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Traumatic brain injury in young children: Postacute effects on cognitive and school readiness skills

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Abstract

Previous studies have documented weaknesses in cognitive ability and early academic readiness in young children with traumatic brain injury (TBI). However, few of these studies have rigorously controlled for demographic characteristics, examined the effects of TBI severity on a wide range of skills, or explored moderating influences of environmental factors on outcomes. To meet these objectives, each of three groups of children with TBI (20 with severe, 64 with moderate, and 15 with mild) were compared with a group of 117 children with orthopedic injuries (OI group). The children were hospitalized for their injuries between 3 and 6 years of age and were assessed an average of $1\frac{1}{2}$ months post injury. Analysis revealed generalized weaknesses in cognitive and school readiness skills in the severe TBI group and less pervasive effects of moderate TBI. Indices of TBI severity predicted outcomes within the TBI sample and environmental factors moderated the effects of TBI on some measures. The findings document adverse effects of TBI in early childhood on postacute cognitive and school readiness skills and indicate that these effects are related to both injury severity and the family environment. (*JINS*, 2008, *14*, 734–745.)

Keywords: Child, Preschool, Brain injuries, Neurobehavior manifestations, Outcome, Moderator variables

INTRODUCTION

Traumatic brain injury (TBI) is one of the most common causes of death and long-term disability in the pediatric age range (Gotschall, 1993; Kraus, 1995). According to a report on emergency department (ED) visits, hospitalizations, and deaths in the United States for the years 1995–2001 (Langlois et al., 2006), nearly half a million children 0–14 years of age had TBI each year during this period. Among survivors, the consequences of TBI in children include physical conditions (e.g., neuromotor impairment, seizures, trauma-related orthopedic injuries), lowered cognitive and academic skills relative to age expectations or preinjury estimates, and problems in school performance, behavior, socialization, and adaptive functioning (Anderson et al., 2006; Ewing-Cobbs et al., 2004a; Schwartz et al., 2003; Stancin et al., 2002; Yeates, 2000; Yeates & Taylor, 1997). Although TBI in school-age children is associated with global cognitive deficits (Anderson et al., 2006; Ewing-Cobbs et al., 2004b; Fay et al., 1994; Levin et al., 1995; Taylor et al., 1999; Yeates, 2000), impairments are especially pronounced on measures of memory, perceptual abilities and psychomotor speed, attention and executive function, and discourse processing (Anderson & Catroppa, 2005; Bawden

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et al., 1985; Chadwick et al., 1981; Dennis & Barnes, 2001; Donders, 2001; Donders & Giroux, 2005; Ewing-Cobbs & Barnes, 2002; Levin & Hanten, 2005; Taylor et al., 1999).

More negative outcomes are predicted by increasing TBI severity and less advantaged family environments (Anderson et al., 2006; Fletcher et al., 1995; Schwartz et al., 2003; Taylor et al., 1999, 2002). Whereas cognitive deficits are well documented in school-age children with moderate to severe TBI (Anderson et al., 2004, 2006, 2005b; Taylor et al., 1999), studies of children with mild TBI have yielded inconsistent findings. Some of these studies have demonstrated only transient cognitive deficits if any and others have suggested emerging consequences over time after injury (Anderson et al., 2001; Gronwall et al., 1997; Keenan et al., 2007; Ponsford et al., 1999).

Younger age at injury is another predictor of worse outcomes. Specifically, children aged 2 to 7 years at the time of injury are more susceptible to deficits in expressive language, attention, and academic achievement compared with children injured at later ages (Anderson et al., 2005a; Barnes et al., 1999; Dennis et al., 1995; Ewing-Cobbs & Barnes, 2002; Ewing-Cobbs et al., 1989, 1997; Morse et al., 1999; Verger et al., 2000). Researchers have speculated that the poorer outcomes in younger children may reflect a greater susceptibility to diffuse brain insult or abnormalities in neurogenesis, or a greater effect of injury on postinjury skill development (Anderson & Moore, 1995; Barnes et al., 1999; Ewing-Cobbs et al., 1997, 2004b; Taylor & Alden, 1997; Wetherington & Hooper, 2006).

Unfortunately, questions remain regarding the nature of the effects on TBI in young children on cognition and achievement. Previous research demonstrates both postacute and persisting effects of TBI in this age group on a wide range of ability measures (Anderson et al., 1999, 2000a,b, 2004, 2006; Ewing-Cobbs et al., 1989, 1997, 2004b; Gronwall et al., 1997). However, methodological limitations make it difficult to interpret these findings, as past studies have either failed to include a comparison group of children without TBI or have used uninjured children as controls. Inclusion of controls without TBI is needed to assess the effects of varying degrees of TBI severity relative to expectations for children without brain insult. But comparison with uninjured controls is also problematic. These children may have fewer preinjury developmental problems and come from more advantaged family backgrounds than children with TBI, raising questions as to whether group differences were present before TBI (Goldstrohm & Arffa, 2005; Keenan et al., 2007).

