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Late intellectual and academic outcomes following traumatic brain injury sustained during early childhood

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Abstract

Object—Although long-term neurological outcomes after traumatic brain injury (TBI) sustained early in life are generally unfavorable, the effect of TBI on the development of academic competencies is unknown. The present study characterizes intelligence quotient (IQ) and academic outcomes an average of 5.7 years after injury in children who sustained moderate to severe TBI prior to 6 years of age.

Methods—Twenty-three children who suffered inflicted or noninflicted TBI between the ages of 4 and 71 months were enrolled in a prospective, longitudinal cohort study. Their mean age at injury was 21 months; their mean age at assessment was 89 months. The authors used general linear modeling approaches to compare IQ and standardized academic achievement test scores from the TBI group and a community comparison group (21 children).

Children who sustained early TBI scored significantly lower than children in the comparison group on intelligence tests and in the reading, mathematical, and language domains of achievement tests. Forty-eight percent of the TBI group had IQs below the 10th percentile. During the approximately 5-year follow-up period, longitudinal IQ testing revealed continuing deficits and no recovery of function. Both IQ and academic achievement test scores were significantly related to the number of intracranial lesions and the lowest postresuscitation Glasgow Coma Scale score but not to age at the time of injury. Nearly 50 % of the TBI group failed a school grade and/or required placement in self-contained special education classrooms; the odds of unfavorable academic performance were 18 times higher for the TBI group than the comparison group.

Conclusions—Traumatic brain injury sustained early in life has significant and persistent consequences for the development of intellectual and academic functions and deleterious effects on academic performance.

Keywords

traumatic brain injury; shaken baby syndrome; academic performance; cognitive outcome; pediatric neurosurgery

Pediatric TBI represents a major public health problem. Authors of recent studies of TBI in the US from 1995 to 2001 have determined that infants and children 4 years of age or younger have higher rates of TBI-related mortality, hospitalization, and emergency department visits

than children 5 to 9 or 10 to 14 years of age.⁴⁰ The external cause of TBI in young children varies with age.⁸ Inflicted neurotrauma is the most common cause in infants younger than 24 months of age; approximately 90% of cases of significant TBI in this age group are caused by physical abuse.^{13,19,39} The most frequent external causes of injury in preschoolers include falls and motor vehicle accidents.³⁹ Despite the high incidence of serious TBI in infants and young children, very little is known about long-term developmental outcomes and academic course in these cases. Retrospective follow-up studies have identified persistent neurological and cognitive sequelae in children who sustained inflicted TBI as infants, with particular deficits in motor, visual, speech/language, general cognitive, and adaptive behavior areas.^{9, 14,20} Using prospective designs to assess outcome over a period ranging from discharge to 2 years after TBI, investigators have documented poorer functional and cognitive outcomes in young children who suffered inflicted injury compared with those who suffered noninflicted injury.^{27,35,36} Cognitive outcomes in children who sustained early TBI are predicted by GCS score,⁵¹ duration of impaired consciousness, the number of intracranial lesions, and whether the TBI was inflicted.⁴³

Even with the extensive array of changes in neural processes that occur in normal development during infancy and early childhood, accumulating evidence indicates that there is limited recovery after moderate to severe TBI sustained early in life.^{5,28,43} Recovery from brain injury is often described in terms of plasticity and recovery of function. Plasticity refers to normal, continual changes of the brain in response to modifications in sensory inputs, internal factors such as awareness, and motor outputs.⁴² In this context, plasticity is not a process that occurs after a brain injury, but rather a reflection of the effect that changes to the brain can have on normal developmental processes. Following the initial resolution of transient changes after TBI, subsequent processes include relearning, which involves initial unmasking and strengthening of existing neural pathways as well as the creation of new ones.⁴²

Recovery of function refers to processes of neural and behavioral adaptation that occur following brain insult.³⁷ In developmental studies, recovery has been viewed in relation to the type of lesion, the age and/or developmental stage at the time of injury and at assessment, and the outcome domain evaluated. Although recovery is generally favorable following focal brain lesions sustained during childhood,⁴⁶ recovery appears to be less favorable following conditions producing diffuse brain insult, such as TBI.^{3,24} The apparent impact of a brain injury on a given skill may depend on the developmental stage at which the lesion is sustained and at which the skill is evaluated.^{31,38} Some skills may show a stable deficit over time, others may show a transient lag and partial catch-up growth, while others may show increasing deficit; when the damaged substrate required for mature expression of specific skills cannot support those skills, children are likely to fall further behind age-level expectations.

Time since injury is a critically important variable. The impact of time since TBI is best characterized using models that depict longitudinal posttraumatic changes in the level, rate of change, and eventual performance level of a given ability or skill and permit assessment of possible moderating effects of socioenvironmental factors. Evaluation of different outcome domains may also yield different findings in relation to early brain injury. For example, early injuries to the orbitofrontal regions in both animals and humans are associated with relatively good recovery of cognitive abilities and poor development of adaptive and social behaviors that becomes increasingly evident with maturation.^{2,22,38}

Little is known about how damage to neural mechanisms sustained early in life interacts with environmental conditions to influence the unfolding of normal developmental processes. The restricted behavioral repertoire of infants limits their “relearning” or “recovery” of skills. Rather, infants must acquire new skills using a damaged or altered substrate. Because infants have only limited behavioral repertoire prior to injury and the substrate they must use to acquire

new skills is damaged by the injury, the impact of TBI on skill acquisition is likely to be greater when TBI is sustained in infancy than when it is sustained later in childhood or in adolescence.

