al., 2009).
[c]Reported at post-acute visit.
[d]Blind radiological review of post-acute MRI scans.

Clinical impairment

The model statistical results for rates of clinical impairment (i.e., standard score < 80) for the cognitive domains are reported in Table 4 and shown in Figure 2.

Reaction Time

Time (linear and nonlinear) and age moderated group differences in the rate of clinical impairment for Reaction Time scores, after adjusting for sex, socioeconomic status, and premorbid PCS. The odds of acute and post-acute clinical impairment were substantially higher after mTBI relative to OI for older children, $OR = 51.33$ (10.07, 261.73) and 8.01 (2.18, 29.39), respectively, but did not differ for younger children (*Supplemental Table 1*). Odds of clinical impairment 3 and 6 months after mTBI relative to OI did not differ by group for younger or older children.

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Table 2. Cognitive domain standard scores and rate of clinical impairment (i.e., standard score ≤ 80) by group and time post-injury

	Time post-injury							
	Acute (≤48 h)		Post-acute (~7 days)		3 Months		6 Months	
Domain	mTBI	OI	mTBI	OI	mTBI	OI	mTBI	OI
Reaction Time								
Assessments, *n* (%)	472 (34.40)	236 (34.05	483 (33.64)	256 (33.95)	444 (33.61)	230 (33.87)	433 (33.72)	231 (33.72)
Standard score, *mean* (*SD*)	86.36 (20.39)	95.02 (14.96)	91.55 (18.37)	96.11 (16.70)	94.64 (17.50)	97.97 (15.84)	96.45 (16.57)	100.11 (14.86)
Clinically impaired, *n* (%)	149 (31.57)	33 (19.98)	117 (24.22)	40 (15.62)	76 (17.12)	29 (12.61)	67 (15.47)	18 (7.79)
Visual Memory								
Assessments, *n* (%)	477 (34.77)	239 (34.49)	480 (33.43)	255 (33.82)	444 (33.61)	228 (33.58)	433 (33.72)	232 (33.87)
Standard score, *mean* (*SD*)	93.89 (17.33)	98.28 (14.23)	94.27 (17.08)	95.45 (15.68)	95.44 (16.12)	98.89 (15.34)	95.49 (16.37)	97.81 (16.76)
Clinically impaired, *n* (%)	80 (16.77)	20 (8.37)	84 (17.50)	40 (15.69)	70 (15.77)	23 (10.09)	72 (16.63)	33 (14.22)
Executive Function								
Assessments, *n* (%)	483 (33.73)	241 (33.66)	486 (33.54)	250 (32.85)	442 (33.23)	223 (32.75)	423 (32.82)	224 (32.61)
Standard score, *mean* (*SD*)	93.64 (16.95)	97.36 (17.44)	105.81 (15.24)	106.92 (14.91)	108.77 (13.74)	109.29 (12.95)	111.38 (13.48)	112.50 (13.29)
Clinically impaired, *n* (%)	84 (17.39)	36 (14.94)	31 (6.38)	15 (6.00)	17 (3.85)	5 (2.24)	11 (2.60)	3 (1.34)