Determining the postacute effects of TBI on cognitive and school readiness skills is especially critical given the need for early identification of children who have been adversely affected by injury. Awareness of postacute deficits would be useful in gauging children's needs for interventions as they are transitioning to school entry or beginning to acquire basic academic competences. Data suggesting persisting or even later-emerging impairments in this age group (Anderson et al., 1999, 2000b, 2004, 2006; Ewing-Cobbs et al., 1989, 1997; Gronwall et al., 1997) further reinforce the importance of an awareness of postacute sequelae. A better understanding of the effects of TBI severity and environmental factors on outcomes would also be useful in identifying children at high risk for sequelae.

The primary objective of the present study was thus to investigate the effects of TBI in young children on postacute cognitive and achievement outcomes using methods that rigorously control for noninjury influences on outcomes. To provide an estimate of the effects of TBI that took into account preinjury risk exposure as well as the experience of hospitalization for injury, children admitted to hospitals for orthopedic injuries but without TBI were recruited as a comparison group. Outcomes were assessed using comprehensive measures of cognitive and early academic skills that were applicable across all or at least a major portion of the 3- to 6-year-old age range. Previous findings suggesting that children's self-regulatory or executive functions may be vulnerable to TBI and may play an important role in children's ongoing development (Anderson et al., 2005b; Blair, 2002; Bronson, 2000; Ewing-Cobbs et al., 2004b) prompted inclusion of several experimental measures of this skill domain. Finally, group comparisons were made controlling for sociodemographic factors.

We hypothesized that young children hospitalized for TBI would have deficits in cognitive and school readiness skills relative to children with orthopedic injuries only, and that these deficits would be most pervasive in children with severe TBI. Given the failure of many previous studies to investigate a wide range of outcomes in young children with TBI, we anticipated wide-ranging deficits and did not have expectations with respect to which skills would be more or less affected. We also hypothesized that outcomes would be worse for children from more disadvantaged environments (Anderson et al., 2006), and we explored the possibility that such environments might even exacerbate the negative consequences of TBI (Taylor et al., 1999, 2002; Yeates et al., 1997).

METHODS

Sample

Children were recruited from consecutive inpatient admissions from 2003 to 2006 of children with TBI or with OI at three tertiary care children's hospitals and a general hospital, all of which had Level 1 trauma centers. The study was approved by the ethics boards of all participating hospitals and informed consent was obtained before participation. Eligibility criteria included age at injury between 3 years, 0 months and 6 years, 11 months, no documentation in the medical chart or in parent interview of child abuse as a cause of the injury, and English as the primary spoken language in the home. Children with a previous history of autism, mental retardation, or a neurological disorder were excluded. Eligibility for the TBI group included a TBI due

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to 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).

Consistent with previous investigations (Anderson et al., 2006; Fletcher et al., 1990; Taylor et al., 1999), severe TBI was defined as one resulting in a GCS score of 8 or less. Moderate TBI was defined as a GCS score of 9–12 or a higher GCS score with abnormal neuroimaging. A final group of children with mild TBI comprised those participants with GCS scores of 13–14 without neuroimaging abnormalities. To insure that evidence for TBI was based on direct physical examination and not on history alone, children with GCS scores of 15 and normal neuroimaging were not recruited. 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.

A total of 221 children (102 with TBI and 119 with OI) and their caregivers were enrolled in the study. Recruitment rates for families contacted were somewhat higher for the combined TBI sample than for the OI group (53% *vs.* 35%). Examination of pre-enrollment screening data indicated that refusal rates were lower for children with the highest GCS scores. However, comparison of participants with nonparticipants on census-based neighborhood income failed to reveal differences for the sample as a whole or for subsets of children with GCS scores <9, 9–12, or 13–14. At least a portion of the test battery was administered to 216 children (98%) at the postacute assessment. The final sample comprised 99 children with TBI (20 severe, 64 moderate, and 15 mild) and 117 with OI. Reasons for failure to test children included injuries that precluded testing (2 with severe TBI) and difficulties in arranging for travel for the assessment (1 with severe TBI and 2 with OI). Untested children did not differ from those assessed in parental marital status, neighborhood income, race, or sex.

As shown in Table 1, the groups did not differ statistically in age at assessment, neighborhood income, distributions of sex, race, and maternal education levels, or parent resources and stressors as measured by the Life Stressors and Social Resources Inventory—Adult Version (LISRES-A; Moos & Moos, 1994). Data collected in parent interview also failed to suggest group differences in preinjury developmental status as assessed by special education services or prior concerns about the child's development, behavior, or learning. The educational classification of special services was not requested and in view of the young age of the sample we did not inquire about attention deficits or learning disorders.

Table 2 lists injury and medical characteristics for each of the groups. The time between injury and assessment was shorter for the OI group than for the TBI groups (significant for mild and moderate TBI groups, nonsignificant trend for severe TBI group). This difference was likely related to our willingness to extend recruitment somewhat beyond our initial recruitment window (3 months after injury) in an effort to enroll as many children with TBI as possible. The groups also differed in their mean New Injury Severity Score (NISS; Osler et al., 1997), defined as the sum of the squares of the Abbreviated Injury Scale (AIS) scores for each child's three most severely injured body regions. *Post hoc* tests indicated higher NISS for the severe and moderate TBI groups compared with the mild TBI and OI groups. The

