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Research Article

Recovery trajectories of IQ after pediatric TBI: A latent class growth modeling analysis

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Abstract

Objective: To identify latent trajectories of IQ over time after pediatric traumatic brain injury (TBI) and examine the predictive value of risk factors within and across recovery trajectories. **Method:** 206 children ages 3–7 years at injury were included: 87 TBI (23 severe, 21 moderate, 43 complicated mild) and 119 orthopedic injury (OI). We administered intelligence tests shortly after injury (1½ months), 12 months, and 6.8 years postinjury. Latent class growth modeling was used to identify latent subgroups. Separate models examined verbal and nonverbal IQ recovery trajectories following TBI versus OI. Variables included: age at injury, sex, race, socioeconomic status, injury severity, quality of the home environment, family functioning, and parenting style. **Results:** Both the TBI and OI analyses yielded different growth models for nonverbal ($k = 3$) and verbal IQ ($k = 3$). Although all models resulted in 3 latent classes (below average, average, and aboveaverage performance); trajectory shapes, contributors to class membership, and performance within each class varied by injury group and IQ domain. TBI severity was associated with class membership for nonverbal IQ, with less severe injuries associated with higher IQ scores; however, TBI severity did not influence verbal IQ class membership. Parenting style had a more prominent effect on verbal and nonverbal IQ within the TBI than OI trajectories. **Conclusions:** Findings suggest TBI severity is related to recovery trajectories for nonverbal but not verbal IQ and parenting style has stronger effects on recovery in TBI than OI. Results highlight the importance of parental factors on long-term recovery after TBI.

Keywords: brain injuries; traumatic; intelligence tests; child; parenting; risk factors; parents

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Traumatic brain injury (TBI) is among the most common causes of morbidity and mortality in children (Taylor et al., 2017). While most injuries are mild result if few, if any, deficits, sustaining a moderate to severe TBI in early childhood (ages 3–6 years) is associated with long-term cognitive (Anderson et al., 2005) and academic (Catroppa & Anderson, 2009; Ewing-Cobbs et al., 2006) impairment. Given the misconception that younger children recover better from moderate - severe TBI than older children (Anderson et al., 2005), the effects of early TBI on later intellectual and academic outcomes may go unrecognized or be misattributed due to a lack of awareness.

Young children with TBI also experience a range of behavioral deficits (Schwartz et al., 2003; Stancin et al., 2002; Taylor et al., 2002; Yeates et al., 2004) that may mask cognitive deficits, which therefore may not be identified or adequately addressed. Global intellectual functioning is associated with wide-ranging cognitive, behavioral, and social outcomes and is a commonly studied outcome following early childhood TBI. Sustaining a TBI in early childhood has been associated with lower intelligence quotient (IQ) scores that persist over time (Babikian & Asarnow, 2009; Crowe et al., 2021). Deficits in IQ appeared to have a dose-response relationship with injury severity, with severe TBI having a moderate to large effect on IQ (Babikian & Asarnow, 2009) and children with moderate TBI appearing more similar to those with severe TBI than children with mild TBI. While some improvements are observed over time, recovery of intellectual abilities often plateaus and deficits persist (Yeates, 2009).

Age at injury also appears to influence outcomes, with younger age at injury associated with poorer intellectual performance. Contrary to earlier views that the plasticity of young brains was protective against poor outcomes after injury, more recent research has documented that children injured in infancy or early childhood are more vulnerable to disruption in development than those injured later in childhood – leading to persistent deficits across domains of functioning (Anderson et al., 2005). This has been called the "double hazard" injury model, whereby severe TBI and younger age at injury are associated with the poorest outcomes (Anderson et al., 2005; Keenan et al., 2019; Kriel et al., 1989). One explanation may be that the young brain is more vulnerable to the effects of injury-related damage – causing a greater interruption of ongoing development. Because few skills are established in early childhood, this early interruption/cessation of development can

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prevent acquisition of later developing skills, leading to cumulative impairment and/or an increasing gap in performance over time (Anderson et al., 2005).

One of the most consistent findings from prospective studies on younger cohorts with TBI is acute and chronic deficits in both nonverbal and verbal IQ (Anderson et al., 2012; Crowe et al., 2021; Ewing-Cobbs et al., 1997; Taylor et al., 2008). In studies that have directly compared TBI in early childhood (< age 7) to TBI in later childhood/adolescence, the younger group had significantly worse intellectual outcomes (Anderson et al., 2000; Anderson et al., 2005; Catroppa & Anderson, 2009; Crowe et al., 2012) again indicating that this early childhood age range (< 7 years of age) may be at increased risk for poor cognitive outcomes.

Beyond injury-related factors, the role of environmental factors such as SES, family functioning, and parenting behaviors in pediatric TBI recovery has been a focus of investigation (Gerring & Wade, 2012). Lower SES, family dysfunction, and maladaptive parenting strategies have been associated with greater behavioral (Li & Liu, 2013; Micklewright et al., 2012; Moscato et al., 2021; Potter et al., 2011; Raj et al., 2014; Schwartz et al., 2003; Wade et al., 2016; Woods et al., 2011; Yeates et al., 2010) and cognitive/intellectual (Anderson et al., 2012; Crowe et al., 2012; Crowe et al., 2021; Crowe et al., 2012; Taylor et al., 2008; Taylor et al., 2001) outcomes. While investigators have noted that SES and parenting may play key roles in behavioral recovery (Potter et al., 2011; Yeates et al., 2010), this has yet to be examined in recovery of intellectual recovery over time. Latent class growth modeling (LCGM) offers a powerful statistical approach to classifying individuals into distinct groups based on latent trajectories across time (Nagin, 2005). This approach considers patterns of intra-individual change and can represent heterogeneity in developmental trajectories (Nagin, 2005), thereby providing a useful tool for examining recovery of IQ postTBI. However, most extant longitudinal studies of neurobehavioral outcomes after pediatric TBI have utilized a variable-centered approach in which the goal is to identify predictors of individual differences in outcomes and describe how a priori, observed independent variables – often injury severity quantified using the Glasgow Coma Scale (GCS) score – are related to these outcomes (Catroppa & Anderson, 2009; Ewing-Cobbs et al., 2006; Gerrard-Morris et al., 2010). LCGM may allow us to identify outcome trajectories present in the data that are obscured by the variable-centered approach.

