Journal of the International Neuropsychological Society (2010), **16**, 157–168.

doi:10.1017/S1355617709991135

Cognitive development after traumatic brain injury in young children

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(Received August 3, 2009; Final Revision September 22, 2009; Accepted September 28, 2009)

Abstract

The primary aims of this study were to examine post-injury cognitive development in young children with traumatic brain injury (TBI) and to investigate the role of the proximal family environment in predicting cognitive outcomes. Age at injury was 3–6 years, and TBI was classified as severe (n = 23), moderate (n = 21), and complicated mild (n = 43). A comparison group of children who sustained orthopedic injuries (OI, n = 117) was also recruited. Child cognitive assessments were administered at a post-acute baseline evaluation and repeated at 6, 12, and 18 months post-injury. Assessment of the family environment consisted of baseline measures of learning support and stimulation in the home and of parenting characteristics observed during videotaped parent–child interactions. Relative to the OI group, children with severe TBI group had generalized cognitive deficiencies and those with less severe TBI had weaknesses in visual memory and executive function. Although deficits persisted or emerged across follow-up, more optimal family environments were associated with higher scores for all injury groups. The findings confirm other reports of poor recovery of cognitive skills following early childhood TBI and suggest environmental influences on outcomes. (*JINS*, 2010, *16*, 157–168.)

Keywords: Head injuries, outcomes, Child development, Child, Preschool, Brain injuries, Neurobehavioral manifestations, Recovery of function

INTRODUCTION

Traumatic brain injury (TBI) is a major public health concern for children 0–14 years, with an estimated annual incidence of 435,000 emergency department visits and 37,000 hospitalizations (Langlois, Rutland-Brown, & Thomas, 2006). Long-term neurobehavioral impairments are well documented following moderate to severe TBI in both younger and older children (Anderson & Catroppa, 2005; Anderson, Morse, Catroppa, Haritou, & Rosenfeld, 2004; Anderson, Catroppa, Dudgeon, Morse, Haritou, & Rosenfeld, 2006; Chadwick, Rutter, Brown, Shaffer, & Traub, 1981; Ewing-Cobbs et al., 2004a; Keenan, Hooper, Wetherington, Nocera, & Runyan, 2007; Yeates, Taylor, Wade, Drotar, Stancin, & Minich, 2002). Ewing-Cobbs et al. (2006) found that children who sustained moderate to severe TBI between the ages of 4 and 71 months had impairments, relative to a community comparison group, in intelligence and academic skills that persisted across a 5-year follow-up period. Similarly, Catroppa, Anderson, Morse, Haritou, and Rosenfeld (2007) observed that children who sustained severe TBI during early childhood (2–7 years) performed more poorly than children with mild TBI on measures of attention and processing speed out to 5 years post-injury. Persistent post-injury cognitive, academic, and behavioral deficits have also been documented in children who sustained moderate to severe TBI during the school-age years (Anderson & Catroppa, 2005; Chadwick et al., 1981; Max et al., 1997; Taylor, Yeates, Wade, Drotar, Stancin, & Minich, 2002; Yeates et al., 2002).

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Consistent with the vulnerability of the temporal and frontal lobes to blunt head injury, deficits in memory and executive function are especially prominent (Anderson & Catroppa, 2005; Anderson et al., 2004, 2006; Barnes & Dennis, 2001; Catroppa & Anderson, 2005; Dennis, Guger, Roncadin, Barnes, & Schachar, 2001; Donders & Giroux, 2005; Ewing-Cobbs et al., 2004b; Levin & Hanten, 2005; Yeates et al., 2002). Although moderate to severe TBI has less pronounced effects on some language skills, at least in children injured during the school-age years, long-standing impairments in this domain are also well documented (Dennis et al., 2001; Ewing-Cobbs & Barnes, 2002; Yeates et al., 2002).

Factors related to worse outcomes of moderate to severe TBI in children include more severe TBI, younger age at injury, and greater environmental disadvantage (Anderson, Catroppa, Morse, Haaritou, & Rosenfeld, 2000a, 2005a, 2005c; Anderson, Catroppa, Dudgeon, Morse, Haaritou, & Rosenfeld, 2006; Ewing-Cobbs, Fletcher, Levin, Francis, Davidson, & Miner, 1997; Slomine et al., 2002; Taylor, Yeates, Wade, Drotar, Stancin, & Klein, 1999; Yeates et al., 2002). Children injured in early childhood (before 7 or 8 years) are especially vulnerable to more generalized deficits, as evident in lower IQ scores and greater deficits in expressive language and reading compared with children injured at later ages (Barnes, Dennis, & Wilkinson, 1999; Ewing-Cobbs & Barnes, 2002; Levin, Ewing-Cobbs, & Eisenberg, 1995). Children who sustain TBI in early childhood also show little evidence for recovery of cognitive functions compared with children injured at later ages (Anderson et al., 2000a, 2004; Anderson, Catroppa, Morse, Haritou, & Rosenfeld, 2005b; Ewing-Cobbs et al., 1997, 2006). With respect to environmental influences, Yeates et al. (1997) found that children with traumatic head or orthopedic injuries from families with higher family stressors made less progress over the first year post-injury on a measure of visual–motor skill. Associations of environmental disadvantage and non-optimal parenting characteristics with lower cognitive abilities and slower cognitive development have also been reported in studies of non–head-injured children (Burchinal, Roberts, Hooper, & Zeisel, 2000; Bradley & Corwyn, 2002; McLoyd, 1998; Breslau, Chilcoat, Susser, Matte, Liang, & Peterson, 2001; Espy, Molfese, & DiLalla, 2001; Landry, Chapaieski, Richardson, Palmer, & Hall, 1990; Landry, Garner, Swank, & Baldwin, 1996; Landry, Miller-Loncar, Smith, & Swank, 2002; Landry, Smith, Miller-Loncar, & Swank, 1997; Landry, Smith, & Swank, 2006; Smith, Landry, & Swank, 2000; Taylor, Schatschneider, & Minich, 2000; Taylor, Minich, Klein, & Hack, 2004).