Table 1. Sample demographic characteristics

	Group			
	Severe TBI (n = 20)	Moderate TBI (n = 64)	Mild TBI (n = 15)	OI (n = 117)
Age at assessment in years, M (*SD*)	4.86 (0.88)	5.19 (1.20)	4.68 (1.00)	5.21 (1.08)
Males, *n* (%)	14 (70%)	37 (58%)	6 (40%)	67 (57%)
Non-white race, *n* (%)	7 (35%)	22 (34%)	6 (40%)	27 (23%)
Census median family income in dollars, M (*SD*)	52,767 (16,435)	57,096 (26,539)	51,556 (25,874)	63,888 (23,410)
Maternal education, *n* (%):				
<2 years high school	0 (0%)	3 (5%)	0 (0%)	2 (2%)
2 years high school	5 (25%)	7 (11%)	1 (7%)	6 (5%)
High school degree/GED	10 (50%)	24 (38%)	7 (50%)	45 (38%)
2 years college	4 (20%)	11 (17%)	3 (21%)	23 (20%)
4 years college	1 (5%)	12 (19%)	3 (21%)	29 (25%)
Graduate degree	0 (0%)	6 (10%)	0 (0%)	12 (10%)
LISRES-A (T score)				
Stressors, M (*SD*)	49.65 (6.87)	47.85 (5.97)	50.02 (5.66)	47.48 (5.93)
Resources, M (*SD*)	49.49 (7.88)	51.99 (6.41)	50.03 (5.69)	51.71 (5.37)

Note. TBI = traumatic brain injury; OI = orthopedic injury; SD = standard deviation; GED = General Education Diploma. All group differences nonsignificant. LISRES-A = Life Stressors and Social Resources Inventory—Adult Version.

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Table 2. Injury and medical characteristics

	Group			
	Severe TBI (n = 20)	Moderate TBI (n = 64)	Mild TBI (n = 15)	OI (n = 117)
Age at injury in years, mean (*SD*)	4.74 (0.88)	5.06 (1.20)	4.55 (1.03)	5.11 (1.07)
Time since injury in months, mean (*SD*)*	1.51 (0.75)	1.51 (0.76)	1.62 (0.82)	1.16 (0.50)
External cause of injury, *n* (%):*[a]				
Transportation	12 (60%)	22 (34%)	5 (33%)	10 (9%)
Bicycle crash	0 (0%)	3 (5%)	1 (7%)	7 (6%)
Fall	6 (30%)	33 (52%)	9 (60%)	84 (72%)
Other	2 (10%)	6 (10%)	0 (0%)	16 (14%)
Length of hospital stay in days, mean (*SD*)*	6.70 (7.24)	2.89 (1.86)	1.60 (0.63)	1.63 (1.08)
NISS total, mean (*SD*)*	12.47 (8.57)	15.08 (7.81)	7.40 (5.87)	7.04 (2.66)
NISS non-head- related, mean (*SD*)*	1.24 (2.11)	2.44 (5.25)	1.60 (2.53)	7.04 (2.66)
Lowest GCS score, mean (*SD*)*	3.95 (1.79)	13.45 (2.00)	13.60 (0.51)	—
Neuroimaging abnormalities, *n* (%):*[b]				
Absent	7/19 (37%)	12/63 (19%)	15/15 (100%)	117/117 (100%)
Mild	2/19 (11%)	14/63 (22%)	0/15 (0%)	0/117 (0%)
Moderate	2/19 (11%)	13/63 (21%)	0/15 (0%)	0/117 (0%)
Severe	8/19 (42%)	24/63 (38%)	0/15 (0%)	0/117 (0%)
Coma duration, *n* (%):*				
None	0 (0%)	64 (0%)	15 (100%)	117 (100%)
<24 hours	15 (75%)	0 (0%)	0 (0%)	0 (0%)
≥24 hours	5 (25%)	0 (0%)	0 (0%)	0 (0%)

Note. TBI = traumatic brain injury; OI = orthopedic injury; SD = standard deviation; NISS = New Injury Severity Score; GCS = Glasgow Coma Scale.
*Significant difference between groups at $p < .05$.
[a]Injuries due to "other" causes included those related to sports and recreation, rough-housing, and falling objects.
[b]See text for definition of severity of neuroimaging abnormality. Abnormality was absent in the mild TBI and OI groups by definition.

groups also differed in mean "non–head-injury" NISS, computed as the NISS minus the AIS for the head region. By virtue of selection criteria for children with OI, the severity of injuries to regions other than the head was higher in this group than in the TBI groups. The distribution of causes of injury for the TBI group were consistent with national trends for young children, with a substantial proportion of both the TBI and OI group sustaining injuries due to falls (Langlois et al., 2006). A significant group difference in cause of injury reflected higher rates of transportation-related injuries in the TBI groups compared with the OI group. Neuroimaging abnormalities were classified based on findings reported by radiologists (records available for all but two children). The four categories of abnormality were: *no lesion*; *mild abnormalities*, defined as a single subdural, subarachnoid, or epidural hemorrhage, or a single intraparenchymal lesion, contusion or hemorrhage; *moderate abnormalities*, defined as multifocal lesions without diffuse abnormality (i.e., no edema, mass effect, swelling, midline shift, volume loss, or diffuse axonal injury); and *severe abnormalities*, defined as any diffuse abnormality, with or without focal lesions. The categorization of neuroimaging was based on previous research relating outcomes of TBI to the presence *versus* absence and type of brain lesions (Bowen et al., 1997; Levin, 1995; Levin et al., 1992; Prasad et al., 2002). At the time of the postacute assessment, 4 children with severe TBI and 3 with moderate TBI were receiving anti-epilepsy drugs, one with mild TBI was receiving Adderall, and none of the children in the OI group was taking a prescription medication.