We applied LCGM analysis to identify latent trajectories of IQ over time following early childhood TBI and orthopedic injuries (OI) and to examine the predictive value of known risk factors within and across recovery trajectories. IQ was selected as our cognitive variable of interest given its vulnerability to impairment after moderate-severe TBI in early childhood (Babikian & Asarnow, 2009) and its associations with acute and long-term academic outcomes following pediatric TBI (Catroppa et al., 2009). We hypothesized that one latent trajectory would involve recovery but persistent IQ deficits over time postinjury for the TBI group. We also hypothesized that social-environmental [parenting, family functioning; (Taylor et al., 1999; Taylor et al., 2002; Wade et al., 2016; Yeates et al., 2004; Yeates et al., 1997)] and injury-related factors [severity and age at injury; (Yeates, 2009)] would be associated with trajectories over time. We anticipated that children with OI would demonstrate greater longitudinal stability in IQ but that associations of family factors with IQ trajectories would be similar across the two groups.

Methods

Participants

All research was conducted in accordance with the Helsinki Declaration. Institutional review boards of all institutions approved all procedures, and written informed consent was obtained from parents of all participants. A concurrent cohort/prospective research design was used. Participants with TBI or OI were recruited from consecutive inpatient admissions from 2003 to 2006 at four Level 1 trauma centers (three tertiary care children's hospitals and a general hospital). The inclusion criteria were: (1) age at injury between 3 years, 0 months and 6 years, 11 months; (2) no documentation of child abuse as cause of the injury; (3) English as the primary spoken language in the home. Exclusion criteria included a previous history of autism, intellectual disability, or a neurological disorder. The study also recruited an OI control group. Inclusion in the OI group required a documented bone fracture in an area of the body other than the head that required an overnight hospital stay, as well as the absence of any evidence of loss of consciousness or other findings suggestive of brain injury.

We prospectively evaluated cognitive, behavioral, and adaptive functioning at baseline (1½ months postinjury), 6, 12, and 18 months postinjury. Additional follow-ups were completed 2 or more years postinjury (average 3.5 years) and when children entered middle school (average 6.8 years postinjury). The current project utilized data from intellectual assessments completed at 1½ months, 12 months, and 6.8 years postinjury on average as these were the only time points when IQ was assessed. A total of 221 participants were enrolled in the study. The GCS score and imaging findings were used to define TBI severity as follows: complicated mild (Cmild) TBI as GCS score of 13–15 with associated CT and/or MRI findings, moderate TBI as GCS score of 9-12, and severe TBI as GCS score of 3–8. Children with uncomplicated mild TBI ($n = 15$) were excluded from the present sample given our focus on long-term outcomes of more severe TBI. A total of 206 children were included in the present analyses: 87 children with TBI (23 severe, 21 moderate, 43 Cmild) and 119 with OI. The injury groups did not differ in terms of demographic variables (see Table 1). The sample had a mean age of 5.07 years at enrollment, was mostly male (59%), and mostly white (73%). Percent of data missing at each of the visits post baseline are as follows: 6 months (12.6%), 12 months (21.4%), 18 months (22.8%), ∼3 years (30.1%), ∼7 years (36.4%). Those that completed all visits did not differ from those who did not complete the extended follow-up (∼7 years) in terms of demographic (injury type and severity, age at injury, sex, race, SES) or any of the outcome variables discussed below.

Measures

IQ

Separate analyses were conducted to determine the trajectories of Verbal IQ and Nonverbal IQ. Two measures of cognitive/intellectual ability were used based on children's age at the time of the visit. The Differential Ability Scales (DASs; Elliott et al., 1990) were administered at baseline and 12 months postinjury. DAS verbal and nonverbal composites served as measures of verbal and nonverbal IQ for those visits. The verbal composite was measured via the verbal comprehension and naming vocabulary subtests that assess receptive and expressive language and comprehension skills. The nonverbal composite was measured

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Table 1. Demographics table. Injury groups did not differ with regards to any demographic variables or preinjury executive functioning scores

		OI ($n = 119$)	CMild TBI ($n = 43$)	Mod TBI ($n = 21$)	Severe TBI ($n = 23$)
Age at Injury, years		5.12 (1.07)	4.99 (1.22)	5.21 (1.18)	4.96 (1.00)
Gender; n (% male)		69 (58%)	25 (58.1%)	12 (57.1%)	16 (69.6%)
Race; n (% White)		91 (76.5%)	33 (76.7%)	10 (47.6%)	16 (69.6%)
SES (z-score)		.17 (.95)	−.05 (.96)	−.26 (1.34)	−.48 (.65)
EC-HOME		42.86 (7.48)	40.63 (7.41)	41.57 (6.98)	41.22 (7.01)
FAD-GF	Baseline	1.54 (.47)	1.55 (.40)	1.58 (.38)	1.67 (.51)
	12-mo	1.57 (.46)	1.58 (.56)	1.63 (.39)	1.75 (.54)
	6.8 years	1.59 (.38)	1.61(.35)	1.62 (.37)	1.85 (.46)
Authoritarian Parenting	Baseline	39.68 (7.93)	38.17 (6.58)	40.0 (7.27)	39.90 (8.59)
	12-mo	37.83 (7.56)	38.39 (8.22)	38.82 (8.92)	40.05 (8.35)
	6.8 years	37.15 (8.03)	36.29 (7.27)	42.17 (11.31)	39.44 (9.97)
Authoritative Parenting	Baseline	114.19 (10.30)	117.45 (8.71)	112.57 (9.01)	111.57 (12.43)
	12-mo	115.47 (10.34)	118.47 (8.82)	112.94 (12.20)	112.48 (11.21)
	6.8 years	113.81 (12.42)	115.32 (11.38)	111.83 (14.01)	111.69 (13.64)
Permissive Parenting	Baseline	31.28 (6.71)	31.07 (5.27)	31.95 (6.28)	34.00 (8.51)
	12-mo	29.36 (5.60)	30.28 (6.05)	31.24 (9.65)	33.52 (8.26)
	6.8 years	28.01 (6.09)	26.86 (5.12)	30.00 (6.40)	33.69 (7.78)
Verbal IQ	Baseline	101.16 (16.21)	100.21 (15.26)	93.28 (12.96)	89.40 (16.65)
	12-mo	104.21 (15.30)	100.19 (15.14)	95.13 (13.18)	93.29 (16.64)
	6.8 years	101.07 (14.85)	103.39 (16.13)	96.00 (15.89)	90.56 (19.29)
Nonverbal IQ	Baseline	102.89 (14.34)	102.98 (14.99)	95.50 (17.67)	83.94 (16.63)
	12-mo	104.32 (13.47)	100.64 (10.77)	97.67 (12.52)	88.86 (14.04)
	6.8 years	101.94 (12.41)	102.46 (15.27)	103.21 (10.89)	87.13 (17.44)