Table 3. Statistical results for the cognitive domain standard scores

		Standard score								
		Reaction Time			Visual Memory			Executive Function		
Predictors		*Wald* χ^2	*df*	*p*	*Wald* χ^2	*df*	*p*	*Wald* χ^2	*df*	*p*
Group (OI – mTBI)		66.04	12	**<.001**	26.61	12	**.009**	16.48	12	.170
	All interactions	37.34	11	**<.001**	11.92	11	.370	12.84	11	.304
Time post-injury (days)		132.50	18	**<.001**	27.46	18	.071	422.10	18	**<.001**
	All interactions	44.11	15	**<.001**	20.51	15	.153	15.75	15	.399
	Nonlinear	56.83	12	**<.001**	19.43	12	.079	139.75	12	**<.001**
Age at injury (years)		62.51	8	**<.001**	32.57	8	**<.001**	12.35	8	.136
	All interactions	40.97	7	**<.001**	12.18	7	.095	10.87	7	.144
Sex (male – female)		15.32	8	.053	10.22	8	.250	4.87	8	.772
	All interactions	6.06	7	.533	9.96	7	.191	4.52	7	.718
Socioeconomic status		5.59	1	**.018**	6.14	1	**.013**	8.82	1	**.003**
Premorbid PCS		12.41	1	**<.001**	5.28	1	**.022**	20.41	1	**<.001**
Group × Time		23.98	9	**.004**	7.66	9	.569	8.70	9	.465
	Linear	13.92	6	**.031**	6.90	6	.330	5.67	6	.461
	Nonlinear	6.18	2	**.045**	0.19	2	.907	1.12	2	.570
Group × Age		23.80	4	**<.001**	3.71	4	.446	4.28	4	.369
Group × Sex		2.73	4	.605	4.47	4	.347	4.22	4	.378
Time × Age		27.37	6	**<.001**	9.82	6	.132	10.40	6	.109
	All interactions	17.26	4	**.002**	7.57	4	.109	2.52	4	.642
	Nonlinear	17.01	2	**<.001**	4.60	2	.100	1.34	2	.513
Time × Sex		5.22	6	.515	7.32	6	.292	0.97	6	.987
	All interactions	4.42	4	.352	3.81	4	.432	0.69	4	.953
	Nonlinear	4.00	2	.135	3.25	2	.197	0.44	2	.804
Group × Time × Age		10.91	3	**.012**	1.41	3	.704	3.80	3	.284
	Nonlinear	5.02	2	.081	0.88	2	.646	1.96	2	.375
Group × Time × Sex		1.83	3	.609	1.88	3	.597	0.69	3	.877
	Nonlinear	1.12	2	.570	1.58	2	.455	0.49	2	.781

Note. **Bolded** = $p < .05$. Final models included covariates socioeconomic status and premorbid PCS scores.

Visual Memory

Group and its associated interactions were not significantly associated with rate of clinical impairment in Visual Memory scores. Age and sex were not significant moderators, after adjusting for socioeconomic status and premorbid PCS.

Executive Function

Group and its associated interactions were not associated with clinical impairment rates in Executive Function, which declined over time. Age and sex were not significant moderators, after adjusting for socioeconomic status and premorbid PCS.

Clinical risk score

The 5P clinical risk score for the mild TBI group is reported in Table 1. Model statistical results for each cognitive domain are reported in Table 5 and shown in Figure 3. The 5P score was not significantly associated with cognitive scores in any of the domains.

Discussion

This prospective, longitudinal study followed children who presented to a pediatric hospital Emergency Department ≤48 hours of sustaining an mTBI or OI for 6 months to understand the severity and recovery trajectories of cognitive changes, and whether age at injury or biological sex moderate cognitive recovery. Study strengths include a larger sample size, broad age range, balanced sex ratio, inclusion of socioeconomic status as a covariate, and assessment of performance validity. Overall, findings suggests that pediatric mTBI can negatively impact cognition up to 6 months post-injury relative to mild OI. Of the

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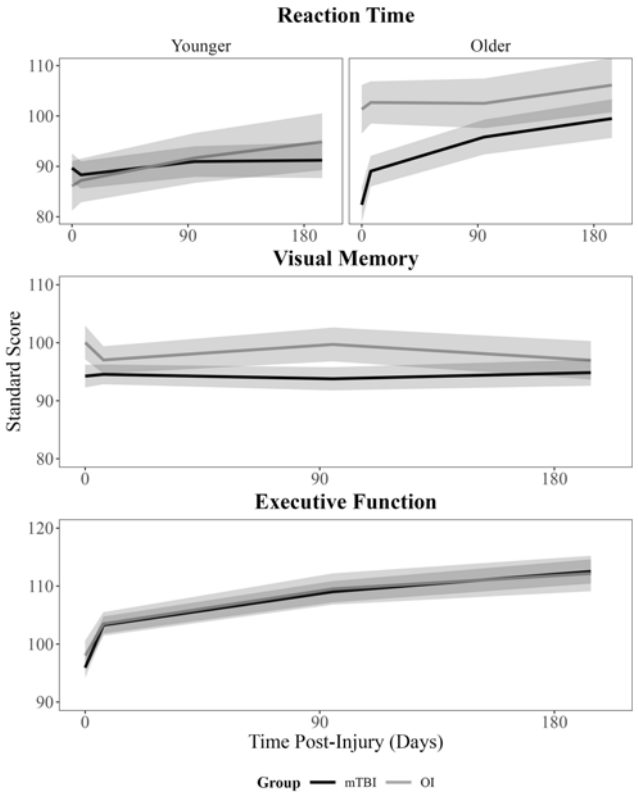