Assessment Procedures

Child and family assessments were conducted in tandem as part of a more comprehensive evaluation of the child and family that also included parent interviews, ratings of child behavior, and video-taped parent-child interactions. Administered by parent interview, the LISRES-A has satisfactory internal consistency and was used to assess interpersonal supports and stressors experienced by the caregiver in a variety of social domains (e.g., with family members, friends, coworkers). Child tests were administered in a fixed order, with three separate but overlapping test batteries given to children in the following 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.

Table 3 lists the child assessment procedures, the age ranges of administration, and the scores used in analysis. To obtain a measure of general cognitive ability, we administered the core subtests needed to compute the General Conceptual Ability (GCA) score of the Differential Ability Scales (DAS; Elliott, 1990). Other standardized tests were used to assess performance in the domains of language, memory, spatial reasoning, and school readiness skills. Nonstandard-

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Table 3. Neuropsychological test battery

Domain/Test	Description	Age range	*n*	Score for analysis
General ability:				
DAS GCA (Elliott, 1990)	Composite of general cognitive ability	3:0–6:11	214	Standard score
Language:				
CASL Pragmatic Judgment (Carrow-Woolfolk, 2000)	Social communication skills	3:0–6:11	211	Standard score
NEPSY Verbal Fluency (Korkman et al., 1998)	Generation of different types of animals and foods/drinks as quickly as possible	3:0–6:11	207	Scaled score
DAS Verbal Comprehension	Demonstration of understanding of oral instructions	3:0–5:11	159	T score
DAS Naming Vocabulary	Naming real objects and pictures	3:0–5:11	158	T score
Memory:				
DAS Recognition of Pictures	Identification of previously seen objects from a display that includes both target and distractor pictures	3:0–6:11	211	T score
DAS Recall of Digits	Repetition of increasingly longer strings of digits	3:0–6:11	206	T score
WJ-III Story Recall (Woodcock et al., 2001)	Immediate recall of a series of brief stories	3:0–6:11	198	Standard score
CASL Sentence Memory	Repetition of increasingly longer sentences	3:0–6:11	205	Scaled score
Spatial reasoning:				
DAS Pattern Construction	Construction of block designs from pictorial representations	3:6–6:11	189	T score
DAS Copying Designs	Paper and pencil reproduction of geometric figures	3:6–5:11	133	T score
DAS Picture Similarities	Identification of pictures and relationships between them	3:0–5:11	159	T score
Executive functioning:				
Delay of Gratification Task (Kochanska et al., 2000)	Inhibition of opening an attractive gift for 150 seconds	3:0–6:11	204	Contact (yes/no)
Delayed Alternation (Espy et al., 1999)	Retrieval of a small reward from under one of two cups, with alternating placement	3:0–6:11	208	Age-standardized *Z*-score of number of correct alternations
Shape School (Espy, 1997)	Stroop-like task involving color and shape naming	3:0–6:11	182–131	Age-standardized *Z*-scores of efficiency (number correct/completion time)
School readiness skills:				
WJ-III Letter/Word Identification	Oral decoding of visually-presented words	3:0–6:11	207	Standard score
WJ-III Spelling	Written production of orally-presented words	3:0–6:11	206	Standard score
WJ-III Applied Problems	Solving orally-presented math word problems	3:0–6:11	208	Standard score
DAS Early Number Concepts	Counting, magnitude comparison, and other elementary number problems	3:6–5:11	138	T score
Bracken SRC (Bracken, 1998)	Six-subtest composite of academic readiness skills	3:0–6:11	216	Standard score

Note. DAS = Differential Abilities Scales; GCA = General Conceptual Ability; CASL = Comprehensive Assessment of Spoken Language; NEPSY = A Developmental Neuropsychological Assessment; WJ-III = Woodcock-Johnson Tests of Achievement, 3rd Ed.; SCR = School Readiness Composite. Variations in sample size were related in large part to the applicability of some of the measures to only a subset of the 3- to 6-year-old age range. Less marked variations in sample size were also related to the inability of some children to complete select tests. Reasons for variation in sample size for the different Shape School conditions is related to the applicability of the Switch and Both conditions only to children age 4 years and older and the inability of some age-eligible children to grasp task demands.

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ized tests of executive function included the Delay of Gratification Task (Kochanska et al., 2000), Delayed Alternation (DA; Espy et al., 1999), and Shape School (Espy, 1997). Delay of Gratification requires the child to inhibit opening an attractive gift, with performance defined in terms of contact *versus* no contact with the gift. In DA, the child is asked to retrieve a reward (e.g., an M&M or a Cheerio) hidden under one of two cups placed side by side. The contingency is then reversed with the reward hidden under the other cup. The child is not allowed to see where the reward is placed, but can learn to anticipate placement because the placement side is reversed after each correct response. Performance was defined in terms of number of consecutively correct alternations. Shape School is a Stroop-like measure of self regulatory abilities in young children. In this task, the child is first taught to name cartoon "pupils" by their shapes or colors. The child is then asked to name the color of some pupils but not others. This test measures the ability to inhibit prepotent responses and the mental flexibility to switch between color and shape names according to learned rules. Conditions include Simple Naming, Inhibition, Switching, and Both (the latter referring to a condition in which both inhibition and set switching are required). An efficiency score was computed for each condition by dividing the number correct by completion time.