However, the few studies that have examined post-injury development in cognition following TBI in early childhood are subject to several limitations. First, by focusing largely on measures of IQ, these studies have not provided information on the nature of cognitive changes across multiple ability domains. Second, the effects of TBI on cognitive development in young children have often been evaluated by comparing children with more severe TBI to children who sustained mild TBI or to non-injured community controls. While comparison to children with mild TBI is useful in assessing injury severity effects, the utility of such a comparison is limited by the fact that mild TBI may itself have adverse effects in young children (Gronwall, Wrightson, & McGinn, 1997). Comparison with community controls is problematic because samples of children who sustain traumatic injuries may differ in pre-injury characteristics from uninjured groups (Goldstrohm & Arffa, 2005; Parslow, Morris, Tasker, Forsyth, & Hawley, 2005). To help control for risk for injury and for the experience of hospitalization, children hospitalized for other traumatic injuries may be a more appropriate comparison group. Finally, previous studies have failed to consider proximal family characteristics, such as the quality of the home environment or parenting styles, in evaluating the effects of TBI on cognitive development.

In an initial study of the present sample investigating the post-acute effects of TBI in early childhood (ages 3–6 years), Taylor, Swartwout, Yeates, Walz, Stancin, and Wade (2008) assessed the effects of varying levels of TBI severity on several cognitive outcomes relative to an orthopedic injury (OI) comparison group. Results indicated that the severe TBI group had lower scores on measures of overall cognitive abilities, memory, spatial reasoning, and executive function, whereas the moderate TBI group had more selective deficits on measures of memory and executive function. Lower socioeconomic status (SES) was also associated with poorer cognitive outcomes for the sample as a whole.

The major aim of the current study was to examine subsequent post-injury cognitive development in the TBI and OI groups. A further aim was to determine if measures of the proximal family environment, as reflected in home and parenting characteristics conducive to cognitive development, would be positively related to outcomes. Research suggests that proximal features of the home environment account for variations in cognitive development not explained by SES and may even mediate some of the effects of SES on children's competencies (Bradley & Corwyn, 2002; Bradley et al., 1989; Bradley, Corwyn, Caldwell, Whiteside-Mansell, Wasserm an, & Mink, 2000; Espy et al., 2001). Based on the existing literature, we hypothesized that (1) cognitive outcomes would be worse and more generalized in children with more severe TBI; (2) little recovery in skills would be evident in the children with TBI relative to children with OI; and (3) home environments less conducive to children's learning and parenting characterized by less warm responsiveness and less support of child development would be associated with poorer test performance and slower post-injury cognitive development. In light of data from our post-acute assessment showing that some outcomes of TBI were worse in children from less advantaged environments (Taylor et al., 2008), and similar evidence from a previous study of TBI in school-age children (Taylor et al., 1999, 2002; Yeates, et al., 1997, 2002), we also explored the possibility that the effects of TBI would be exacerbated by home environments that are less focused on child learning and by less supportive parenting.

METHODS

Sample

As described in our previous report (Taylor et al., 2008), children who sustained TBI or OI between the ages of 3 years, 0 months and 6 years, 11 months were recruited from three tertiary care children's hospitals and a general hospital, all with Level 1 trauma centers. The study was approved by the ethics boards of all participating hospitals, and informed consent was obtained before participation.

Eligibility requirements for the TBI group included blunt trauma requiring overnight admission to the hospital and either a Glasgow Coma Scale (GCS; Teasdale & Jennett, 1974) score < 15, suggesting altered neurological status, or evidence for TBI-related brain abnormalities from computed tomography (CT) or magnetic resonance imaging (MRI). The TBI group was divided into severe, moderate, and complicated mild severity groups consistent with previous investigations (Anderson et al., 2006; Fletcher, Ewing-Cobbs, Miner, Levin, & Eisenberg, 1990; Taylor et al., 1999). Severe TBI was defined by a GCS score of 8 or less, moderate TBI by a GCS score of 9–12, and complicated mild TBI by a GCS score of 13–15 with neuroimaging abnormality. Justification for including children with mild complicated injuries includes adult and child findings showing greater cognitive impairments with this type of injury compared with uncomplicated mild TBI (Levin et al., 2008). The GCS score assigned to the child was the lowest one recorded. 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, and the absence of any evidence of loss of consciousness or other findings suggestive of brain injury. Children were excluded from the study if English was not the primary language spoken in the home or if they had histories of child abuse, autism, mental retardation, or a neurological disorder.