Figure 1. Graphs illustrating group differences in cognitive domain standard scores up to 6 months post-injury. Group differences in Reaction Time standard scores were moderated by time and age, adjusting for sex, socioeconomic status, and premorbid PCS, whereby scores were lower after mild TBI relative to OI for older children (i.e., 95th percentile age), with differences that were large acutely, $d = -1.11$, medium post-acutely, $d = -0.70$, and small at 3 months, $d = -0.29$, and 6 months, $d = -0.21$, but did not differ at any timepoint in younger children (i.e., 5th percentile age). Visual Memory standard scores were mildly lower after mTBI relative to OI, $d = -0.20$, across time, age, sex, socioeconomic status, and premorbid PCS. Groups did not differ in Executive Function standard scores, which increased over time. Estimated marginal means with 95% CI (shading) are shown for each group and domain score.

domains examined, reaction time and, to a lesser extent, visual memory were the most negatively impacted by mTBI. Reaction time scores were substantially reduced ≤48 hours (acutely) and remained decreased for up to 6 months after mTBI in older children (i.e., adolescents), but not in younger children. Children with mTBI also had mildly reduced visual memory scores up to 6 months post-injury, regardless of age or sex. The odds of clinically impaired reaction time scores were significantly higher in adolescents with mTBI relative to OI at acute and post-acute timepoints. Executive function scores did not differ in mTBI relative to OI, but improved with time post-injury across groups. In contrast to the moderating effects of time post-injury and age at injury, sex did not moderate cognitive outcomes after mTBI. Finally, the 5P clinical risk score did not predict cognitive domain scores in the mTBI group.

Prior evidence has suggested mild to moderate reductions in reaction time, visual memory, and executive function after pediatric mTBI relative to OI (Beauchamp et al., 2018; Chadwick et al., 2021) and healthy comparison groups (Sicard et al., 2021). The overall pattern of the current results is consistent with a growing body of research based on computerized testing that suggests pediatric mTBI can affect reaction time, especially during complex tasks, but does not negatively impact executive functioning per se (Brooks, Khan, et al., 2014; Chadwick et al., 2021; Hou et al., 2023). Executive functions are complex higher-order cognitive processes that support goal-directed behavior. The current executive function domain scores provide a measure of cognitive flexibility (Plourde et al., 2018). However, other studies have identified changes in some aspects of executive functioning, including cognitive flexibility, after pediatric mTBI that may differ from the current results due to test selection (e.g., Chadwick et al., 2021; Cossette et al., 2016). Timing of recovery for reaction time and visual memory varies in prior studies, with some suggesting that recovery occurs by 3 months after mTBI relative to OI (Brooks, Khan, et al., 2014; Chadwick et al., 2021), whereas a recent meta-analysis suggests that reaction time reductions persist up to 6 months after mTBI (Hou et al., 2023).

The odds of clinically impaired reaction time was more than 50 times higher acutely and 8 times higher post-acutely after mTBI than OI in older children. However, the 95% CIs were very large, suggesting a lack of precision in the estimates. The large OR and wide 95% CI observed for rates of clinically impaired scores could be sample dependent (i.e., due to small cell sizes for clinical impairment) or result from model overfitting. Regardless, even the lower bound of the 95% CI suggests that, for older but not younger children, concussion has a very strong and statistically significant positive association with clinical impairment, with the odds being at least 10 times higher acutely and at least 2.2 times higher post-acutely after mTBI relative to OI.