Data Analysis

Before analysis, raw scores on the outcome measures were converted to age-standardized scores using published norms. Because published norms were unavailable for DA and Shape School, age-expected scores on these tests were generated based on regression analysis of data from the OI group. Age-adjusted z scores were computed for each measure by dividing the differences between each observed and age-predicted score by the standard error of the estimate. Potential influences of extreme scores on results were limited by truncating, or windsorizing, standard scores to within 3 standard deviations of the mean score (Tabachnick & Fidell, 1989). Examination of the scores revealed acceptable distributions for all continuous measures.

Preliminary analysis revealed that primary caregiver education level and median census tract income were positively correlated with each other and with most neuropsychological outcomes. Socioeconomic status (SES) was thus defined as the mean of the sample z-scores for these two variables. Additional sociodemographic variables (e.g., parent marital status and occupation) were examined but were excluded after initial analyses failed to reveal associations with outcomes independent of parent education and census income.

Group comparisons on the continuous measures of outcome were made using analysis of covariance (ANCOVA). Group effects were defined by preplanned contrasts of each TBI group with the OI group. Covariates included SES, sex, and race (white/nonwhite), as justified by evidence for associations of these factors with cognitive abilities in children (McDermott, 1995). Time since injury was not considered as analysis failed to reveal associations with the performance of the TBI sample. Covariate-adjusted logistic analysis was used to examine group differences in odds of contact *versus* no contact on the Delayed Gratification Task, with age at assessment entered as an additional covariate in analysis of this measure.

To assess the dose-response relationship of TBI presence and severity with outcome, a set of secondary analyses examined the linear trend between degree of TBI (none or 0 = OI; 1 = mild TBI, 2 = moderate TBI, and 3 = severe TBI) and covariate-adjusted test scores. To further investigate the relation of injury severity to outcomes for the children with TBI, we conducted regression analyses of data from the three TBI groups combined. In these analyses, the GCS score and coma duration (none, $<$24 hr, $\geq$24 hr) were entered (separately) into a hierarchical regression following entry of SES, race, and sex.

Regression analysis was also used to examine moderating effects of SES, LISRES-A stressors and resources scores, and age at injury on the group differences. To test for moderation, each of these factors was entered separately into a regression along with the TBI-OI group contrast terms and the interaction of each contrast with that factor. Models that included the covariates were used to subsequently examine the moderating effects of LISRES-A resources and stressors and age at injury. Moderating effects of race and sex were not examined due to small cell sizes for the severe and mild TBI groups. Logistic regression was conducted to investigate moderating effects on the Delayed Gratification Task, with age at assessment again included as an additional covariate.

The Holm's modification of Bonferroni procedure (Jaccard & Guilamo-Ramos, 2002) was used to adjust for multiple comparisons within each test domain, with domain-wise alpha set at .05. Because of the more experimental nature of measures in the executive function domain and the lack of published age standards, this adjustment was not applied to the measures in that domain. However, effect sizes were computed for all group contrasts, and only significant differences of at least medium effect size (d = .5) were considered in interpreting results from the tests of executive function. Statistical power computations indicated that the study was adequate for detection of a medium effect size for the moderate TBI-OI group contrasts but under-powered for detection of an effect of this magnitude for the severe TBI-OI and mild TBI-OI group contrasts. These results suggest that only relatively large effects of severe or mild TBI were likely to reach levels of statistical significance.

RESULTS

Group Differences

As shown in Table 4, the severe TBI group had lower scores than the OI group on the GCA, all four memory tests, Pat-

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Table 4. Group comparisons on neuropsychological and school readiness measures