Neural processes involved in recovery from brain injury both influence and are influenced by diverse environmental and social factors, including socioeconomic status and psychosocial stressors. Additional studies are needed to examine 1) how brain injury affects the reorganization of existing skills and the acquisition of new skills, and 2) ways that socioenvironmental factors interact with the injury to enhance or disrupt skill development.²³

Recovery curves appear to differ in relation to age at TBI. For example, age-adjusted IQ and academic achievement test scores in older children and adults who sustain moderate to severe TBI typically show initial deficit, significant increase during the first 6 months, and then a plateau representing a stable deficit relative to performance of individuals with less severe injuries.^{3,23,33} However, recovery curves depicting IQ across the 1st year postinjury in infants and children of preschool age who sustained moderate to severe TBI show lower initial scores and less recovery over time. In young children, curves depicting the posttraumatic recovery of IQ across time are either flat, indicating no improvement in scores after the initial injury,²³ or show a decline across time,³ indicating failure to develop new skills at age-appropriate rates. The less complete recovery in young children may reflect damage to mechanisms involved in learning and memory, which interferes with the acquisition of new information and skills.⁴⁷ Therefore, individuals who suffer TBI at a young age are at high risk for lifelong reduction in cognitive abilities. In particular, brain injury sustained early in life may interfere with the acquisition of later-developing academic skills due to the combined impact of lower IQ and impaired learning efficiency.

Despite the high incidence of and significant morbidity from TBI sustained during infancy and the preschool years, there are no prospective longitudinal studies examining cognitive outcomes beyond 2.5 years postinjury and no studies of the impact of early TBI on the development of academic skills and classroom performance. The purpose of this paper is to characterize IQ and academic outcomes an average of more than 5 years postinjury in children who sustained moderate to severe TBI prior to 6 years of age and were followed in a prospective, longitudinal study. Relative to a community comparison group, children with TBI were hypothesized to have: 1) lower IQ, with no evidence of recovery of function, as indicated by stable intelligence test scores from 2 months to at least 3 years postinjury; 2) lower scores on all measures of academic skills; and 3) reduced class-room performance and greater utilization of special education services. In addition, IQ and academic achievement test scores were expected to be moderated by the family's access to resources and the presence of psychosocial stressors.

Clinical Material and Methods

Study Population and Follow Up

Children who presented with TBI from 1994 to 1998 at either of two children's hospitals in Houston, Texas were enrolled in a prospective, longitudinal study of outcome after early inflicted or noninflicted TBI. Written informed consent to participate was obtained from the children's guardians. The protocol was approved by the institutional review boards at the University of Texas Health Science Center at Houston, Baylor College of Medicine, and the affiliated children's hospitals.

Longitudinal intelligence scores were available from assessments completed at 2, 12, and 24 months after TBI for the injured children and at similar intervals after study enrollment for comparison children. Long-term IQ, academic achievement, and classroom placement variables were assessed an average of 5.7 years (range 3.8–8.3 years) after TBI for the injured

children and after study enrollment for the comparison children. Outcomes were examined prospectively at least 3 years postinjury in 23 children who sustained moderate or severe TBI between the ages of 4 and 71 months. The performance of children with TBI was compared with that of children in a community comparison group (21 children from comparable sociodemographic backgrounds). Inclusion criteria were: 1) moderate to severe TBI; 2) sufficient recovery of cognitive skills to permit standardized assessment; 3) no known premorbid neurological or metabolic disorder; 4) no history of prior TBI; and 5) birth after at least 30 weeks of gestation. The community comparison group was composed of children born at the hospitals in which the children with TBI were hospitalized, children who attended federally subsidized well-baby clinics, and children whose parents responded to community notices. Children in the comparison group met criteria 3, 4, and 5 for entry into the study. The two groups did not differ significantly in age at assessment, sex, ethnicity, grade level, or access to financial and social resources (Table 1).

Cause and Severity of TBI

The external cause of injury was inflicted TBI in 10 cases; in these cases, the primary central nervous system insult was extraaxial hemorrhage and/or intracerebral contusion or focal edema rather than global hypoxic–ischemic injury. Noninflicted injuries included motor vehicle accidents (four cases), vehicle/pedestrian collisions (four cases), and falls (five cases).