The current study selected a clinical impairment threshold (i.e., standard score < 80) based on current recommendations for uniform labeling of standard scores for normally distributed measures (Guilmette et al., 2020). This threshold was selected to optimize the base rate of low scores given the normal intra-individual variability and frequency of low scores in the normative population (Binder et al., 2009; Brooks, 2010; Brooks et al., 2009, 2010). Comparisons of the current rates of clinical impairment to published rates are difficult because studies have used varying thresholds for classifying clinical impairment, e.g., standard score ≤ 85 versus standard score ≤ 70 (Beauchamp et al., 2018; Lambregts et al., 2018). Less conservative thresholds (e.g., standard score < 85), which can be used to identify subtle effects but could overestimate impairment rates, have yielded rates of acute clinical impairment for several cognitive domains after pediatric mTBI (e.g., 35%) similar to those of the present study (Beauchamp et al., 2018; Rieger et al., 2013). More conservative thresholds (e.g., standard score ≤ 70), which could underestimate true impairments that are subtle or transient, or classification of clinical impairment based on performance across tests in a comprehensive battery (e.g., based on two or more measures with standard scores ≤ 70; Beauchamp et al., 2015) have yielded lower rates of clinical impairment post-acutely (10%) and 3 months (5%) post-injury relative to the present study (Beauchamp et al., 2018). Methodological differences could contribute to inconsistencies across studies (e.g., computerized versus paper–pencil tests, timing of assessment post-injury, included cognitive domains, selected measures, etc.).

Children in the OI group demonstrated higher rates of scores below the clinical impairment threshold (i.e., standard score < 80) than would be expected in healthy (normative) populations for age-normalized standard scores. This is not surprising. Clinical impairment has been reported acutely in up to 50% of children with OI (Rieger et al., 2013). Children with OI and mTBI are similar in premorbid factors that predispose children to traumatic injury generally, as well as post-injury factors (e.g., pain, disruption

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Table 4. Statistical results for the cognitive domain clinical impairment rate

		*Clinical impairment**								
		Reaction Time			Visual Memory			Executive Function		
Predictors		*OR*	*CI*	*p*	*OR*	*CI*	*p*	*OR*	*CI*	*p*
Group (OI – mTBI)		0.11	0.03–0.33	**<.001**	0.47	0.20–1.10	.082	0.59	0.22–1.58	.294
Time post-injury (days)		0.88	0.81–0.95	**.001**	0.99	0.92–1.06	.751	0.83	0.74–0.93	**.001**
	All interactions	13.06	1.02–167.68	**.048**	0.54	0.05–5.70	.607	23.30	0.53–1033.71	.104
	Nonlinear	0.06	<0.01–1.00	**.050**	2.00	0.15–26.91	.600	0.03	<0.01–2.09	.107
Age at injury (years)		1.12	0.98–1.27	.084	0.94	0.84–1.06	.297	0.99	0.86–1.14	.906
Sex (male – female)		0.74	0.39–1.40	.351	0.86	0.49–1.52	.604	0.62	0.31–1.27	.192
Socioeconomic status		1.00	1.00–1.01	.266	1.01	1.00–1.01	**.035**	1.01	1.00–1.02	**.045**
Premorbid PCS		1.01	0.98–1.03	.616	1.00	0.98–1.02	.754	1.01	0.98–1.04	.499
Group × Time		1.14	0.98–1.34	.092	1.07	0.94–1.21	.301	0.99	0.79–1.24	.937
	All interactions	0.02	<0.01–2.59	.111	0.16	<0.01– 8.37	.362	76.40	<0.01– 40124006910978.38	.753
	Nonlinear	93.08	0.35–24556.11	.111	7.53	0.09–598.45	.366	<.01	<0.01– 1690621232305.01	.752
Group × Age		0.56	0.40–0.77	**<.001**	0.81	0.62–1.05	.105	0.88	0.66–1.16	.353
Group × Sex		3.03	0.76–12.13	.117	0.89	0.28–2.83	.843	1.45	0.39–5.45	.579
Time × Age		0.98	0.96–0.99	**.010**	1.00	0.98–1.01	.606	1.01	0.98–1.04	.641
	All interactions	2.11	1.16–3.83	**.014**	1.19	0.65–2.17	.574	0.68	0.26–1.76	.425
	Nonlinear	0.44	0.23–0.85	**.014**	0.83	0.43–1.60	.573	1.53	0.53–4.39	.428
Time × Sex		1.09	0.99–1.20	.084	0.99	0.90–1.08	.762	1.01	0.87–1.18	.871
	All interactions	0.11	<0.01–2.60	.171	2.52	0.12–53.27	.553	1.06	0.01–160.15	.982
	Nonlinear	11.27	0.35–368.07	.173	0.35	0.01–10.19	.545	0.90	<0.01– 228.41	.972
Group × Time × Age		1.05	1.00–1.09	**.031**	1.02	0.99–1.06	.232	1.02	0.97–1.08	.407
	All interactions	0.22	0.06–0.90	**.035**	0.52	0.16–1.68	.273	0.65	0.10–4.21	.655
	Nonlinear	5.19	1.13–23.85	**.034**	2.05	0.56–7.46	.276	1.55	0.19–12.37	.678
Group × Time × Sex		0.92	0.76–1.12	.411	1.04	0.88–1.23	.660	1.03	0.78–1.36	.839
	All interactions	22.29	0.05–10802.58	.325	0.16	<0.01–36.99	.509	0.01	<0.01–7113162480.30	.730
	Nonlinear	0.03	<0.01–27.45	.314	7.78	0.02–3129.11	.503	382.72	<0.01–24469835560161024 0.00	.732