	Group						
	Severe TBI (n = 20)		Moderate TBI (n = 64)		Mild TBI (n = 15)		OI (n = 117)
Domain/measure	Adj. M (se)[a]	ES[b]	Adj. M (se)	ES	Adj. M (se)	ES	Adj. M(se)
General ability: GCA[c]*	89.55 (2.98)	0.68	98.58 (1.66)	0.10	97.19 (3.53)	0.19	100.14 (1.23)
Language:							
CASL Pragmatic Judgment[c]	104.44 (3.06)	0.01	99.70 (1.62)	0.34	96.73 (3.42)	0.56	104.33 (1.20)
NEPSY Verbal Fluency[e]	8.28 (0.66)	0.29	8.49 (0.37)	0.21	7.58 (0.82)	0.53	9.11 (0.27)
DAS Verbal Comprehension[d]	41.34 (2.13)	0.34	43.73 (1.32)	0.11	43.93 (2.40)	0.09	44.82 (0.94)
DAS Naming Vocabulary[d]	49.24 (2.25)	0.22	50.88 (1.40)	0.06	51.99 (2.54)	0.04	51.60 (0.99)
Memory:							
DAS Recognition of Pictures[d]*	44.11 (2.40)	0.56	49.90 (1.36)	0.04	46.57 (2.84)	0.34	50.33 (0.99)
DAS Recall of Digits[d]*†	46.22 (2.30)	0.61	48.08 (1.35)	0.43	47.32 (2.83)	0.50	52.62 (0.95)
WJ-III Story Recall[c]*	103.95 (3.36)	0.65	109.21 (1.70)	0.26	107.62 (3.48)	0.38	112.70 (1.23)
CASL Sentence Memory[e]*†	8.43 (0.62)	0.59	8.86 (0.35)	0.43	9.57 (0.72)	0.17	10.05 (0.25)
Spatial reasoning:							
DAS Pattern Construction[d]*	44.29 (2.16)	0.97	54.39 (1.26)	0.07	52.68 (2.60)	0.11	53.74 (0.87)
DAS Copying Designs[d]*	41.83 (1.99)	0.63	48.69 (1.36)	0.15	50.62 (2.47)	0.37	47.35 (0.91)
DAS Picture Similarities[d]	44.52 (2.61)	0.47	49.68 (1.61)	0.01	50.99 (2.95)	0.10	49.82 (1.15)
Executive function:							
Gift Delay, no contact, n (%)	8 (44%)	—	23 (38%)	—	7 (50%)	—	32 (29%)
DA, consecutive alternations[f]	−0.02 (0.24)	0.01	0.13 (0.13)	0.14	0.12 (0.27)	0.13	0.02 (0.10)
Shape School efficiency[f]:							
Simple Naming condition	−0.54 (0.25)	0.51	−0.05 (0.14)	0.02	−0.57 (0.28)	0.53	−0.03 (0.10)
Inhibit condition	−0.26 (0.24)	0.19	−0.19 (0.13)	0.12	−0.29 (0.28)	0.23	−0.07 (0.09)
Switch condition*	−0.63 (0.26)	0.61	−0.38 (0.14)	0.35	−0.64 (0.31)	0.62	−0.07 (0.10)
Both condition*†	−0.74 (0.26)	0.76	−0.41 (0.15)	0.40	−0.57 (0.32)	0.57	−0.04 (0.10)
School readiness skills:							
WJ-III Letter/Word Identification[c]	103.83 (3.62)	0.06	103.69 (2.01)	0.07	107.27 (4.19)	0.15	104.87 (1.46)
WJ-III Spelling[c]	95.42 (2.95)	0.29	98.30 (1.63)	0.06	100.11 (3.29)	0.07	99.14 (1.21)
WJ-III Applied Problems[c]	96.65 (2.96)	0.46	103.14 (1.64)	0.01	107.41 (3.54)	0.32	102.97 (1.19)
DAS Early Number Concepts[d],*	40.94 (2.08)	0.70	47.34 (1.48)	0.02	45.03 (2.53)	0.27	47.56 (0.96)
Bracken SRC[c]*	93.63 (3.09)	0.73	100.47 (1.71)	0.29	104.64 (3.53)	0.03	105.03 (1.27)

Note. Group sizes vary across tests depending on whether the procedures were appropriate for all or a portion of the 3- to 6-year-old age range. Abbreviations: TBI = traumatic brain injury; OI = orthopedic injury; Adj. M = covariate-adjusted mean; se = standard error; ES = effect size; DAS = Differential Abilities Scales; GCA = General Conceptual Ability; CASL = Comprehensive Assessment of Spoken Language; NEPSY = A Developmental Neuropsychological Assessment; WJ-III = Woodcock-Johnson Tests of Achievement, 3rd Ed.; SCR = School Readiness Composite; Bracken SRC = Bracken Basic Concept Scale School Readiness Composite.

[a]Means are adjusted for effects of SES, sex, and race.

[b]Effect sizes defined by Cohen's d: difference between estimated (covariate-adjusted) means/estimate of pooled within-group SD.

[c]Standard score.

[d]T score

[e]Scaled score.

[f]Age-standardized Z score.

*Significant difference, severe TBI *versus* OI.

†Significant difference, moderate TBI *versus* OI.

tern Construction, Copying Designs, Early Number Concepts, and SRC. The moderate TBI group had lower scores than the OI group on Sentence Memory, Recall of Digits, and the Shape School Both condition. Many of the effect sizes for the severe TBI-OI group contrasts were of medium magnitude (Cohen's d = .5–.8), whereas most effects for the moderate TBI-OI group contrasts were small (Cohen's d = .2–.5). Effect sizes for several of the mild TBI-OI group contrasts were in the medium range and in the hypothesized direction despite a lack of statistical significance, with nonsignificant trends (unadjusted $ps < .1$) for Verbal Fluency, Recall of Digits, and the Shape School Simple Naming and Switch conditions.

Other Factors Related to Outcome

According to results from the ANCOVAs, all three covariates accounted for unique variance in at least some outcomes. Higher SES was associated with better performance on all tests except for the Delayed Gratification Task, DA, and the Shape School Both condition. Whites scored higher than nonwhites on Verbal Comprehension, Naming Vocab-

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ulary, and the Shape School Both condition. Females outperformed males on the GCA, Pragmatic Judgment, Verbal Comprehension, Recognition of Pictures, Recall of Digits, Story Recall, Shape School Simple Naming and Inhibition conditions, and Spelling.