CMild = complicated mild, EC-HOME = early childhood – home observation for measurement of the environment, FAD-GF = family assessment device – global functioning, Mod = moderate, OI = orthopedic injury, TBI = traumatic brain injury.

via the picture similarities and pattern construction that assess picture matching ability, spatial organization ability, and non-verbal reasoning. The Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) was administered at the long-term follow-up visit (6.8 year postinjury). Standard score transformations of the T-scores from the WASI Vocabulary and Matrix Reasoning subtests provided measures of verbal and nonverbal IQ for the long-term visit. The vocabulary subtest reflects word knowledge, verbal concept formation, and overall fund of knowledge. The matrix reasoning subtest assesses visual information processing and abstract reasoning skills. Both the DAS and WASI are considered to be valid and reliable measures of intelligence appropriate for assessment in the TBI population (McCauley et al., 2012).

Time-invariant risk factors

TBI severity and variables potentially related to outcomes (age at injury, sex, SES, and quality of the home) were included as predictors of trajectory class membership. SES was determined by using the average of the z-scores for maternal education and median income for the census tract in which the family resided. To assess the quality of home environment, the Early Childhood-Home Observation for Measurement of the Environment (EC-HOME; Bradley et al., 2003) was administered at baseline. Administration involved an in-home visit by an assessor who rated observed levels of parental stimulation and support for the child. A total EC-HOME score was calculated by summing ratings across domains. Higher scores indicate greater levels of structure, stimulation, and support in the home environment. The EC-HOME is a reliable and valid predictor of cognitive development in children that incorporates factors not wholly captured by SES (Bradley et al., 2003). Time-invariant risk factors are used to predict class membership, and differences *between* identified classes.

Time-varying risk factors

Measures of general family functioning and parenting behaviors were collected at each of the assessments and included as time-varying covariates to help clarify the potential dynamic relationship between family environment and cognitive functioning over time. The 12-item General Functioning scale from the Mc-Master Family Assessment Device (FAD-GF) was used to measure family functioning (Epstein et al., 1983). This measure has demonstrated good reliability and validity and has been recommended to be used as a core measure in pediatric TBI research (McCauley, 2012). FAD-GF scores range from 1 to 4, with higher scores reflective of greater dysfunction. Parenting behaviors were assessed via the Parenting Practices Questionnaire (Robinson et al., 1995). The Parenting Practices Questionnaire is a 62-item self-report questionnaire of parenting behaviors, with satisfactory reliability and validity (Robinson et al., 2001), and produces three summary scores - authoritarian, authoritative, and permissive parenting styles. Time-varying risk factors predict variation *within* each identified class.

Data analysis plan

LCGM analysis was conducted in SAS using PROC TRAJ. Separate analyses were conducted for TBI and OI groups as we hypothesized that the trajectory shapes would vary as a function of injury type (TBI vs OI). Separate analyses also were conducted to examine the trajectories of verbal IQ and nonverbal IQ as we hypothesized that predictors might vary for the two outcomes.

Model selection involved the iterative estimation of the number of trajectory classes, as well as the shape of each trajectory class. We considered a range of one to five classes, as well as flat (i.e., intercept-only), linear, quadratic, and cubic trajectory shapes. The Bayesian information criterion statistic, model estimation convergence, percentage of population represented in each subgroup (>10%), minimization of the residual variance statistic (sigma),

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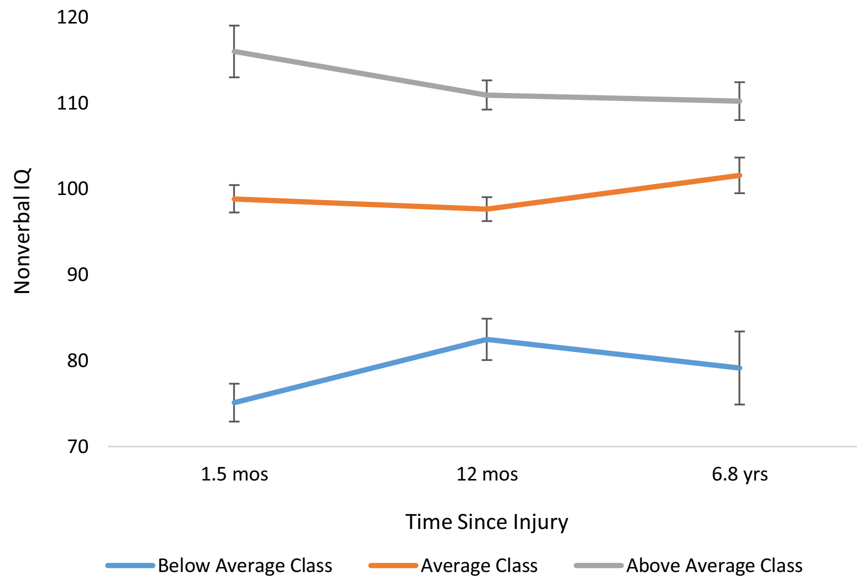

Figure 1. Nonverbal IQ trajectories for TBI group.

and examination of posterior subgroup classification probabilities were all factors in determining the best fitting model.

Results

Nonverbal IQ trajectories

TBI group

LCGM analysis resulted in a final model with three trajectory classes (Fig. 1, Table 2). The average probability of being assigned to the identified class was>93%, indicating good fit and suggesting that the model is appropriately grouping individuals with similar IQ trajectories and discriminating individuals with dissimilar trajectories. The three trajectory classes included one class with scores in the below-average range over time (22.7%), a second with scores in the average range over time (52.1%), and a third with scores in the above-average to high-average range over time (25.2%). The parameter estimates for the time-invariant risk factors are presented in Table 3 and time-varying covariates in Table 4.