As depicted in Table 2, severity of TBI was determined by three factors: GCS score,⁵¹ the duration of impaired consciousness, and acute computed tomography or brain magnetic resonance imaging findings. The GCS was originally developed for adults. We modified two scales—the verbal and the motor scales—to accommodate the behavioral capabilities of infants and children from birth through 35 months of age. “Following commands” on the original GCS was replaced with spontaneous movement for infants 6 months of age and younger and goal-directed movements for children between the ages of 7 and 35 months. “Confused” and “oriented” on the original scale were replaced with “cries” and “cries to indicate need.” The modified GCS motor scale was used to determine duration of impaired consciousness, which was defined as the number of days a child was unable to follow a one-stage command or engage in goal-directed movements. Moderate TBI was defined as injuries resulting in lowest postresuscitation GCS scores of 9 to 12. Children with GCS scores of 9 to 15 were considered to have moderate TBI if imaging demonstrated extraaxial bleeding, intraparenchymal hemorrhage, or edema; if neurological deficits were present; or if impaired consciousness persisted for less than 24 hours. Children were considered to have severe TBI if their lowest postresuscitation GCS score was between 3 and 8 or their level of consciousness was impaired (GCS motor score < 6) for more than 24 hours. We have used this categorization system successfully in prior studies of infants and young children with TBI.²⁷

Impaired consciousness persisted for an average of 3.1 days (range 0–20 days). Glasgow Outcome Scale³⁴ scores indicated that fewer than half of the children were rated as having a good recovery at discharge. At the late follow-up examination, the GOS score had changed one category in seven of 23 children. Scores were as likely to improve (three cases) as to decline (four cases). Neuroimaging studies indicated that extraaxial hemorrhages were the most frequently occurring acute finding. Parenchymal hemorrhage and focal regions of edema/infarction were noted less frequently. Chronic conditions included subdural hygroma and ex-vacuo ventriculomegaly; findings of these conditions on scans obtained in the acute phase were interpreted as evidence of abnormalities that existed before the TBI. The distribution of GOS scores and data regarding neurological status and acute imaging findings was similar in children with inflicted and noninflicted TBI (all $p > 0.15$). The children with inflicted TBI were injured at significantly younger ages than those with noninflicted TBI ($df = 21$, $t = 3.25$, $p = 0.0038$).

Examination of Attrition

To ascertain comparability of the present sample to the original sample of children with TBI who were enrolled in our study between 1994 and 1999, we examined demographic and neurological variables for the 23 children with TBI who returned for long-term follow up and the 37 children who were lost to follow up. The groups did not differ on age at injury ($df = 58$, $t = 0.0$, $p = 0.9809$), sex (60 children, $df = 1$, $\chi^2 = 0.9040$, $p = 0.3417$), ethnicity (60 children, $df = 3$, $\chi^2 = 3.5892$, $p = 0.7517$), or socioeconomic status (60 children, $df = 2$, $\chi^2 = 4.0915$, $p = 0.1293$). Neurological variables assessing the severity of TBI were also comparable in children who returned and in the original sample; GCS scores ($df = 58$, $t = 0.30$, $p = 0.7619$), duration of impaired consciousness ($df = 58$, $t = 0.54$, $p = 0.5948$), the presence of hemiparesis (58 children, $df = 1$, $\chi^2 = 0.9741$, $p = 0.3237$), and the proportion of children with GOS scores³⁴ indicating a good recovery versus moderate or severe disability (60 children, $df = 1$, $\chi^2 = 0.1001$, $p = 0.7517$) were comparable.

Outcome Measures

The SB4⁵⁴ was administered. This scale yields a standard age score reflecting the level of general cognitive function with a mean of 100 and an SD of 16; the scores were restandardized to a mean of 100 and an SD of 15 to make them comparable to other general cognitive scores. The test is composed of scales reflecting verbal reasoning, visual reasoning, and short-term memory. The Vocabulary, Pattern Analysis, Memory for Sentences, and Bead Memory subtests were examined (mean 50, SD = 8).

Selected subtests from the WJ-III⁵⁶ were administered to assess basic skill development, skill application, and fluency in reading, mathematics, and language areas. For reading, the Word Attack, Letter-Word Identification, Reading Fluency, and Passage Comprehension subtests were administered. Mathematics subtests included Calculation, Applied Problems, and Math Fluency. Language subtests included Spelling, Writing Fluency, and Oral Comprehension. Fluency subtests were only given to children who were at least 7 years of age.

The GORT-4⁵⁵ was administered to children who were at least 7 years of age at follow up to examine their reading speed, decoding accuracy, and comprehension of connected text (mean 10, SD = 3). Age-based scores were used for all academic tests.

Academic performance was categorized as favorable or unfavorable. Outcome was classified as unfavorable if a child either failed a grade, required support services in a self-contained special education program (partial- or full-day), or both.

Family Environment

At the same time as the IQ and academic achievement tests were administered to the children, data pertaining to the family environment were collected. These data were obtained from a biological parent in all cases of noninflicted TBI and in five of 10 cases of inflicted TBI. In the remaining five cases of inflicted TBI, the data were obtained from biological relatives who had adopted the children.

The adequacy of access to financial, physical, and social resources was measured using the Family Resource Scale.²¹ Possible scores on this scale range from 0 to 150, with higher scores indicating more favorable access.

The level of parental stress was assessed using the Total Stress scale from the Parenting Stress Inventory (mean 0.0, SD = 1.0).¹ This scale provides an index of the overall level of parenting stress and incorporates measures of parental distress, stress emanating from the parent's

interaction with the child, and stress related to the child's behavioral characteristics. Lower scores indicate lower levels of parent stress.