A total of 204 children and their caregivers were enrolled in the study. At least a portion of the test battery was administered to 201 children (98.5% of the sample) at the post-acute baseline assessment completed an average of 1.5 months after injury. Subsequent follow-up assessments were conducted at approximately 6, 12, and 18 months post-injury. The final sample comprised 87 children with TBI (23 severe, 21 moderate, and 43 complicated mild) and 117 with OI (see Table 1 for sample demographics). To be included in the sample, children had to have completed at least one post-injury assessment. Comparisons of participants in the TBI and OI groups with children from these groups who met age and injury severity criteria but were not recruited failed to reveal significant differences in census-based median income of the neighborhood of residence (using the Federal Financial Institutions Examinations Council Geocoding System, 2005).

Because we extended the recruitment window slightly to enroll as many children with TBI as possible, the time between injury and the baseline assessment was somewhat longer for the TBI groups than for the OI group. The groups also differed in race, maternal education, and a composite SES measure defined as the average sample *Z* scores for maternal education and census-based median income. Only the severe TBI and OI groups differed significantly in SES. Attrition rates were relatively low, with follow-up of 179 (88%) of the sample at the 6-month assessment, 160 (78%) at the 12-month assessment, and 157 (77%) at the 18-month assessment. Attrition was not significantly related to group, sex, race, or SES.

Assessment Procedures

Child and family assessment at baseline included administration of a neuropsychological test battery to the child, a parent interview to obtain information on family SES and the home environment, and videotaped parent–child interactions. Children were administered neuropsychological tests in a fixed order with differing, but overlapping batteries tailored to the age ranges 3 years 0 months to 3 years 5 months, 3 years 6 months to 5 years, 11 months, and 6 years 0 months to 6 years 11 months (Taylor et al., 2008). Table 2 lists tests administered according to cognitive domain and indicates the age range and sample size for each measure. The rationale assessing these cognitive domains was our interest in measuring a range of skills while focusing on those considered most susceptible to injury effects (Yeates, 2000). Given that executive function is both highly vulnerable to injury and important for children's ongoing development, special emphasis was placed on assessments of this domain (Taylor et al., 2008) The test battery for the baseline and 12-month assessments included all measures, but the global cognitive ability and spatial reasoning domains were not evaluated at the 6- and 18-month assessments. Most of the measures were applicable across the full age range over which children were assessed (i.e., out to maximum of 8 years 4 months at the final visit). Sample size reductions reflected the inapplicability of certain tests to younger or older children and inability of some younger children to meet test demands.

The quality of the home environment was assessed by administering the Home Observation for Measurement of the Environment (HOME, Caldwell & Bradley, 2000). The HOME assesses parental stimulation and support to the child by observing the child's home and discussing child-related activities with parents. Specifically, in the course of a home visit, the examiner gathered information regarding learning materials, developmental stimulation, physical environment, and parental supportiveness. The overall HOME score was the sum of the ratings across the eight domains, with higher scores reflecting greater structure, stimulation, and support within the home environment. The HOME has good reliability and is a valid predictor of children's cognitive development (Caldwell & Bradley, 2000). The correlation between the HOME and SES for the total sample was moderately high (r = .53; $p < .001$), suggesting that these measures were related but nonequivalent.

The parent–child interactions consisted of two 10-min interaction sessions that were coded based on structured rating

Table 1. Sample demographic characteristics

	Group			
	Severe TBI (n = 23)	Moderate TBI (n = 21)	Mild-complicated TBI (n = 43)	OI (n = 117)
Age at injury in years, M (*SD*)	5.0 (1.0)	5.2 (1.2)	5.0 (1.2)	5.1 (1.1)
Time since injury at baseline (in months)*	1.6 (.8)	1.5 (.8)	1.5 (.7)	1.2 (.5)
Males, n (%)	16 (69.6%)	12 (57.1%)	25 (58.1%)	67 (57.3%)
Lowest GCS score, mean (*SD*)*	4.0 (1.7)	10.9 (1.2)	14.7 (.5)	—
Non-white race, n (%) *	7 (30.4%)	11 (52.4%)	11 (25.6%)	27 (23.1%)
Census median family income in thousands of dollars, M (*SD*)	54.3 (15.8)	53.9 (34.0)	59.0 (21.7)	63.9 (23.4)
Maternal education, n (%)*				
<High school	6 (26.1%)	6 (28.6%)	4 (9.5%)	8 (6.8%)
High school grad	10 (43.5%)	6 (28.6%)	18 (42.9%)	45 (38.5%)
>High school grad	7 (30.4%)	9 (42.9%)	20 (47.6%)	64 (54.7%)
SES*	−.5 (.6)	−.3 (1.3)	−.1 (1.0)	.2 (.9)

Note. TBI = traumatic brain injury (TBI); OI = orthopedic injury (OI); GCS = Glasgow Coma Scale; SES = socioeconomic status, defined as composite (z score average) of maternal education and median income for the census tract in which the family resided.
*Significant difference between groups, $p < .05$.