The below-average class demonstrated a cubic trajectory, with a rapid increase in nonverbal IQ during the first year following injury, followed by a more gradual decline in performance during the remainder of the study period. This class was composed of 12 children with severe TBI (63.2%), 4 with moderate TBI (21.1%), and 3 with Cmild TBI (15.8%), representing 52.2% of the severe TBI group, 19.1 % of the moderate TBI group, and 7.3% of the Cmild TBI group. Within the below-average class, greater levels of authoritarian parenting and lower levels of permissive parenting were associated with greater nonverbal IQ.

The average class demonstrated a flat trajectory with stable levels of nonverbal IQ throughout the study period. This class was made up of 11 children with severe TBI (24.4%), 13 children with moderate TBI (28.9%), and 21 children with Cmild TBI (46.7%), representing 47.8% of the severe TBI group, 61.9% of the moderate TBI group, and 51.2% of the Cmild TBI group. Injury severity was the only significant risk factor with less severe injury associated with a higher probability of membership to the average class relative to the below-average class (Table 3). Age at injury, sex, SES, and home environment were not associated with class membership. Within this trajectory class, lower levels of authoritarian parenting were associated with higher nonverbal IQ.

The above-average class displayed a flat shape with stable levels of nonverbal IQ throughout this study period. This group was composed of no children with severe TBI, 4 with moderate TBI (19.1%), and 17 with Cmild (81%), representing 0% of the severe TBI group, 19.1% of the moderate TBI group, and 41.5% of the Cmild TBI group. Less severe injury, older age at injury, and greater SES were associated with a higher probability of membership in the above-average class relative to the below-average group (Table 3). Neither sex nor home environment were associated with class membership. Within this class, greater levels of authoritarian parenting were associated with higher nonverbal IQ (Table 4).

OI group

Analyses of the OI group resulted in a final growth model with three trajectory classes (Fig. 2, Table 5). The average probability of being assigned to the identified class was>86%, indicating good fit and suggesting that the model is appropriately grouping individuals with similar trajectories over time and discriminating individuals with dissimilar trajectories. The three trajectory classes (Fig. 2) included one class with scores in the below-low average range over time (13.8%), another with scores in the average range over time (55.1%), and a third with scores in the above-average range over time (31.1%). The parameter estimates for the time-invariant risk factors are presented in Table 6 and time-varying covariates in Table 7.

The below-average class demonstrated a linear trajectory, with an increase in nonverbal IQ over time. None of the time-varying covariates were associated with nonverbal IQ within the below-average class (Table 7). The average class demonstrated a flat trajectory with stable levels of nonverbal IQ. Older age at injury was associated with a higher probability of membership in the average class relative to the below-average class (Table 6). Sex, SES, and home environment were not associated with class membership. Within this trajectory class, lower levels of authoritarian parenting were associated with greater nonverbal IQ (Table 7). The above-average class also displayed a flat shape with stable levels of nonverbal IQ. Older age at injury and greater SES were associated with a higher probability of membership in the above-average class

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Table 2. IQ trajectory models for the TBI group

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Intercept	3.73	26.63	.14	.89
	Linear	10.75	4.89	2.20	.03
	Quadratic	−3.16	1.19	−2.67	.008
	Cubic	.21	.08	2.66	.009
Average	Intercept	99.79	15.19	6.57	<.0001
Above Average	Intercept	81.62	33.50	2.44	.02

Table 3. Results for time-invariant risk factor variables for nonverbal IQ model, TBI group. Bolded items indicate statistically significant predictors of class membership. The below-average class serves as the reference group

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Constant	–	–	–	–
Average	**Injury severity**	**1.55**	**.62**	**2.51**	**.01**
	Age at injury	.95	.50	1.91	.06
	Sex	−1.23	1.17	−1.05	.30
	SES	.72	.58	1.24	.22
	HOME	.05	.08	.61	.54
Above Average	**Injury severity**	**3.80**	**1.75**	**2.17**	**.03**
	Age at injury	**1.51**	**.77**	**1.97**	**.05**
	Sex	−.48	1.77	-.27	.79
	SES	**2.58**	**1.12**	**2.31**	**.02**
	HOME	.28	.15	1.87	.06

Table 4. Results of the effect of time-varying covariates within each class for nonverbal IQ model, TBI group. Bolded items indicate items with significant association with nonverbal IQ

Group	Parameter	Estimate	SE	t	p
Below Average	Authoritative	.32	.17	1.92	.06
	Authoritarian	**1.12**	**.29**	**3.86**	**.0002**
	Permissive	**−.80**	**.30**	**−2.63**	**.009**
	FAD-GF	9.03	5.68	1.59	.11
Average	Authoritative	.02	.11	.16	.88
	Authoritarian	**-.30**	**.15**	**−2.03**	**.04**
	Permissive	.16	.15	1.07	.28
	FAD-GF	1.87	2.43	.77	.44
Above Average	Authoritative	.18	.23	.78	.44
	Authoritarian	**.69**	**.34**	**2.05**	**.04**
	Permissive	−.64	.37	−1.75	.08
	FAD-GF	2.30	4.23	.54	.59

relative to the below-average group (Table 6). Neither sex nor the home environment was associated with class membership. Within the above-average class, higher levels of authoritarian parenting were associated with greater nonverbal IQ (Table 7).

Verbal IQ models

TBI group

LCGM analysis of verbal IQ scores in the TBI group resulted in a final growth model with three trajectory classes (Fig. 3, Table 8). The average probability of being assigned to the class was>89%, indicating good fit. The three trajectory classes included: 1) a below-average class (30.3%), 2) an average class (42.9%), and 3) an above-average class (26.9%). The parameter estimates for the time-invariant risk factors are presented in Table 9, and time-varying covariates in Table 10.

The below-average class displayed a flat trajectory shape with stable levels of verbal IQ. This group included 8 children with severe TBI (32.0%), 6 children with moderate TBI (24.0%), and 11 children with Cmild TBI (44.0%), representing 34.8% of the severe TBI group, 28.6% of the moderate TBI group, and 26.8% Cmild TBI group. Within this class, greater authoritarian parenting and lower levels of permissive parenting were associated with higher verbal IQ (Table 10).