In regressions examining the effect of group along a continuum from OI to severe TBI, significant linear trend effects were found for GCA, Sentence Memory, Story Recall, Recall of Digits, Pattern Construction, Shape School Switch and Both conditions, Early Number Concepts, and SRC (all adjusted ps $< .05$). For each of these outcomes, scores decreased with increasing TBI severity. Regressions conducted on data from the children with TBI indicated that a lower GCS score predicted worse outcomes on GCA, Pattern Construction, Copying Designs Early Number Concepts, and SRC; and longer coma duration predicted worse outcomes on GCS, Pattern Construction, Copying Designs, and Early Number Concepts (all adjusted ps $< .05$).

Moderators of TBI Effects

Lower SES was associated with more adverse effects of severe TBI on Naming Vocabulary, $B = 9.46$ (3.39), adjusted $p < .05$; and increasing parent stressors were associated with more negative consequences of moderate TBI on Spelling, $B = -0.78$ (0.29), adjusted $p < .05$. Results failed to reveal moderating effects of parent resources or age at injury on any of the outcomes.

DISCUSSION

Effects of TBI in Young Children

Consistent with findings from past research on young children, the participants in this study with moderate to severe TBI performed more poorly than the OI group on a wide range of neuropsychological and achievement tests (Anderson & Catroppa, 2005; Anderson et al., 1997, 1999, 2006; Ewing-Cobbs et al., 1989, 1997, 2004a,b). Compared with the OI group, children with severe TBI had poorer general cognitive ability as measured by the GCA and lower scores on tests of memory, spatial reasoning, executive function, and school readiness skills. The moderate TBI group performed more poorly than the OI group on tests of memory and executive function, but not in general ability. The moderate TBI-OI group contrasts had smaller effect sizes than the severe TBI-OI group contrasts, suggesting that children with moderate TBI group had more selective and less pronounced deficits than those with severe TBI. Specifically, visual-perceptual and memory skills were most clearly affected, and there was no evidence for effects of moderate TBI on what might be regarded as established language skills. The deficits observed in this group are consistent with past evidence of selective impairments in children with TBI and with expectations based on the brain regions most susceptible to insult in TBI (Anderson et al., 1997, 2005b, 2006; Donders & Giroux, 2005; Ewing-Cobbs et al., 1997; Levin & Hanten, 2005; Yeates, 2000). The present findings do not, however, contraindicate effects of TBI on language functions not tapped by our test battery, such as discourse processing and inferencing (Chapman et al., 1998; Dennis & Barnes, 2001; Dennis et al., 2001; Ewing-Cobbs & Barnes, 2002; Morse et al., 1999).

Although none of the mild TBI-OI contrasts was significant, the lower mean scores of the mild TBI group corresponded to medium effects sizes for several measures (Verbal Fluency, Recall of Digits, and the Shape School Simple Naming and Switch conditions). Given the limited statistical power for detection of these effects, results are interpreted as offering tentative support for postacute cognitive effects of mild TBI. Previous studies have yielded inconsistent effects of mild TBI, with some studies demonstrating adverse consequences for cognition or achievement (Anderson et al., 2001; Dennis & Barnes, 2001; Gronwall et al., 1997; Jaffe et al., 1992; McKinlay et al., 2002; Ponsford et al., 1999) and others not (Anderson et al., 1999, 2005b, 2006). In a study comparing children with mild to moderate TBI with children hospitalized for other injuries, Goldstrohm and Arffa (2005) found differences similar to ours, but they did not isolate the effects mild TBI. The consequences of such injuries may vary depending on when after TBI children are assessed and the criteria used to define mild injury (Bijur & Haslum, 1995; Satz et al., 1997). We recruited children who were hospitalized for at least 1 day and had some impairment in consciousness as defined by a GCS score of 13 or 14. For this reason, our mild TBI group may have had more significant trauma than children discharged home from emergency departments or with GCS scores of 15.

Additional Evidence for Effects of Injury Severity

As further evidence for a relationship between TBI severity and outcomes, scores on many of the same tests that discriminated the severe TBI and OI groups were linearly related to the degree of TBI. Tests of the linear trend across groups—from OI to mild, moderate, and severe TBI—demonstrated that TBI severity was associated with the Switch and Both conditions of Shape School, offering further evidence for negative consequences of TBI on executive function in young children. Analyses of the effects of GCS score and coma duration on outcomes within the TBI sample provided additional support for injury severity as a predictor of the cognitive and achievement outcomes of TBI in young children (Bowen et al., 1997; Foreman et al., 2007; Levin, 1995; Prasad et al., 2002).

Noninjury Factors Related to Outcomes of TBI

Consistent with another study of young children (Anderson et al., 2006), better performance on nearly all measures was associated with higher SES, and these associations did not

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vary by group. The finding of higher scores in girls than boys for the majority of the measures was unexpected given the general absence of sex differences in on our previous research on a school-age TBI cohort (Yeates et al., 2002). Gender differences in rates of developmental disorders or early language skills may help to explain this finding (Thompson et al., 2003). Alternatively, a male predilection for preinjury developmental problems may have been exacerbated in our sample if these disorders contributed more to risk of injury in boys than in girls.

The findings also documented moderating influences of noninjury factors on some of the group differences. In keeping with results of our previous study of older children with TBI (Taylor et al., 2002; Yeates et al., 1997), weaknesses in Naming Vocabulary in the severe TBI group were evident only at lower levels of SES, and weaknesses in Spelling in the moderate TBI group were found only at higher levels of parent stressors. Potential explanations for these findings are that these skills were not as well established in children from less advantaged backgrounds and thus more easily disrupted by TBI, or that fewer resources were available after injury to support postinjury recovery (Taylor et al., 2002). The fact that both measures entail knowledge-based skills is consistent with these interpretations.