system validated by Landry and colleagues (Landry et al., 1990, 1997, 2002; Landry, Smith, Swank, Assel, & Vellet, 2001). In the first or “free play” session, the parent was instructed to spend time with his/her child as if they were at home. Developmentally appropriate toys and parent magazines were available in the exam room. Parent behavior was rated on a 5-point scale (higher scores indicating more positive behavior) along the dimensions of parental warm responsiveness. Parental warmth was rated based on the presence and intensity of verbal and nonverbal warmth, affection, and positive regard toward the child. Contingent responsiveness ratings reflected the degree of the parent’s sensitivity and responsiveness to the child’s behavior. The interactions were divided into two 5-min segments that were coded independently and averaged to increase the stability of the measures. Because they were highly correlated, the warmth and contingent responsiveness scales were averaged to form a single “warm responsiveness” scale (Landry et al., 2006). In the second “teaching” task, the parent was instructed to guide their child to completion of a developmentally challenging cognitive task (Landry et al., 1996). Parental scaffolding was measured by the frequency with which parents provided verbal support for the child during this task. Ratings of 15% of the tapes by the entire rating team revealed a satisfactory level of inter-rater reliability, with intraclass correlation coefficients ≥ 0.8 for all codes. Procedures for maintaining reliability between blinded and un-blinded raters minimized any bias due to the awareness of some of the raters of the nature of the child’s injury (TBI *vs.* OI).

Data Analysis

General linear mixed-model analysis, also known as hierarchical linear or growth modeling, was used to examine changes in test performance across follow-up. With the exception of the standard score for General Conceptual Ability (GCA) from the Differential Ability Scales (DAS, Elliott, 1990), analysis was conducted on raw scores. Because of its equal-interval property, the W score equivalent of the raw score was examined for the Woodcock Johnson Tests of Achievement—Third Edition (Woodcock, McGrew, & Mather, 2001) Story Recall test. The rationale for examining raw scores is their potential to reveal changes in performance that may be obscured by transforming scores based on normative standards. A mixed-model approach enables utilization of data from all participants, even those not seen at every assessment, and does not require equal intervals between assessments (Francis, Fletcher, Stuebing, Davidson, & Thompson, 1991). Analysis was conducted using SAS Proc Mixed (Singer, 1998).

The first set of analyses was conducted to examine group differences across follow-up. The effects of each level of TBI severity were examined by including contrast terms comparing each TBI group with the OI group. The effect of time since injury was modeled as linear and quadratic change in scores across the follow-up assessments, with only linear change included in models for the GCA and tests of spatial reasoning. Covariates were baseline SES, race, sex, and age at injury. Three-way interactions were also included to investigate moderating effects of age at injury and SES on the group differences in change across follow-up. To evaluate potential bias due to attrition, we conducted additional analyses in which children who completed follow-up were compared with children who dropped out before the final assessment. Differences between these two subgroups were found for Story Recall, with lower scores in the children who dropped out. However, there were no other differences and results were not substantially changed for any outcome when completer

Table 2. Neuropsychological test battery and ages of administration

Domain/measure	Description	Age range	*N* for analysis
Global Cognitive Ability:			
DAS GCA	Composite of tests of verbal and nonverbal abilities	3:0+ years	203
Language:			
CASL Pragmatic Judgment	Social communication skills	3:0+ years	202
NEPSY Verbal Fluency	Naming of different animals and foods/drinks as quickly as possible	3:0-6:11 years	194
Verbal Memory:			
WJ-III Story Recall	Immediate recall of a series of brief stories	3:0+ years	202
Visual Memory:			
DAS Recognition of Pictures	Identification of previously seen objects from a display that includes both target and distractor pictures	3:0+ years	202
Auditory Working Memory:			
DAS Recall of Digits	Repetition of increasingly longer strings of digits	3:0+ years	202
NEPSY Sentence Repetition	Repetition of increasingly longer sentences	3:0+ years	201
Spatial Reasoning:			
DAS Pattern Construction	Construction of block designs from pictorial representations	3:6+ years	199
DAS Copying	Paper and pencil reproduction of geometric figures	3:6–5:11 years	142
DAS Picture Similarities	Identification of pictures and relationships between them	3:0–5:11 years	146
Inhibition and Set Switching:			
SS Inhibit condition	Stroop-like task involving inhibition of overlearned response set	3:0+ years	195
SS Switch condition	Cognitive switching between color and shape naming	3:0+ years	186
SS Both condition	Cognitive switching and inhibitory control in a Stroop-like naming task	3:0+ years	181

Note. DAS = Differential Ability Scales (Elliott, 1990); GCA = General Conceptual Ability; WJ-III = Woodcock Johnson Tests of Achievement—Third Edition (Woodcock et al., 2001); CASL = Comprehensive Assessment of Spoken Language (Carrow-Woolfolk, 2000); NEPSY = A Developmental Neuropsychological Assessment (Korkman et al., 1998); SS = Shape School (Espy, 1997). Tests comprising the DAS GCA and spatial reasoning domains were administered only at baseline and 12 months post injury. Sample size for the DAS spatial reasoning tests was also reduced because of the more limited age ranges over which children are eligible for these procedures. DAS Verbal Fluency was only given to children younger than 6 years because older children receive a different version of the test.

versus non-completer status was included in the models. There was thus little reason to suspect bias due to incomplete longitudinal data.

A second series of mixed model analyses was carried out to investigate direct effects of the proximal home environment, as assessed by HOME and parent warm responsiveness and scaffolding, on the cognitive measures. We also examined potential moderating effects of these factors on group differences by adding each factor (considered separately), along with its interaction with group, time since injury, and group × time since injury, to the models obtained from the first series of analyses described above. Because of our interest in determining how the family environment at the beginning of follow-up predicted subsequent cognitive development, only baseline measures of the home environment were considered in analysis.