Note * = Domain standard score < 80; **Bolded** = $p < .05$; OR = odds ratio. Final models included covariates socioeconomic status and premorbid PCS scores.

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Table 5. Statistical results for the 5P clinical risk scores on cognitive domain standard scores in the mTBI group

		Standard score								
		Reaction Time			Visual Memory			Executive Function		
Predictor	Predictor	*Wald* χ^2	*df*	*p*	*Wald* χ^2	*df*	*p*	*Wald* χ^2	*df*	*p*
5P clinical risk score		9.36	4	.053	2.01	4	.734	3.54	4	.471
	All interactions	6.21	3	.102	1.99	3	.574	3.54	3	.315
Time post-injury (days)		79.08	6	**<.001**	4.67	6	.587	297.13	6	**<.001**
	All interactions	6.21	3	.102	1.99	3	.574	3.54	3	.315
	Nonlinear	28.53	4	**<.001**	1.94	4	.746	100.99	4	**<.001**
Socioeconomic status		10.74	1	**.001**	16.91	1	**<.001**	21.86	1	**<.001**
5P score × Time		6.21	3	.102	1.99	3	.574	3.54	3	.315
	Nonlinear	3.81	2	.149	1.90	2	.387	2.64	2	.267
	All interactions	3.81	2	.149	1.90	2	.387	2.64	2	.267

Note. **Bolded** = $p < .05$. Final models included the covariate socioeconomic status.

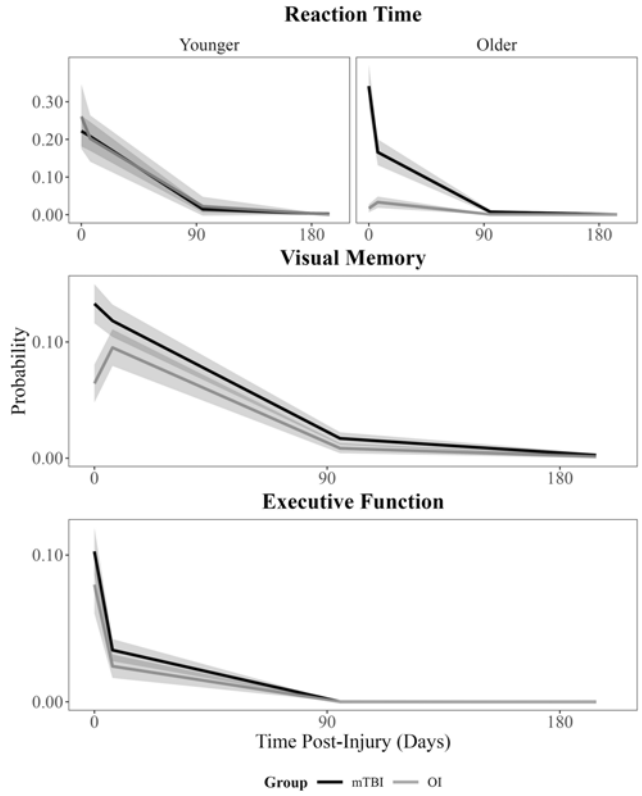


Figure 2. Rate of clinical impairment (i.e., standard score < 80) within the cognitive domains. Time and age moderated group differences in the odds of clinical impairment (i.e., standard score < 80) for Reaction Time, after adjusting for sex, socioeconomic status, and premorbid PCS. Odds of acute and post-acute clinical impairment for Reaction Time after mTBI relative to OI were 51.33 to 8.01 times higher for older children, respectively, but did not differ for younger children at any timepoint or at 3 and 6 months for older children. Rates of clinical impairment for Visual Memory and Executive Function did not differ by group. Estimated marginal means with 95% CI (shading) are shown for each group and domain score.