The average class displayed a flat trajectory with stable verbal over time. This class was made up of 11 children with severe TBI (30.6%), 11 children with moderate TBI (30.6%), and 14 with Cmild TBI (38.9%), representing 47.8% of the severe TBI group, 52.4% of the moderate TBI group, and 34.2% of the Cmild TBI group. None of the risk factors was significantly associated with probability of being assigned this trajectory class relative to the below-average class, although SES approached significance (Table 9). Within this class, greater authoritative parenting and greater authoritarian parenting were associated with higher verbal IQ (Table 10).

The above-average class also demonstrated a flat trajectory with stable levels of verbal IQ scores. The group was composed of 4 children with severe TBI (16.7%), 4 with moderate TBI (16.7%), and 16 with Cmild (66.7%), and represented 17.4% of the severe TBI group, 19.1% of the moderate TBI group, and 39.0% of the Cmild group. Greater SES was associated with a higher probability of being in the above-average class relative to the below-average class (Table 9). Injury severity, age at injury, sex, and home environment were not associated with class membership. Within this class, lower levels of permissive parenting were associated with higher verbal IQ (Table 10).

OI group

LCGM analyses of verbal IQ scores in the OI group resulted in a final growth model with three trajectory classes (Fig. 4, Table 11). The average probability of being assigned to the identified class was>91%, indicating good fit. The three trajectory classes (Fig. 4) included: 1) a class with scores in the below – low average range over time (24.5%), 2) a class with scores in the average range throughout the study (55.5%), and 3) a class with scores in the above range throughout the study (20.0%). The parameter estimates for the time-invariant risk factors are presented in Table 12 and time-varying covariates in Table 13.

The below-average class demonstrated a cubic shape, with a sharp increase in verbal IQ during the first year after injury followed by a more gradual decline in verbal IQ during the remainder of the study. None of the time-varying covariates were associated with verbal IQ within the below-average class (Table 13). The average class demonstrated a flat trajectory with stable levels of verbal IQ over time. Older age at injury, higher SES, and higher HOME scores, but not sex, were associated with a higher probability of membership in the average class relative to the below-average class (Table 12). Within this class, lower levels of permissive parenting were associated with greater verbal IQ (Table 13). The above-average class also demonstrated a cubic trajectory, with a sharp increase in verbal IQ during the first year after injury followed by a more gradual decline in verbal IQ over time. Older age at injury, higher SES, and higher HOME scores, but not sex, were associated with a higher probability of membership in the above-average class relative to the below-average group (Table 12). Within this class, higher levels of authoritarian parenting were associated with higher verbal IQ scores (Table 13).

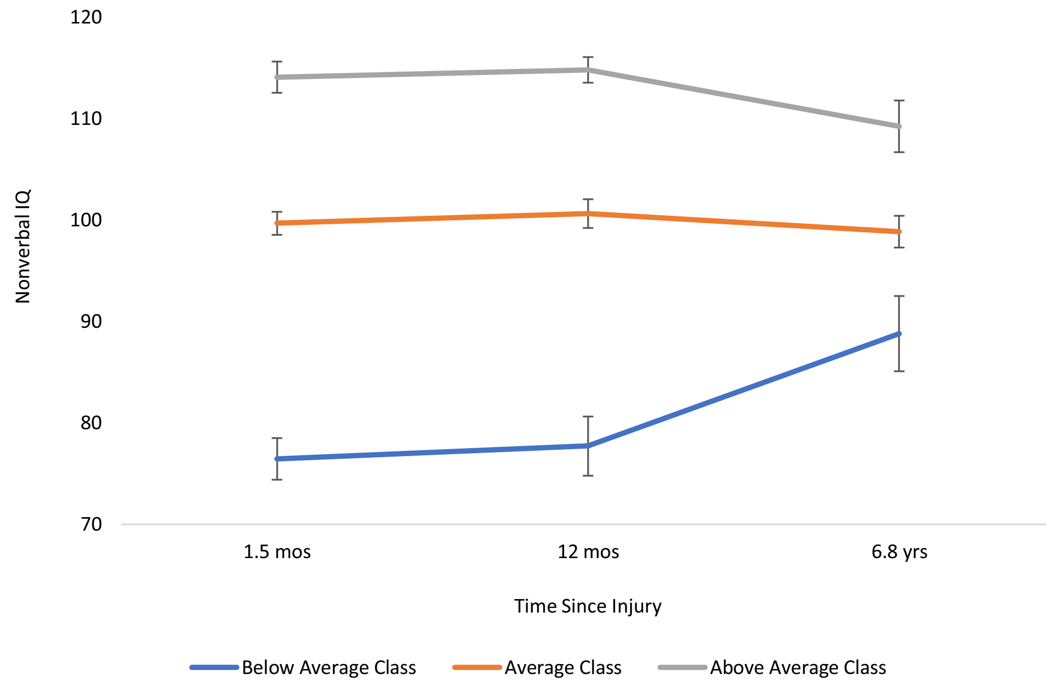

Figure 2. Nonverbal IQ trajectories for OI group.

Discussion

The present study adds to our knowledge of the impact of injury-related and social-environmental factors on the trajectory of IQ following pediatric TBI by taking a data-driven approach that helps characterize growth patterns over time. We found that children with TBI and OI displayed three distinct trajectories of nonverbal and verbal IQ. Although all models resulted in three latent classes (below average, average, and above-average performance), trajectory shapes, factors associated with class membership, and variability within each class varied by injury group and IQ domain. We found largely stable trajectories over time with a few notable exceptions. Specifically, for nonverbal IQ, children with TBI in the below-average group, which included a preponderance of children with severe TBI, demonstrated a curvilinear trajectory, reflecting rapid recovery followed by gradual deterioration. In contrast, the below-average trajectory for nonverbal IQ in children with OI showed linear increases over time. Although we do not know whether postinjury performance reflected deficits relative to preinjury abilities, none of the trajectories in the TBI group reflected a similar pattern of improving scores over time that would be consistent with ongoing recovery of skills. Further, these results suggest that children with severe TBI are at higher risk than children with OI of falling further behind their peers over time rather than catching up. Therefore, educational and vocational supports may need to be adapted over time and developed with long-term outcomes in mind.