Models for both sets of analyses were trimmed by eliminating nonsignificant higher- and then lower-level interaction. A family-wise alpha level of .05 was used to determine statistical significance, with Bonferroni correction applied to individual tests within test domains (i.e., alpha for tests within 2- and 3-test domains of .025 and .0167, respectively). Effects sizes for significant TBI *versus* OI contrasts were estimated using Cohen's *d* (Cohen, 1988).

RESULTS

Group Differences Across Follow-up

Findings from mixed-model analysis revealed group main effects for measures from multiple ability domains. As shown in Table 3, the severe TBI scored significantly lower than the

https://doi.org/10.1017/S1355617709991135 Published online by Cambridge University Press

Table 3. Results of mixed models analysis of cognitive measures

Domain/measure	Effect	Estimate	*SE*	df	t	*p*
Global Cognitive Ability:						
DAS GCA	Sev TBI vs. OI	−10.48	2.56	195	−4.09	<.001
	SES	7.06	0.87	207	8.12	<.001
	Age at Injury × TSI [F(1,170) = 5.73 *p* = .018]					
Language:						
CASL Pragmatic Judgment	SES	2.09	0.46	191	4.59	<.001
	Age at Injury × TSI [F (2,166) = 15.96, *p* = <.001]					
	Group × TSI [F (6,167) = 3.70, *p* = .002]					
NEPSY Verbal Fluency	Sev TBI vs. OI	−2.41	0.96	156	−2.52	0.013
	Age at Injury	4.58	0.29	197	15.75	<.001
	SES	1.10	0.32	171	3.46	0.001
	TSI [F (2,126) = 62.52, *p* = <.001]					
Verbal Memory:						
WJ-III Story Recall	Sev TBI vs. OI	−5.42	1.18	185	−4.6	<.001
	SES	0.99	0.40	194	2.46	0.015
	Age at Injury × TSI [F (2,193) = 11.09, *p* = .001]					
Visual Memory:						
DAS Recognition of Pictures	Sev TBI vs. OI	−9.72	2.46	185	−3.95	0.000
	Mod TBI vs. OI	−7.61	2.61	188	−2.92	0.004
	SES	2.68	0.85	193	3.17	0.002
Auditory Working Memory:						
DAS Recall of Digits	Sev TBI vs. OI	−10.96	4.11	194	−2.66	0.008
	Mod TBI vs. OI	−11.93	4.32	203	−2.76	0.006
	CM TBI vs. OI	−7.56	3.21	195	−2.35	0.020
	SES	5.61	1.39	202	4.03	<.001
	Age at Injury × TSI [F (2,194) = 30.00, *p* = <.001]					
NEPSY Sentence Repetition	Sev TBI vs. OI	−2.11	0.65	191	−3.24	0.001
	Mod TBI vs. OI	−1.89	0.69	200	−2.76	0.006
	CM TBI vs. OI	−1.41	0.51	191	−2.78	0.006
	SES	0.95	0.22	198	4.28	<.001
	Gender (Female)	0.93	0.41	195	2.27	0.024
	Age at Injury × TSI [F (2,184) = 22.91, *p* = <.001]					
Spatial Reasoning:						
DAS Pattern Construction	Sev TBI vs. OI	−12.30	3.43	176	−3.59	0.000
	SES	5.58	1.15	193	4.85	<.001
	Age at Injury × TSI [F(1.158) = 66.47 *p* = <.001]					
DAS Copying	Sev TBI vs. OI	−11.23	3.56	130	−3.16	0.002
	Age at Injury	24.48	1.51	181	16.25	<.001
	SES	4.92	1.19	138	4.12	<.001
	TSI	22.52	1.83	65	12.29	<.001
DAS Picture Similarities	Age at Injury	12.02	1.06	160	11.36	<.001
	SES	4.45	0.90	146	4.94	<.001
	TSI	13.91	1.60	81.7	8.71	<.001
Inhibition and Set Switching:						
SS Inhibit Condition	Sev TBI vs. OI	−0.20	0.07	199	−2.99	0.003
	Mod TBI vs. OI	−0.18	0.07	197	−2.59	0.010
	Age at Injury	0.23	0.02	206	12.27	<.001
	SES	0.09	0.02	198	3.93	0.000
	Gender (Female)	0.11	0.04	187	2.73	0.007

Table 3. Continued

Domain/measure	Effect	Estimate	*SE*	df	t	*p*
SS Switch Condition	Sev TBI vs. OI	−0.11	0.03	187	−4.03	<.001
	Mod TBI vs. OI	−0.08	0.03	189	−2.86	0.005
	Age at Injury	0.11	0.01	211	13.1	<.001
	SES	0.03	0.01	190	2.99	0.003
	TSI					
	[F (2,170) = 57.50 *p* = <.001]					
SS Both Condition	Sev TBI vs. OI	−0.13	0.04	171	−3.52	0.001
	Age at Injury	0.14	0.01	198	12.34	<.001
	SES	0.04	0.01	176	2.86	0.005
	Gender (Female)	−0.06	0.02	162	−2.69	0.008
	Race (non)white)	−0.08	0.03	169	−3.07	0.003
	TSI					
	[F (2,159) = 73.21 *p* = <.001]					

Note. Sev = severe; Mod = moderate; CM = complicated mild; OI = orthopedic injury; DAS: Differential Ability Scales; GCA = General Conceptual Ability; WJ-III: Woodcock Johnson Test of Achievement—Third Edition; CASL: Comprehensive Assessment of Spoken Language; NEPSY: NEPSY: A Developmental Neuropsychological Assessment; SS: Shape School. Only significant effects from each model are listed. Model estimates for group effects are group differences in raw scores for all measures except GCA Model estimates are not given for time since injury, as this represents the conjoint effects of linear and quadratic terms. SES = socioeconomic status. Metrics: premorbid (raw score), age at injury (years), SES (z-score).