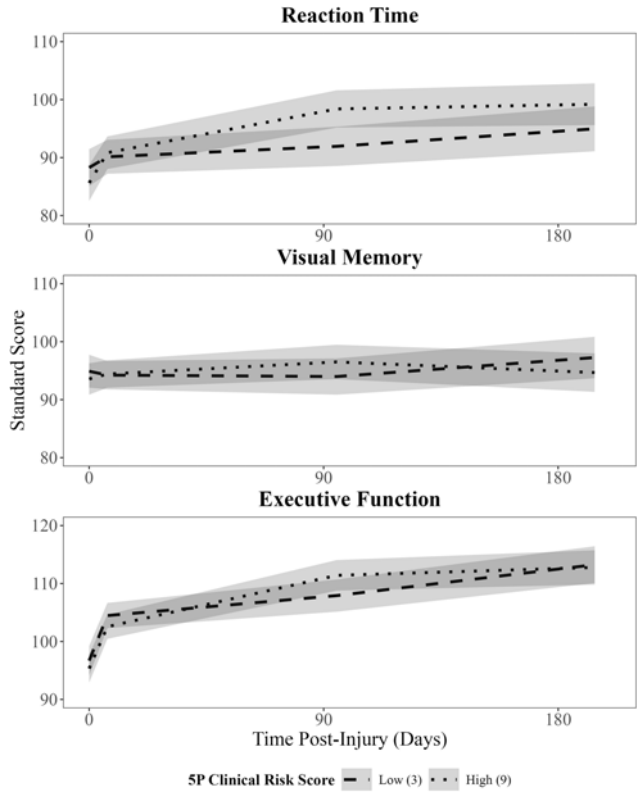


Figure 3. The 5P clinical risk score was not associated with cognitive domain standard scores in the mTBI group, across time and covarying for socioeconomic status. Estimated marginal means with 95% CI (shading) are shown for low (5P score = 3) and high (5P score = 9) clinical risk and domain score.

of routine, etc.), and differ from uninjured typically developing children (Babikian et al., 2013). An OI comparison group also offers high relevance for research on clinical diagnosis and prognostication in pediatric mTBI. Thus, our inclusion of children with OI is viewed as a study strength.

Age moderated reaction time after pediatric mTBI. Adolescents demonstrated larger reductions in reaction time acutely after mTBI than school-aged children. This is consistent with prior findings (e.g., Baillargeon et al., 2012). Age at injury is a known moderator of self-reported cognitive symptoms of mTBI (Mayer et al., 2024; Moser et al., 2018; Zemek et al., 2016). Younger age at injury is associated with more optimal recovery after pediatric mTBI as compared with older age (Beauchamp et al., 2019). Brain maturation is strongly influenced by age in childhood and adolescence, and could account for age-related differences in reaction time after pediatric mTBI (Blakemore, 2012; Corrigan et al., 2021). We previously found that age-related brain structure and function changes after mTBI in this sample (Onicas et al., 2024; Ware et al., 2020; Ware, Yeates, Geeraert, et al., 2022), suggesting that the maturational status of the brain at the time of injury influences neurological effects of pediatric mTBI. However, more research is needed to directly link the present findings to brain structure and function.

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In contrast to time and age, sex was not a significant moderator of cognitive functioning in pediatric mild TBI. This is consistent with some prior research (Yeates et al., 2022). However, results regarding sex differences in pediatric mTBI sequelae generally are mixed (Merritt et al., 2019). Sex can influence recovery in pediatric mTBI (Beauchamp et al., 2025), and is a key moderator of cognitive symptoms (Ledoux et al., 2019; Mayer et al., 2020). It can influence recovery of fluid cognitive processes, such as processing speed (Rieger et al., 2013), with higher risk of more severe acute cognitive dysfunction in females relative to males (Sandel et al., 2017). Overall, though, support for sex differences in cognitive functioning in pediatric mTBI is mixed. Some studies found sex differences in visual memory (Covassin et al., 2012) and processing speed (Colvin et al., 2009; Majerske et al., 2008), whereas other studies found no moderating effects of sex on cognitive functioning (Sufrinko et al., 2017; Yeates et al., 2022; Zuckerman et al., 2012). In typical development, sex differences in cognition occur, but are generally minimal and dependent on maturational stage (Gur et al., 2012; Toivainen et al., 2017).