Design and Analyses

The design includes one between-subjects factor, membership in the TBI or comparison groups. Group differences on the outcome variables were examined using t-tests for symmetrically distributed variables and the chi-square test for categorical variables. Pearson product-moment correlation coefficients were used to examine relationships of both age at injury and severity of TBI to outcome scores. Multiple regression models were used to examine the degree to which general cognitive and academic achievement test scores were predicted by family environment and neurologic variables. The models were constructed to test hypotheses in a hierarchical fashion rather than for variable selection or model building. Separate analyses were performed for each academic outcome as expressed by achievement test results. To address whether the effect of each predictor was moderated by group, the model for each outcome was constructed to contain all the variables, including the interaction terms. In each model, the interaction terms were tested first to examine possible moderating effects and were then trimmed if nonsignificant. One-tailed significance tests were used to test hypotheses regarding the direction of group differences on outcome measures. Logistic regression models were used to examine predictors of academic placement.

Growth-curve analysis allows modeling of the processes of change that underlie development and recovery of function.³⁰ Individual growth-curve analyses were used to model the level of IQ, change in IQ over time, and the rate of change in IQ change from the initial assessment 2 months postinjury to subsequent evaluations at 1 year, 2 years, and 3–7 years postinjury. The growth curve analyses examined longitudinal cognitive scores from the Bayley Scales of Infant Development¹² for evaluations performed prior to age 3; all other evaluations used the SB4⁵⁴ composite score. The IQ standard scores were analyzed using linear mixed models by allowing the scores to be expressed as functions of the time since the injury. A three-parameter polynomial function of time was used, with intercept, slope, and curvature as the parameters. The time since injury was centered at 48 months to minimize multicollinearity between the linear and quadratic terms and because 4 years postinjury represents a reasonable point at which to compare the TBI group and the control group. Thus, the intercept represented the level of outcome at 4 years postinjury, the slope represented the rate of growth in the outcome at 4 years postinjury, and the curvature (quadratic term) represented the acceleration or deceleration of the curve, that is, the rate at which the slope was changing.

Results

Group Differences on General Cognitive and Academic Achievement Test Scores

General Cognitive Scores—The descriptive and inferential statistics for the IQ and academic achievement test scores for the TBI and comparison groups are provided in Table 3. Preliminary analyses revealed no significant differences in cognitive or academic achievement test scores between children with inflicted TBI and those with noninflicted TBI. Therefore, in subsequent analyses we examined the performance of all children with TBI in relation to the comparison group.

As indicated in Table 3, the SB4 composite score was significantly reduced in the TBI group relative to the comparison group. Forty-eight percent of the children in the TBI group and 19% of those in the comparison group had composite scores below the 10th percentile (chi square = 4.05, df = 1, 44 children, $p = 0.0443$). On the component subtests, the children in the TBI group scored significantly lower than those in the comparison group on the Pattern Analysis, Memory for Sentences, and Vocabulary subtests. These subtests identified reductions in

visual-spatial reasoning, phonological short-term memory, and oral definition of word meanings, respectively. The performance of the two groups was comparable on the Bead Memory subtest, which evaluates storage of information in visual short-term memory.

To compare changes in IQ over time between the children with TBI and the comparison group, a general linear mixed modeling procedure was used. Specifically, the model was set up as a random-coefficients, or growth-curve, model. Intelligence scores were modeled as a function of time since the baseline evaluation. Because IQ was not assessed in all children at the same time or even the same number of times, a mixed modeling procedure was used. Mixed models rely on maximum likelihood rather than least squares and do not require listwise deletion of data. The time variable was centered at 48 months the approximate mean age across all assessments. Random intercept and slope were modeled in addition to a fixed quadratic (curvature) term to account for potential nonlinearity. Group membership was added as a between-subjects variable. There are several methods available to estimate df for mixed models. We estimated the model using the containment method and the Satterthwaite and Kenwood-Rogers procedures as well as the traditional between- and within-subjects df from a general linear model. Although the df varied somewhat across models, the results were consistent. We report df from the Satterthwaite procedure.

The model was based on 145 observations from 44 children; most children contributed IQ scores from three or four different testing periods to the analysis. The results indicated that the intercepts (levels at 48 months) differed significantly between the groups ($df = 53, t = 4.51, p < 0.0001$), with almost a 14-point difference in IQ (TBI group 85.3, comparison group 99.1). However, the slope (rate of change) and quadratic (curvature) terms were not significantly different from zero or from each other, indicating that the rate of change in each group was similar and did not differ with respect to the norm group. The actual and expected mean IQ values are shown by group across time in Fig. 1.

Academic Achievement Test Scores—As indicated in Table 3, children with TBI scored significantly lower than children in the comparison group on tests of reading, mathematics, and language. Scores on the WJ-III reading subtests examining phonological word decoding, word identification, and reading comprehension for sentence-level text were significantly reduced in the TBI group. Reading fluency, which could only be evaluated in older children, did not differ between the two groups. The GORT-4 subtests examine reading performance for connected text. Scores on these subtests were significantly lower in the TBI group than in the comparison group for decoding accuracy, reading speed, and comprehension of written text. The TBI group scored lower than the comparison group in written calculation, solving word problems, and the speed of retrieval of math facts from long-term memory. Performance on oral and written language subtests indicated that the TBI group had significantly lower auditory comprehension of word and sentence meanings, less accurate written spelling, and reduced speed of production of written text (Table 4).