OI group on most of the measures, with fewer deficits found in the moderate and complicated mild TBI groups. Effect sizes for the severe TBI *versus* OI contrasts were medium to large (.79 for GCA, .56 for Verbal Fluency, .91 for Story Recall, .78 for Recognition of Pictures, .52 for Recall of Digits, .63 for Sentence Repetition, .75 for Pattern Construction, .76 for Copying, and .51, .80, and .74, respectively, for the Shape School Inhibition, Switch, and Both conditions). Effect sizes were medium for the moderate TBI *versus* OI contrasts (.59 for Recognition of Pictures, .54 for Recall of Digits, .54 for Sentence Repetition, and .51 and .54, respectively, for the Shape School Inhibition and Switch conditions), and small for the complicated mild TBI *versus* OI contrasts (.38 for Recall of Digits and .46 for Sentence Repetition).

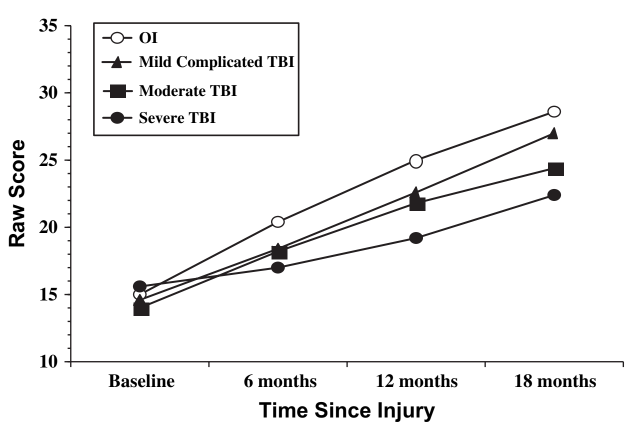

Figure 1. Estimates from mixed model analysis of group mean scores on Pragmatic Judgment across follow-up. Analysis revealed significant differences between the severe traumatic brain injury (TBI) and orthopedic injury (OI) groups only at 12 and 18 months after injury, and between the moderate TBI and OI groups only at 18 months after injury.

Analysis also revealed a group × time since injury interaction for Pragmatic Judgment. Estimated scores of the four groups across the four assessments are graphed in Figure 1. Follow-up tests to examine the sources of the interaction indicated emerging deficiencies over time post-injury in the severe and moderate TBI groups relative to the OI group, with significant deficits only at 12 and 18 months post-injury in the severe TBI group and at 18 months in the moderate TBI group.

Associations of Proximal Family Environment With Test Performance

In the second series of mixed models, three of the measures of the proximal home environment were related to outcomes, even with SES in the model. A higher HOME score was associated with higher GCA, $F(1,194) = 9.00$; $p = .003$; Pragmatic Judgment, $F(1,188) = 10.89$; $p = .001$; Verbal Fluency, $F(1,190) = 11.87$; $p = .001$; Recognition of Pictures, $F(1,182) = 20.34$; $p = < .001$; and Shape School Switch, $F(1,180) = 9.29$; $p = .003$. A HOME × time since injury (quadratic component) interaction for Sentence Repetition, $F(1,186) = 6.23$; $p = .013$, indicated that a higher HOME score was associated with more rapid growth from baseline to 12 months post-injury after which the HOME had a less pronounced effect. Higher warm responsiveness predicted higher GCA, $F(1,187) = 5.21$; $p = .029$, and Pragmatic Judgment, $F(1,185) = 5.52$; $p = .020$. Higher scaffolding predicted higher scores on Pragmatic Judgment, $F(1,187) = 8.15$; $p = .005$; Verbal Fluency, $F(1,191) = 7.14$; $p = .008$; Recognition of Pictures, $F(1,176) = 5.80$; $p = .017$; Recall of Digits, $F(1,189) = 6.72$; $p = .010$; Sentence Repetition, $F(1,182) = 7.39$, $p = .007$; and Shape School Switch, $F(1,166) = 7.82$; $p = .006$.

A group × scaffolding interaction, $F(3,179) = 3.07$; $p = .029$, provided the only evidence for a moderating effect of the

https://doi.org/10.1017/S1355617709991135 Published online by Cambridge University Press

home environment on the outcomes of TBI. To examine the source of this interaction, each TBI *versus* OI contrast was tested at levels of low and high scaffolding as defined by scaffolding counts that were 1 standard deviation (*SD*) below and above the sample mean, respectively. Results revealed that deficits were significant for the severe TBI at a low level of scaffolding and for the moderate TBI group at a high level of scaffolding.