The factors associated with class membership varied across groups and nonverbal versus verbal IQ. Consistent with a dose-response relationship, TBI severity was associated with class membership for nonverbal IQ, with less severe injuries associated with membership in classes with higher IQ scores. In line with previous research, TBI severity was not associated with verbal IQ trajectories. These findings suggest that verbal IQ is largely preserved following TBI, even in young children, and raise the possibility that prior learning or cognitive reserve may play a greater role in verbal versus nonverbal intelligence over time postinjury. Comparable proportions of children with TBI, relative to those with OI in an above-average verbal IQ class, are also consistent with this possibility. Age at injury also influenced class membership in nonverbal IQ trajectories for both the TBI and OI groups, with children injured at older ages more likely to be in the average ($p = .06$ for TBI) and above-average classes. These findings suggest that the adverse effects of early injury on nonverbal IQ may not be unique to TBI and may also apply to orthopedic injuries requiring hospitalization.

Environmental factors were also associated with class membership in both the verbal and nonverbal IQ models for both TBI and OI groups. Most consistently higher SES was associated with membership to groups with higher IQ scores for survivors of TBI and survivors of OI. Notably, the HOME was only associated with class membership in verbal IQ trajectories for participants with OI indicating that greater quality of the home environment was associated with membership to higher functioning verbal IQ group, only among OI survivors. These findings are consistent with the developmental literature reporting higher cognitive functioning in children from families with higher SES (Donders, 1996, 1999; Doners, 1998; Glutting et al., 1997; Noble et al., 2005) and from more stimulating home environments (Bradley et al., 1989; Bradley & Corwyn, 2002). Studies of children with TBI have also consistently reported associations between higher SES and more advantaged family/home environments with cognitive abilities (Anderson et al., 2006; Gerrard-Morris et al., 2010; Taylor et al., 2008). The associations between SES/home environment were fairly consistent across TBI and OI groups, suggesting that optimal environments may be associated with higher intellectual functioning regardless of injury type, and that lower SES or disadvantaged family environments may help to identify patients at risk for poorer intellectual outcomes. The limited effect of family functioning was somewhat surprising; however, it is consistent with existing studies that report significant influence of parenting behaviors and SES, but not family functioning, on behavioral and

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Table 5. Nonverbal IQ trajectory model, OI group

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Intercept	90.71	22.99	2.67	.008
	Linear	1.88	.62	3.06	.003
Average	Intercept	109.95	13.45	8.18	<.0001
Above Average	Intercept	81.35	23.77	3.42	.0007

Table 6. Results for time-invariant risk factors for nonverbal IQ model, OI group. Bolded items indicate statistically significant predictors of class membership. The below-average class serves as the reference group

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Constant	–	–	–	–
Average	**Age at injury**	**.83**	**.40**	**2.09**	**.04**
	Sex	−1.85	1.01	−1.83	.07
	SES	.96	.78	1.22	.22
	HOME	.07	.06	1.15	.25
Above Average	**Age at injury**	**1.09**	**.54**	**2.01**	**.05**
	Sex	−1.77	1.32	−1.34	.18
	SES	**2.47**	**.94**	**2.63**	**.009**
	HOME	.16	.11	1.54	.13

Table 7. Results of the effects of time-varying covariates within the nonverbal IQ model, OI group. Bolded items indicate items with significant association with nonverbal IQ

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Authoritative	−.01	.20	−.05	.96
	Authoritarian	−.25	.34	−.75	.46
	Permissive	−.01	.49	−.01	.99
	FAD-GF	−.47	4.85	−.10	.92
Average	Authoritative	−.03	.09	−.29	.77
	Authoritarian	**−.36**	**.14**	**−2.55**	**.01**
	Permissive	.31	.17	1.87	.06
	FAD-GF	−.81	2.53	−.32	.75
Above Average	Authoritative	.21	.16	1.32	.19
	Authoritarian	**.40**	**.20**	**1.98**	**.05**
	Permissive	−.31	.23	−1.32	.19
	FAD-GF	.84	2.96	.28	.78

executive functioning outcomes after pediatric TBI (Potter et al., 2011; Yeates et al., 2010).

Finally, through examining the time-varying covariates, which were evaluated within each class, we found differential effects of family factors within classes depending on injury type and range of intellectual functioning. Parenting style, but not other social-environmental characteristics, had a more prominent association with both verbal and nonverbal IQ within TBI trajectories than OI trajectories, supporting the critical role of parenting behaviors identified in previous pediatric TBI research and suggesting that parent training interventions could be beneficial during the recovery process for children and families following TBI. Consistent with previous research, lower levels of permissive parenting were associated with higher IQ within each class. Contrary to expectations, within each class, higher levels of authoritarian parenting were associated with higher nonverbal IQ for both injury groups and better verbal IQ for children with TBI in the below-average trajectory. This finding is somewhat unexpected given previous research suggesting authoritarian parenting is a maladaptive approach for typically developing children (Baumrind, 1967, 1971; Cole et al., 2005). Within this same pediatric TBI cohort, Yeates and colleagues found that high levels of authoritarian parenting were associated with better behavioral adjustment at 6 months postinjury; however, by 18 months postinjury it was associated with worse adjustment (Yeates et al., 2010). They theorized that authoritarian parenting may suppress behavior problems initially following TBI in young children but is not effective and may exacerbate problems longer term. The current findings reflect within class associations rather than associations in the group as whole and thus cannot directly be compared to previous findings. However, they suggest that this stricter, more disciplinarian approach to parenting may continue to be protective for children following pediatric TBI who are lower functioning compared to their average or above-average functioning peers. Studies have found that authoritarian parenting can be beneficial in lower SES environments (Hoff et al., 2002) and similar benefits may be occurring for this high-risk group following injury. Alternatively, authoritarian and authoritative parenting approaches both reflect higher parental involvement and expectation setting, which may be related to the finding that both were associated with higher IQ in the present study.