Academic Performance

Children were enrolled in academic programs ranging from kindergarten to the sixth grade. Forty-eight percent of the TBI group and 38% of the comparison group were enrolled in kindergarten or first grade at the time of assessment. Children with TBI were significantly more likely than the children in the comparison group to experience an unfavorable academic outcome, defined as failing a grade or requiring education in a self-contained special education classroom for at least two major academic subjects ($\chi^2 = 10.26, df = 1, 44 \text{ children}, p = 0.0014$). Forty-eight percent of the children with TBI and 5% of the children in the comparison group had an unfavorable academic outcome. Of the 11 children with TBI who had an unfavorable outcome, four failed a grade, four were in partial- or full-day self-contained

classes, and three had failed a grade and required self-contained placement. An additional four children received content-mastery services or instructional modifications within the regular classroom setting. Thirty-nine percent of the children with TBI had required extensive rehabilitation services during their preschool years and continued to require speech/language, occupational, and/or physical therapies in elementary school.

Neurological and Environmental Predictors of General Cognitive and Academic Outcomes

For the total sample, multiple regression analyses were performed to analyze whether IQ, reading, and math outcomes were predicted by 1) the presence or absence of TBI, 2) family environment variables reflecting concurrent measures of family access to financial, social, and personal resources, and 3) the degree of parenting stress. Tests of moderating effects revealed that the group \times family resources and group \times parent stress interaction terms were not significant, so these terms were trimmed from each model. The level of parenting stress also did not contribute to the prediction of outcomes and this variable was therefore also trimmed. Variables remaining in the model were found to be significant at a probability level of 0.05 using a one-tailed test of directional hypotheses. (Refer to Table 4 for statistics for regression analyses.)

The SB4 composite score was predicted by the presence or absence of TBI and the level of family resources. The model accounted for 27.2% of the variance in cognitive scores. Word decoding scores also were predicted by group membership and family resources; the model R^2 value was 0.394. Mathematical reasoning was predicted only by the presence or absence of TBI; the model accounted for 23.9% of the variability in math scores.

Logistic regression analysis was used to examine predictors of performance in school. Poor academic performance was predicted solely by group membership. Family environment variables did not contribute to prediction of academic performance. For children with TBI, the odds of failing a grade and/or requiring placement in a self-contained special education program were 18 times greater than for the children in the comparison group (44 children, $df = 1$, chi square = 11.68, $p = 0.0006$; point estimate = 0.055; confidence interval 0.006–0.477).

Relationships of Age at TBI and Severity of TBI with Outcome Variables

Relationships of age at the time of injury and severity of TBI with outcome variables in the 23 children with TBI were examined initially using Pearson product-moment correlation coefficients. Age at the time of TBI was not significantly correlated with any of the SB4 intelligence scores. For academic achievement test scores, age at TBI was negatively correlated only with scores on the WJ–III Letter–Word Identification ($r = -0.451$, $p = 0.0306$) and Reading Fluency subtests ($r = -0.569$, $p = 0.0268$); older age at TBI was associated with less adequate performance. Neither math nor language scores showed significant relationship with age at injury.

Outcome scores were more consistently related to the lowest postresuscitation GCS score than to the duration of impaired consciousness. The GCS scores were positively correlated with scores on the SB4 Vocabulary subtest ($r = 0.452$, $p = 0.0304$) and the WJ–III Word Attack ($r = 0.482$, $p = 0.0316$), Reading Fluency ($r = 0.730$, $p = 0.0020$), Applied Problems ($r = 0.448$, $p = 0.0318$), Spelling ($r = 0.682$, $p = 0.0018$), and Oral Comprehension ($r = 0.693$, $p = 0.0007$) subtests. In contrast, the duration of impaired consciousness was negatively correlated with performance on the WJ–III Math Fluency ($r = -0.713$, $p = 0.0019$), Reading Fluency ($r = -0.650$, $p = 0.0088$), and Oral Comprehension ($r = -0.460$, $p = 0.0412$) subtests. Longer duration of impaired consciousness was associated with poorer performance.

Multiple regression analyses were used to assess potential predictors of neurological function in children with TBI. Factors examined included the lowest postresuscitation GCS score, external cause of TBI, and the number of intracranial lesions. Prediction of scores was not enhanced by inclusion of the external cause of TBI, which was trimmed from the models. Regression analyses revealed that the GCS score and the number of lesions shared substantial variance. The GCS score contributed to prediction of performance on the Letter–Word Identification subtest of the WJ–III, but not to prediction of other outcomes. With both variables in the equation, the number of lesions significantly predicted general cognitive performance (the SB4 composite score) and the performance on the Applied Problems subtest of the WJ–III math battery (Table 5). The models accounted for 37.8% of the variability in the general cognitive scores, 17.3% of variability in the reading scores, and 34.5% of the variability in the math scores.