DISCUSSION

In support of our first hypothesis, cognitive deficits in young children with severe TBI were more pronounced and generalized than those associated with moderate or complicated mild TBI. These results parallel findings from our previous report of baseline outcomes (Taylor et al., 2008), as well as those from past research on the cognitive sequelae of TBI in young children (Anderson et al., 2000a, 2004, 2005a, 2006; Ewing-Cobbs et al., 1997). Consistent with our second hypothesis, these consequences persisted across the 18-month follow-up interval. There were no indications of recovery and a deficit in Pragmatic Judgment was not evident until 12 months post-injury. Previous studies have observed limited recovery in children with TBI during early childhood (Anderson et al., 2004; Catroppa et al., 2007; Keenan et al., 2007; Ewing-Cobbs et al., 1997), but the present findings demonstrate that even children with complicated mild TBI have persistent weaknesses on tests of auditory working memory and inhibition. Anderson, Catroppa, Rosenfeld, Haritou, and Morse (2000b) found that memory deficits in young children with TBI emerged over the first year post-injury. To our knowledge, however, the present study is the first to indicate later-appearing deficits in pragmatic language.

The later appearing deficit in Pragmatic Judgment is subject to at least two interpretations. One explanation is that cognitive deficits that occur immediately after TBI or damage to underlying neural structures have a growth-limiting effect on the post-injury development of pragmatic language. In this instance, TBI would be expected to have increasingly adverse effects across follow-up independent of the age range over which the child is followed. A second possibility is that the effects of TBI on these abilities do not become manifest until later ages, due either to the insensitivity of the test to injury effects at earlier ages or to developmental factors. One developmental explanation is that pragmatic language skills are rapidly emerging during early school age, and that such skills are more susceptible to disruption following early brain injury (Dennis, 1988). However, if the child's age at assessment was the critical factor, one would expect deficits to become more pronounced at older ages more so than with increasing time post-injury. As the deficit in Pragmatic Judgment was related only to time post-injury and not to the age range across which follow-up took place, the findings are more consistent with the first interpretation. However, restrictions in the age range over which children were followed preclude any firm conclusions, and follow-up to later ages would provide a stronger test of age-related deficits.

One possible explanation for finding age-related increases in deficits in the severe TBI group only on Pragmatic Judgment is that the social use of language may be developing especially rapidly during this period of childhood, regardless of the exact age interval over which the child is followed (Ewing-Cobbs & Barnes, 2002). The fact that Pragmatic Judgment draws on children's abilities to make inferences about pictured social interactions, appreciate the intentions of the persons in the pictures, and use social discourse may also help account for this finding. The test thus taps into several of the skills that are most vulnerable to TBI (Dennis et al., 2001; Yeates et al., 2007).

Our third hypothesis was confirmed by associations of cognitive outcomes with the HOME and with the parenting measures warm responsiveness and scaffolding. Specifically, we found that higher scores on one or more of these environmental measures were related to higher test scores on several tests. These results parallel findings showing that SES is related to diverse cognitive abilities (Farah et al., 2006; Noble, Norman, & Farah, 2005). In the present study, however, associations with proximal family factors were independent of the effects of SES. Our findings thus confirm previous data demonstrating that proximal family factors account for variability in cognition not explained by more distal measures such as SES (Bradley et al., 1989; Bradley, Corwyn, Caldwell, Whiteside-Mansell, Wasserman, & Mink. 2000; Espy et al., 2001). A higher HOME score also predicted faster growth over the follow-up interval in Sentence Repetition, as is consistent with other evidence for family influences on cognitive development (Burchinal et al., 2000; Espy et al., 2001; Landry et al., 2002, 2006; Murray & Hornbaker, 1997; Smith et al., 2000). Because most of these effects did not vary by group, the results suggest that more optimal family environments promote cognitive development similarly in children with TBI and in children without brain injuries.

The only evidence for environmental moderation of the consequences of TBI was provided by the differential effect of parental scaffolding on the GCA. Specifically, a deficit in GCA was significant for the severe TBI group only at a low level of scaffolding and for the moderate TBI group only at a high level of scaffolding. These two disparate findings are difficult to reconcile and suggest that the interaction may have been spurious. Nevertheless, results for the severe TBI group are consistent with evidence that higher family function buffers the adverse effects of later-childhood TBI on memory (Yeates et al., 1997). This pattern of environmental moderation is also similar to that reported by Landry et al. (1990, 1997) and Landry, Smith, Miller-Loncar, and Swank (1998), who found that supportive parenting was more strongly related to positive developmental outcomes of very low birth weight in children at higher neurological risk.

Although we did not examine the effects of early *versus* later childhood TBI in this study, the lack of recovery in cognitive abilities contrasts with results obtained in post-injury follow-up of children injured at older ages (Anderson & Catroppa, 2005; Anderson et al., 2000a, 2005b; Chadwick et al., 1981; Taylor et al., 1999; Verger et al., 2000). Explanations for the lack of even short-term recovery in skills following TBI at younger ages include the greater vulnerability of the younger brain to diffuse insult, the potential for early insults to result in greater alterations in neural development, and a greater effect of cognitive deficits acquired at an earlier age on subsequent developmental progress (Anderson et al., 2000, 2005b; Bittigau et al., 1999; Ewing-Cobbs et al., 2004b; Taylor & Alden, 1997). As in our previous study, however, we failed to find moderating effects of age at injury on cognitive outcomes (Taylor et al., 2008). Variations in age at injury within the early childhood period (3–6 years) may be less important for outcome than differences between early and later childhood insults.