Results did not reveal moderating effects of age at injury on outcomes of TBI. The lack of evidence for worse outcomes in younger children contrasts with results from previous studies that have examined TBI across wider age spans (Anderson et al., 2005a; Barnes et al., 1999; Dennis et al., 1995; Ewing-Cobbs & Barnes, 2002; Levin et al., 1995; Verger et al., 2000) and suggests that outcomes may be less strongly related to age at injury during early childhood (Ewing-Cobbs et al., 1997). Alternatively, the impact of younger age at injury may become more pronounced with increasing time since injury (Anderson et al., 2000a,b; Ewing-Cobbs et al., 2004a).

Limitations

Despite measuring a wide range of skills and assessing outcomes of TBI relative to those of an orthopedic injury group, the study was limited in several respects. First, only clinical neuroimaging, in most instances CT scans, were available to determine the presence and nature of the brain insults in the TBI sample. Imaging methods with greater sensitivity to white matter damage and focal lesions would likely have provided information useful in enhancing prediction of variations in outcomes of TBI (Scheibel & Levin, 1997; Wilde et al., 2006). Second, the mild and severe TBI groups were relatively small despite recruitment from multiple hospitals, and larger group sizes would have increased statistical power for detection of effects. Third, the lowest GCS score was used to define injury severity. This measure likely overestimated TBI severity in some of the children who were sedated and intubated, though past studies showed that efforts to remove this confound yielded little improvement in predictive validity (Foreman et al., 2007; Zafonte et al., 1996). Finally, we failed to assess some important cognitive outcomes, such as speed of processing (Catroppa & Anderson, 2005), and we examined individual test scores rather than multiple-indicator latent constructs. The latter approach would have allowed us to more clearly distinguish the skills most and least affected by TBI and reduced the probability of Type I error.

CONCLUSIONS AND IMPLICATIONS

Study findings suggest several conclusions with respect to the postacute effects of TBI on young children, and provide a basis for formulating more specific hypotheses about how TBI affects young children:

1. Severe TBI sustained during early childhood can result in generalized cognitive impairment and deficits in school readiness skills. Furthermore, memory, spatial reasoning, and executive function may be more affected than some language skills.
2. Children with moderate TBI have more specific and less pronounced impairments than those with severe TBI.
3. Indices of TBI severity, including the GCS score and coma duration, are related to cognitive and school readiness skills.
4. Although age at injury is not related to most postacute effects of TBI on cognitive and school readiness skills, at least within the 3- to 6-year-old age range, further follow-up is needed to determine whether age-at-injury effects emerge with increasing time since injury.
5. Measures of environmental disadvantage predict lower scores on most tests in children with and without TBI but also amplify the effects of TBI on some tests.

The primary clinical implication of these findings is that young children with TBI are at risk for postacute deficits in cognition and school readiness skills and that measures used in this study, or similar ones, are sensitive to these deficits. Although generalized cognitive deficits may be present in more severely injured children, even those with less severe TBI may be at risk for weaknesses in memory and executive function. As early academic readiness skills appear to be compromised, children who have sustained a recent TBI may be vulnerable to learning difficulties as they begin formal academic instruction. Monitoring of cognitive and readiness skills is thus recommended relatively soon after hospital discharge. Based on research showing slow recovery and emerging deficits in this age group (Anderson et al., 2000a,b, 2004, 2006), ongoing follow-up is additionally advised. The pattern of deficits observed in the present TBI sample also provides clues as to potentially useful educational interventions. In view of weaknesses in nonverbal abilities and executive function, children who are experiencing new-onset learning problems after TBI may benefit from structured teaching methods. Similarly, memory deficits suggest that it may be useful to provide these children

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with memory cues, repeated presentations of materials, and opportunities to practice newly taught skills.

Another clinical implication of the findings is the need to consider both injury-related and environmental factors in assessing risks for adverse outcomes of TBI. Lower SES and higher TBI severity contributed independently to poorer performance on many of the tests, but lower SES and parent stressors also potentiated the negative effects of TBI on some outcomes. These results underscore the complexity of influences on the recovery process (Taylor, 2004).

Further research is required to better understand the consequences of the full range of TBI severity on young children's brain development, and how brain pathology maps onto neurobehavioral outcomes. Larger scale studies of outcome will also be required, especially in examining the consequences of mild TBI. Further research on this subset of children might explore factors contributing to the decision to hospitalize these children and track acute changes in cognitive functioning. Assuming that mild TBI results in residual deficits in only a minority of children with mild TBI (Bigler, 2008; Kirkwood et al., in press), the identification of ways to distinguish affected from unaffected individuals may be more helpful than studies of group differences. The development of age-appropriate tests that clarify the effects of TBI and study of the factors that contribute to skill development following injury will be essential in improving our capacity to identify and treat the negative consequences of TBI in young children. We are currently following the present cohort to determine the nature of changes in cognitive and achievement outcomes across time post injury, evaluate behavioral sequelae, and investigate the effects of family factors on outcomes.

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