Discussion

Moderate-to-severe TBI sustained prior to the age of 6 years has adverse and persistent consequences for intellectual and academic development. When IQ was assessed an average of 5.7 years after moderate-to-severe TBI, injured children scored significantly lower than healthy children from similar sociodemographic backgrounds. Low scores on subtests evaluating vocabulary, verbal short-term memory, and visual–spatial reasoning indicated areas of particular vulnerability. As predicted, examination of the longitudinal course of recovery of IQ, based on testing performed between 2 months and an average of 5.7 years after TBI revealed neither acceleration nor deceleration in the rate of change in IQ over the first 3 to 7 years after injury. The lack of change in IQ over the protracted recovery period indicates a persistent deficit with no evidence of catch-up growth. Even though 43% of the children with TBI received long-term rehabilitation therapies extending into the preschool and school years, the performance gap between their scores and those of the children in the comparison group persisted. These findings are consistent with previous studies showing limited recovery of diverse cognitive abilities after TBI sustained early in life.^{5,10,15,16,24,53}

Academic achievement test scores were reduced in the TBI group relative to the comparison group. Academic skills were reduced in most areas evaluated, including word decoding, reading fluency and comprehension, mathematical calculation, solving mathematical word problems, and speed of retrieval of mathematical facts. Language scores were reduced on indices of spelling, writing fluency, and oral comprehension. Across content areas, the children in the TBI group had difficulty with basic academic skills, such as word decoding, spelling single words, and performing mathematical calculations. They also showed difficulty on academic reasoning tasks requiring reading and language comprehension as well as mathematical problem solving. Fluency was reduced in all academic areas, indicating slowed processing speed for decoding and producing written text as well as for retrieval of mathematical facts.

Relatively good intellectual and academic outcomes are often seen after early nonprogressive focal brain injury.^{6,7,11} In young children who sustain diffuse or multifocal brain injury from TBI or from other causes, such as cranial irradiation, infection, or endocrine disturbance, however, cognitive skills are more vulnerable to disruption.^{4,44,45,48} Despite the dynamic progressive and regressive neural processes regulating axonal and dendritic development and connectivity during infancy and the preschool years,³² there appear to be significant limits on neural and cognitive plasticity after early TBI. The mechanisms involved in recovery and deficits after early brain injury may be clarified through future studies in which longitudinal neuropsychological follow-up data are integrated with data from enhanced neuroimaging incorporating diffusion tensor and functional imaging methodologies.^{26,52}

In our study, early TBI had an adverse effect on academic performance in the classroom. Forty-eight percent of the children with TBI failed a grade or required special education support services. These findings probably underestimate the total occurrence of academic failure in our group relative to that in groups of older children with TBI, because half of the children in our TBI group were enrolled in kindergarten or first grade at the time of assessment and had limited opportunity to repeat grades. The odds of significant academic performance problems were 18 times greater for children with TBI than for children in the comparison group. The significant effect of early TBI on academic failure and the need for special education services is similar to the effects noted in children who sustain TBI during their elementary school years or adolescence. In older children, achievement test scores suggest generally good recovery of basic academic achievement skills in conjunction with poor functional academic recovery, as demonstrated by failing grades and the need for support services.^{18,25,29,50} Several factors in a child's pre- and postinjury environment, including social and economic disadvantages and family climate,^{49,57} may facilitate or retard recovery. In the present study, neurological variables such as the number of intracranial lesions, and to a lesser degree, the lowest postresuscitation GCS score, were significantly related to development of general cognitive and mathematical skills. The association between indices of injury severity and outcome is quite robust as these indices predicted outcomes across an average span of 5.7 years. As in previous studies,^{9,24} in the present study, age at injury was not strongly related to outcomes in children who sustained TBI as infants or during the preschool years, most likely due to the restricted age range. Other studies examining the influence of age at injury within the whole pediatric age range did identify poorer recovery of intelligence scores in infants and preschoolers relative to older children and adolescents.²³ In our study family environment variables were not strong predictors of IQ and academic performance. The degree of stress experienced by parents did not predict outcomes. In contrast, family access to financial and social resources was related to general cognitive and reading scores but did not significantly affect math scores or academic performance.

Outcome studies are influenced by differences in sampling and inclusion criteria. In general, the distribution of intelligence or developmental quotients in the population of young children with moderate to severe TBI is bimodal, with peaks at about 80 to 90 (the 10th–25th percentiles) in children who recover to testable levels and about 50 (< 1st percentile) in children who develop multiple posttraumatic disabilities and are able to be assessed with functional outcome measures due to severe sensory, motor, and cognitive limitations precluding traditional academic and neuropsychological assessment. The focus of this study was on specific neuropsychological outcomes; therefore, only children who recovered to a testable level were enrolled and followed up. Excluding untestable children yielded a more favorable estimate of outcomes than if the entire spectrum of severe cases had been assessed. However, for the IQ and academic achievement tests administered in this study, scores can only be calculated if the child is able to pass at least one item; zero-base scores are not available for children unable to perform the tests.

Limitations of the present study include the relatively small sample size and resultant reduction in statistical power as well as issues regarding sampling. Although the study was sensitive to differences between the TBI and comparison groups, because of the small sample size it had limited power to detect possible differences between children with inflicted and noninflicted TBI. Sampling differences have a major effect on measured outcomes. The children with inflicted TBI who participated in this phase of the long-term follow-up study had been placed with a nonoffending parent or family member rather than being removed from the extended family following the protective agency's investigation of the abusive injury. Even though selective attrition was not noted, it is possible that the children who continued to participate had more intact families and better outcomes than those who were lost to follow up.