The associations of a higher quality home environment and more optimal parenting characteristics with higher test scores may be explained in terms of the positive effects of parental guidance and attention, cognitive stimulation, and learning resources on cognitive development (Bradley & Corwyn, 2002). Conversely, cognitive development may be hampered by less optimal family environments (McLoyd, 1998). Associations between child outcomes and family factors also could have reflected bidirectional relationships between child and family characteristics or even genetically based similarities between parenting styles and children's abilities (Collins, Maccoby, Steinberg, Hetherington, & Bornstein, 2000; Rutter, Pickles, Murray, & Eaves, 2001; Taylor, Yeates, Wade, Drotar, Stancin, & Brunett, 2001; Wade et al., 2008). Although the findings do not allow us to distinguish among these interpretations, they provide an impetus for further studies of mechanisms of effect. Consideration of multiple and interactive factors is needed for a fuller account of environmental influences on cognitive development, including peer and neighborhood effects, family stress, and family characteristics in addition to those measured in this study (Burchinal et al., 2000; Conger & Donnellan, 2007; Fiese, 2001).

Several study limitations must be kept in mind in interpreting these findings. First, despite statistical control for background differences in SES and race and data suggesting that our sample was representative of children with TBI treated at the participating hospitals, we advise caution in generalizing findings to broader populations. Second, although we did not find systematic differences in background or outcomes between children who completed follow-up and those who did not, our estimates of longitudinal change may have been biased by unmeasured factors. A third concern relates to the lack of initial assessments of some skills in the youngest children in the sample. The vast majority of participants were assessed at all post-injury visits, and age at injury was taken into account in the analysis, but estimates of growth rates may have been less precise in this subset of our sample. A further limitation is that children with TBI were divided into severity categories based only on the GCS score and on findings from clinical neuroimaging. Imaging methods with greater sensitivity to TBI, such as more advanced MRI techniques, may have provided a more valid metric for assessing the type and degree of brain insult in relation to cognitive outcomes (Brenner, Freier, Holshouser, Burley, & Ashwal, 2003; Serra-Grabulosa, Junque, Verger, Salgado-Pineda, Maneru, & Mercader, 2005; Wilde et al., 2006).

Despite these limitations, the present study is one of only a few studies to assess the cognitive development in young children with TBI relative to an "other injury" comparison group. The results document both persisting and later appearing deficits following TBI, with persisting deficits in executive function found even in children with moderate and complicated mild TBI. We did not find evidence that any of the environmental factors facilitated cognitive recovery. Such recovery would be demonstrated by a "catch-up" in cognitive skills over time post-injury for children with TBI relative to children with OI under some environmental conditions. However, by demonstrating that more stimulating and supportive home environments are associated with better cognitive performance, our findings confirm the potential benefits of intensive family-based interventions targeting child-centered activities and positive parenting (Landry, Smith, & Swank, 2003; Wade, Oberjohn, Burhardt, & Greenberg, 2009). In particular, positive parenting skills interventions that teach parental warm responsiveness through the use of specific praise, behavioral descriptions, and reflection of the child's verbalizations, such as Parent–Child Interaction Therapy (Eyberg, 1988), may facilitate cognitive recovery through both enhanced parent–child interactions and heightened verbal stimulation. Parents can be trained to provide critical environmental supports or scaffolding for the child's behavior. From this perspective, parents can function as the interventionist as well as the target of the intervention (Braga, Da Paz, & Ylvisaker, 2005).

Further follow-up of the sample is needed to investigate longer-term consequences of early childhood TBI. While neural reorganization may support partial recovery in some cognitive functions with advancing age (Stiles, Reilly, Paul, & Moses, 2005), early cognitive weaknesses also increase risks for later-emerging deficits (Blair, 2006; Taylor, 2004). Longitudinal monitoring of outcomes in these and other children who have sustained TBI in early childhood is critical to ensure awareness of cognitive weaknesses and to recommend instructional approaches to facilitate their learning progress. Increasing deficits in pragmatic language among children with severe TBI are particularly concerning and underscore the importance of more in-depth analysis of the cognitive factors that contribute to such age-related changes and the need for interventions aimed at improving communication and social skills. Additional research will be useful to enhance knowledge of the longer-term consequences of early childhood TBI, identify risk factors, and elucidate the mechanisms responsible for environmental effects on cognition.

ACKNOWLEDGMENTS

Supported by grant R01 HD42729 to Dr. Wade from NICHD, in part by USPHS NIH grant no. M01 RR 08084, and by Trauma Research grants from the State of Ohio Emergency Medical Services. The authors wish to acknowledge the contributions of Christine Abraham, Andrea Beebe, Lori Bernard, Anne Birnbaum, Beth Bishop, Tammy

Matecun, Karen Oberjohn, Elizabeth Roth, and Elizabeth Shaver in data collection and coding. The Cincinnati Children's Medical Center Trauma Registry, Rainbow Pediatric Trauma Center at Rainbow Babies & Children's Hospital, Nationwide Children's Hospital Trauma Program, and MetroHealth Center Department of Pediatrics and Trauma Registry provided assistance with recruitment.

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