Limitations

While this study adds to our understanding of IQ recovery over time following pediatric TBI, results should be considered within the limitations. Firstly, statistical power and determining whether sample size is suited for statistical approach is very complex for LCGM (Berlin et al., 2014; Muthén & Muthén, 2002) with recommended sample sizes quite variable (Muthén & Muthén, 2002; Wolf et al., 2013) depending on the complexity of model. Among the consequences of insufficient sample size include lack of model convergence and failure to identify meaningful subgroups (Berlin et al., 2014) which were not issues in the current analyses. While the sample size in the current study is somewhat small, it does fall within the lower end of the recommended ranges, and model fit and results support that the sample is sufficient for addressing hypotheses. That being said, the number of participants with severe TBI group was quite small, and future studies would benefit from a larger severe TBI group. Secondly, due to the absence of a healthy control group, we cannot assess the impact of TBI on IQ trajectories relative to expectations for noninjured children. Additionally, a person-centered approach to examining longitudinal data is limited in that individuals must remain on the trajectory to which they are assigned over time. Future studies would benefit from using latent transition analysis, which allows for movement of individuals between trajectory groups (i.e., movement from below-average class to average class) and for the examination of the factors associated with these transitions. Next, we did track who completed measures at all visits – with a transition in reporter occurring in only 3.8% of participants. However we did not document changes in household/caregiver structure over time. Given the impact that household/caregiver structure could have on socioeconomic and/or family factors, future studies should consider how change in household structure may impact salient variables. In addition, as preinjury IQ was not assessed, analysis did not control for preinjury functioning. While a strength of the present study is the focus on the early childhood

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Table 8. Verbal IQ trajectory models, TBI group

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Intercept	90.56	17.48	5.18	<.0001
Average	Intercept	57.55	18.22	3.16	.002
Above Average	Intercept	123.53	27.48	4.50	<.0001

Table 9. Results for time-invariant predictors from verbal IQ model, TBI group. Bolded items indicate statistically significant predictors of class membership. The below-average class serves as the reference group

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Constant	–	–	–	–
Average	Injury Severity	−.03	.38	−.09	.93
	Age at injury	.31	.34	.93	.36
	Sex	.09	.71	.12	.90
	SES	.85	.48	1.78	.08
	HOME	.002	.06	.03	.97
Above Average	Injury Severity	.40	.59	.68	.50
	Age at injury	.54	.46	1.19	.24
	Sex	.94	1.09	.86	.39
	SES	**2.11**	**.68**	**3.10**	**.002**
	HOME	.10	.10	1.00	.32

Table 10. Results of the effects of time-varying covariates within each class in verbal IQ model, TBI group. Bolded items indicate items with significant association with verbal IQ

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Authoritative	−.05	.12	−.44	.66
	Authoritarian	**.92**	**.22**	**4.25**	**<.0001**
	Permissive	**−1.22**	**.27**	**−4.58**	**<.0001**
	FAD-GF	−3.76	3.56	−1.05	.29
Average	**Authoritative**	**.27**	**.13**	**2.15**	**.03**
	Authoritarian	**.31**	**.15**	**1.99**	**.05**
	Permissive	−.14	.14	−1.00	.32
	FAD-GF	.89	2.47	.36	.72
Above Average	Authoritative	.13	.18	.72	.47
	Authoritarian	.41	.30	1.39	.17
	Permissive	**−1.41**	**.35**	**−4.08**	**.0001**
	FAD-GF	.64	3.92	.16	.87

age range, shown to infer greater risk of poor outcome, it fails to include children injured younger than 3 years of age, and future studies may benefit from this younger age range. Further, we did not have information regarding enrollment in structured education programing at the time of injury, limiting our understanding of how this may influence cognitive recovery over time. Importantly, interpretation of results must take into consideration that the measures of IQ changed between the 12 months and 7 years visits. There are notable differences in demands across the two measures. The verbal subtests on the DAS assess comprehension as well as expressive and receptive language, while the verbal subtest on the WASI assesses word knowledge and overall fund of knowledge. Further, the nonverbal tasks on the DAS assesses picture matching and spatial, nonverbal reasoning with a motor component, while the nonverbal task on the WASI assesses nonverbal reasoning without a motor component. While the DAS correlates well with Wechsler measures of intelligence (Elliott et al., 1990), there are no studies to our knowledge directly comparing the convergent validity of the DAS Early Years and WASI given the lack of age-appropriate norms across tests. This is a challenge across many longitudinal studies in pediatrics given the need to assess children in developmentally appropriate ways and further psychometric research is needed to address this area of need. Finally, the enrolled sample had limited racial variability, resulting in few children from some racial groups, prohibiting meaningful comparison across groups. Therefore, the decision was made to

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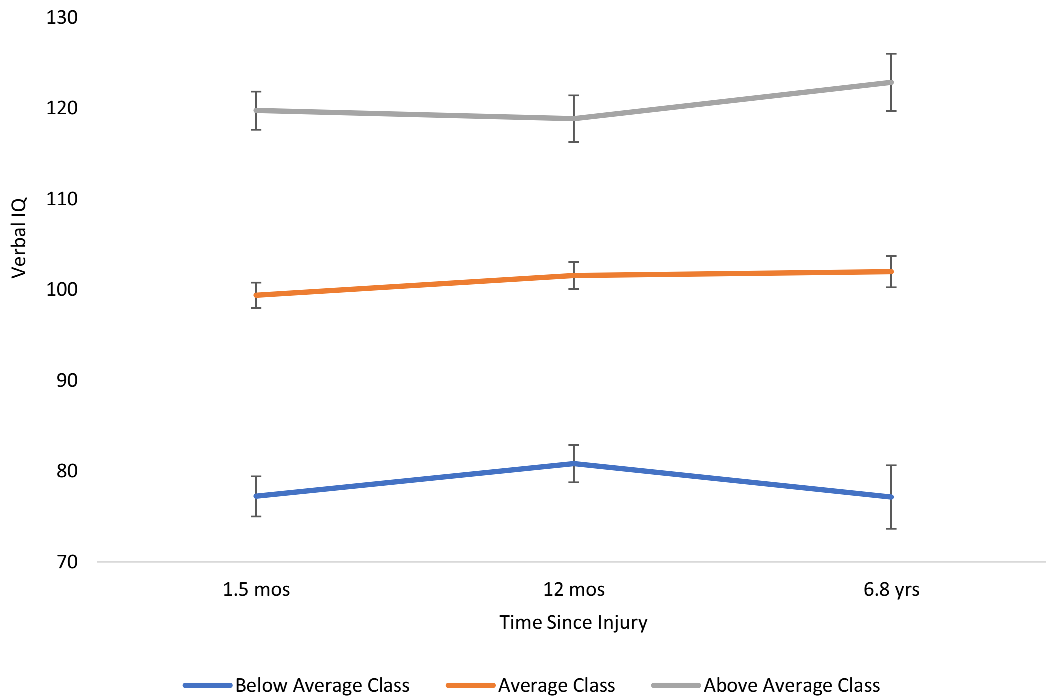

Figure 3. Verbal IQ trajectories for TBI group.