Strengths of the study include the prospective longitudinal design, inclusion of a community comparison group, detailed information on acute injury variables, long-term follow up based on direct examination of each child's abilities, and information on actual school performance. Retrospective studies have been important in highlighting the unfavorable outcomes in young children with TBI. However, retrospective studies may not capture the full range of outcomes. Prospective designs may capture a greater range of positive outcomes compared with designs that use retrospective identification of patients. For example, authors of prospective studies^{27,36} have identified a higher rate of favorable outcomes than have those who identified cases using retrospective methods.²⁰ In addition, this study examined long-term influences of both neural and environmental variables on cognitive and academic outcomes and identified striking needs for continuing special education and rehabilitation services.

Conclusions

The societal costs of TBI are high, not only during the initial hospitalization but also during long-term stages of recovery due to persistent neurobehavioral deficits that often necessitate years of rehabilitation and educational interventions. Children who sustain TBI early in life suffer significant and persistent consequences in the development of intellectual and academic functions as well as deleterious effects on academic performance. In the present sample, long-term cognitive and academic outcomes were unfavorable in children who sustained early TBI. Forty-eight percent of the children with TBI had intelligence test scores below the 10th percentile and experienced academic failure or placement into self-contained special education classrooms. Furthermore, repeated measurement of IQ during the period from 2 months to an average of 5.7 years postinjury showed no change over time, indicating no measurable recovery of function during the lengthy follow-up period. Academic achievement scores were significantly lower in the TBI group than in the comparison group in nearly all areas evaluated, including reading, mathematics, oral language, and written language. Cognitive and academic performance gaps between the TBI and comparison groups may be presumed to represent a lasting deficit in the children with TBI, because there is no evidence of improvement over time or lessening of the performance gap. Nearly half of the children with TBI continued to require rehabilitation therapies to support their academic performance.

Age at the time of injury was not related to developmental outcomes across the infant and preschool age ranges. Acute measures of the severity of TBI, including the GCS score and the number of intracranial and extraaxial lesions, were significantly related to cognitive and academic outcomes.

The continuing cognitive and academic deficits noted after early TBI have a cumulative, negative impact on academic performance in the classroom. Although nearly half of the children with TBI received intervention services through state-mandated early childhood and preschool programs for children with disabilities, others did not qualify for services because they were performing above the deficient range when screened.

Given the lack of recovery of cognitive functions, high rates of academic failure, and substantial need for special education services in elementary school, greater emphasis should be placed on prevention initiatives as well as on providing additional cognitive and motor rehabilitation services during preschool years for children with a broader range of cognitive disabilities. To reduce the high rate of posttraumatic morbidity, increased attention should be paid to the development of acute-care treatment protocols that minimize secondary brain injury and enhance neuronal repair as well as to prevention efforts, which have demonstrated significant reduction in the occurrence of abusive injuries through parent education programs¹⁷ and of motor vehicle injuries through proper use of infant and child restraints.⁴¹

Abbreviations used in this paper

df, degrees of freedom; GCS, Glasgow Coma Scale; GORT-4, Gray Oral Reading Tests, 4th edition; GOS, Glasgow Outcome Scale; IQ, intelligence quotient; SB4, Stanford-Binet Intelligence Scales, fourth edition; SD, standard deviation; TBI, traumatic brain injury; WJ-III, Woodcock-Johnson III.

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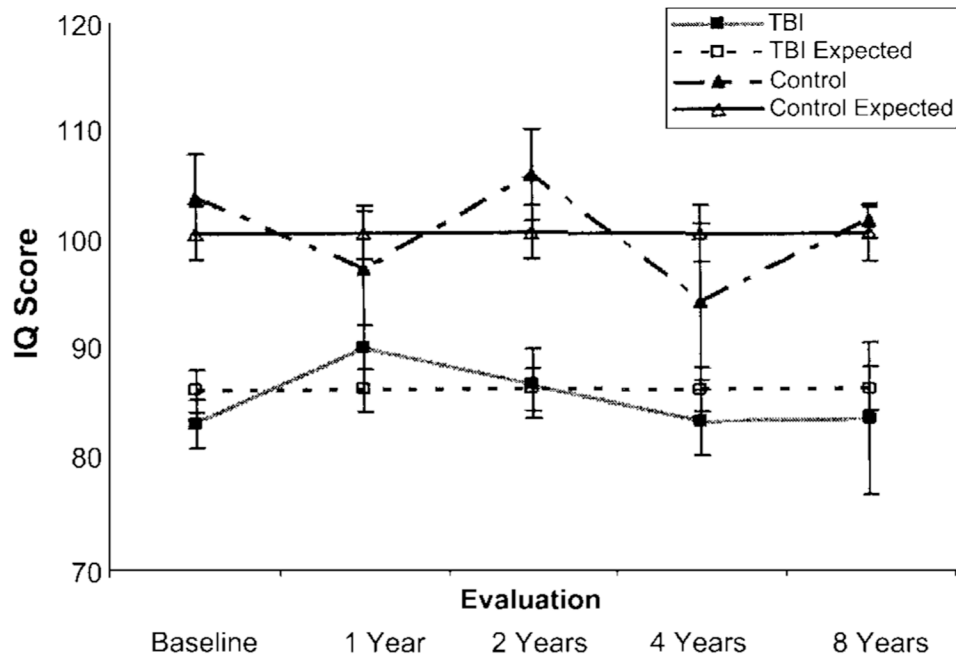


FIG. 1. Graph depicting growth-curve analysis of longitudinal IQ scores from 2 months to an average of 5.7 years after TBI indicates a persistent deficit relative to the comparison group. Nonsignificant slope and curvature terms indicate that there was no recovery of IQ scores across the follow-up period for the TBI group. Mean and standard error values are provided for actual and expected scores.