The 5P clinical risk score was not predictive of cognitive domain scores in the children with mTBI. This is somewhat surprising given the robust clinical utility of using 5P score to predict subjective symptom recovery 4 weeks after pediatric mTBI (Zemek et al., 2016). Subjective symptoms and objective cognitive functioning are correlated, but not uniformly across cognitive domains, developmental stage, or recovery progression in pediatric mTBI (Jones et al., 2023; Robertson-Benta et al., 2024). These findings suggest that the factors that increase risk of prolonged symptom recovery differ from those that increase risk of persisting cognitive dysfunction after pediatric mTBI.

The current results have clinical implications. Greater acute cognitive impairment predicts longer symptom recovery and poorer quality of life in children with mTBI (Brooks, Daya, et al., 2016). Cognitive dysfunction also has implications for problems in other functional domains, including emotion dysregulation (Betz et al., 2024) and adaptive behavior (Shultz et al., 2016). Children and young adults with more severe or persistent self-reported cognitive symptoms after mTBI can have poor long-term (i.e., up to 2 years) sport participation and academic functioning (Lambregts et al., 2018), but further research is needed to determine whether decreased objective cognitive function is associated with similar long-term effects. Children with clinically impaired cognitive functioning could potentially benefit from early cognitive rehabilitation, which can improve aspects of fluid cognition (Treble-Barna et al., 2016). Finally, computerized testing may offer greater sensitivity to the subtle and generally transient cognitive problems that can occur after mTBI in children, especially in reaction time. However, reductions in fluid cognitive processes have been demonstrated in pediatric mTBI using both computerized (e.g., NIH Toolbox; Betz et al., 2024; Chadwick et al., 2021; Dufour et al., 2020) and paper–pencil tests (Beauchamp et al., 2015).

Limitations

The A-CAP study recruited from the Emergency Department of children's hospitals. Results may not generalize to children who do not seek treatment or who seek treatment at other settings. The sample was predominantly White and came from regions with higher socioeconomic status. Results may not generalize to groups with reduced access to material resources, including health care. Study attrition could limit generalizability of results. However, study attrition rates are similar to those of other published pediatric mTBI studies (e.g., Chadwick et al., 2021; Taylor et al., 2015), and demographic characteristics of the children in the final sample did not differ from the those who were excluded. We measured cognitive functioning in three domains using selected tests from the CNS Vital Signs computerized battery. Results may not generalize to other cognitive domains or other computerized measures or paper–pencil tests. The study included children between the ages of 8 and 17 years of age. Results may not generalize to young children (Beauchamp et al., 2024) or adults (Davis et al., 2017). Finally, other factors that can influence cognition after mTBI, such as pain or depression (Grandhi et al., 2017; Terry et al., 2019), were not investigated here but could be examined in future analyses. The family environment, parental distress, and other aspects of psychosocial functioning also are associated with cognition after severe TBI (Gerrard-Morris et al., 2010) and persistent symptoms after mTBI (Babikian et al., 2013; Olsson et al., 2013; Rausa et al., 2018) in children, but research examining their association with cognitive performance following mTBI is needed.

Conclusions and future directions

Pediatric mTBI was associated with reductions in reaction time and visual memory within 48 hours post-injury that decreased in magnitude but persisted up to 6 months post-injury. Up to 32% of children with mTBI demonstrated clinical impairment in reaction time acutely. Time post-injury and age moderated outcomes, but sex did not. Overall results suggest that changes in cognitive functioning following mTBI are typically most apparent acutely, in reaction time, and among adolescents, but persist in a small percentage of children. Future research is needed to understand the implication of these results for determining appropriate accommodations for return-to-school and return-to-sport. Additional research also is needed to understand the functional implications of these results. Finally, future research focused on identifying interventions to promote cognitive recovery is needed to enhance clinical management of affected children.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1355617726102124.

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