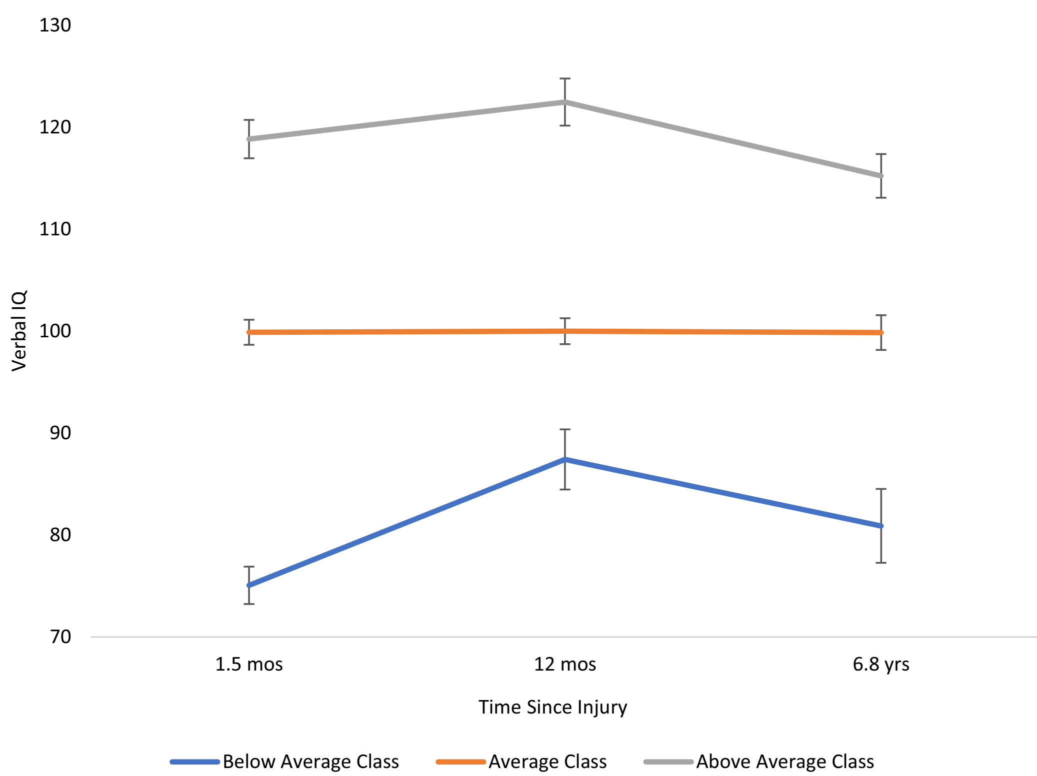

Figure 4. Verbal IQ trajectories for OI group.

categorize the racial breakdown of the sample as white and nonwhite. Because it would be inappropriate to examine the effects of race on outcomes while collapsing across all nonwhite racial groups, it was not included as a predictor in the current models. Future studies would benefit from enrollment of a more racially diverse sample that would allow for an adequately powered examination of the role of race in long-term recovery following pediatric TBI.

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Table 11. Verbal IQ trajectory model, OI group

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Intercept	64.85	22.87	2.84	.005
	Linear	14.24	4.37	3.26	.001
	Quadratic	−3.31	1.02	−3.25	.001
	Cubic	.20	.07	3.08	.002
Average	Intercept	100.87	13.26	7.61	.000
Above Average	Intercept	90.64	30.67	2.94	.004
	Linear	7.49	4.83	1.55	.122
	Quadratic	−2.99	1.49	−2.01	.046
	Cubic	.26	.13	2.06	.041

Table 12. Results from time-invariant predictors for verbal IQ model, OI group. Bolded items indicate statistically significant predictors of class membership. The below-average class serves as the reference group

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Constant	–	–	–	–
Average	**Age at injury**	**1.71**	**.64**	**2.65**	**.008**
	Sex	−1.39	1.05	−1.32	.19
	SES	**3.06**	**1.22**	**2.51**	**.01**
	HOME	**.18**	**.09**	**2.03**	**.04**
Above Average	**Age at injury**	**2.35**	**.77**	**3.05**	**.003**
	Sex	−2.39	1.33	−1.80	.07
	SES	**4.04**	**1.33**	**3.04**	**.003**
	HOME	**.46**	**.15**	**2.99**	**.003**

Table 13. Results of the effects time-varying covariates within each class for verbal IQ model for OI group. Bolded items indicate items with significant association with verbal IQ

Group	Parameter	Estimate	SE	*t*	*p*
Below Average	Authoritative	.18	.15	1.21	.229
	Authoritarian	.13	.21	.64	.522
	Permissive	−.13	.26	−.49	.626
	FAD-GF	−4.11	3.29	−1.25	.212
Average	Authoritative	.003	.09	.04	.969
	Authoritarian	.09	.15	.60	.547
	Permissive	**−.33**	**.16**	**−2.05**	**.042**
	FAD-GF	4.53	2.38	1.91	.057
Above Average	Authoritative	.32	.20	1.58	.116
	Authoritarian	**.30**	**.24**	**1.24**	**.215**
	Permissive	-.49	.38	−1.28	.200
	FAD-GF	−3.72	5.12	-.73	.468

Conclusions

Findings suggest TBI severity is related to recovery trajectories for nonverbal but not verbal IQ and parenting style has stronger effects on recovery in TBI than OI. Results highlight the importance of parental factors on long-term recovery after TBI and suggest parent training as an intervention to optimize cognitive development postinjury.

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Competing interests. None.

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