TABLE 1
Demographic information for the TBI and comparison groups

Variable	TBI Group (23 children)	Comparison Group (21 children)	Total Tested (44 children)	Statistic (df)	p Value
sex (no. of children)					
female	11	11	44	$\chi^2 = 0.09$ (1)	0.7628
male	12	10			
ethnicity (no. of children)					
Caucasian	9	7	44	$\chi^2 = 1.36$ (3)	0.7141
African-American	8	9			
Hispanic	3	4			
other/multiethnic	3	1			
age at testing in mos*	89.6 ± 26.2	101.0 ± 29.0	42	t = 1.38 (42)	0.1763
Family Resource Scale score*	118.4 ± 20.6	127.7 ± 14.6	42	t = 1.70 (42)	0.0959
Parenting Stress Scale score*	-0.16 ± 1.2	-0.66 ± 0.9	41	t = 1.56 (42)	0.1264
school grade (no. of children)					
Kindergarten-1	11	8	44	$\chi^2 = 0.42$ (1)	0.5151
2-6	12	13			

* Scores are given as means ± SDs.

TABLE 2

Neurological information for the TBI group

Variable	Value
age at injury in mos (mean \pm SD)	21.2 \pm 21.9
mos from injury to test (mean \pm SD)	68.3 \pm 15.4
lowest postresuscitation GCS score (no. of children)	
3–8	11
9–12	6
13–15	6
days of impaired consciousness (mean \pm SD)	3.1 \pm 5.0
GOS score (no. of children)	
discharge	
good recovery	10
moderate/severe disability	13
follow up	
good recovery	9
moderate/severe disability	14
acute imaging findings (no. of lesions/no. of children)*	
intracerebral lesions	
hemorrhage/contusion	8/6
edema	10/7
shear injury	20/6
extraaxial lesions	
subdural hematoma	36/13
epidural hematoma	1/1
subarachnoid hemorrhage	8/6
chronic findings	
subdural hygroma	4/3
ex vacuo ventriculomegaly	3/3
total lesions/no. of children	90/21*

* Abnormalities were noted on acute neuroimaging studies obtained in 21 of 23 children with TBI.

TABLE 3

Descriptive and inferential statistics for intelligence and academic achievement test scores for the TBI and comparison groups*

Measure	TBI Group (23 children)	Comparison Group (21 children)	t Statistic (df)	p Value
SB4				
composite score	83.0 ± 14.0	95.7 ± 10.5	3.39 (42)	0.0008
component subtests				
Vocabulary	44.5 ± 7.5	48.9 ± 7.1	1.96 (42)	0.0284
Pattern Analysis	44.2 ± 7.2	49.5 ± 5.6	2.82 (42)	0.0037
Memory for Sentences	44.2 ± 7.3	50.0 ± 8.0	2.60 (42)	0.0065
Bead Memory	44.1 ± 9.1	46.1 ± 8.7	0.77 (42)	0.2235
WJ-III reading subtests				
Letter-Word Identification	92.8 ± 12.4	108.9 ± 13.1	4.21 (42)	0.0001
Word Attack	93.9 ± 10.4	108.4 ± 11.7	4.12 (39)	0.0001
Reading Fluency	91.0 ± 13.3	99.9 ± 17.6	1.28 (28)	0.1051
Passage Comprehension	93.0 ± 12.9	100.5 ± 13.2	1.82 (41)	0.0340
GORT-4				
Fluency	6.5 ± 3.6	10.1 ± 4.3	2.39 (32)	0.0119
Accuracy	7.5 ± 3.2	10.3 ± 3.6	2.13 (32)	0.0208
Comprehension	8.1 ± 3.9	10.9 ± 2.6	2.19 (32)	0.0185
WJ-III mathematics subtests				
Calculation	94.1 ± 13.2	104.2 ± 12.2	2.56 (34)	0.0076
Applied Problems	94.2 ± 12.2	107.2 ± 11.5	3.49 (42)	0.0005
Math Fluency	85.5 ± 13.5	102.3 ± 18.8	2.56 (30)	0.0080
WJ-III oral and written language subtests				
Oral Comprehension	94.2 ± 14.6	107.1 ± 11.6	2.96 (38)	0.0027
Spelling	91.6 ± 13.7	109.1 ± 14.1	3.83 (37)	0.0003
Writing Fluency	85.6 ± 17.4	104.7 ± 17.4	2.90 (29)	0.0036

* Scores are presented as means ± SD.

TABLE 4
 Predictors of cognitive and academic achievement test scores for the total sample*

Variable	TBI or Comparison Group		Family Resource Scale		Model R ²
	t Statistic (df)	p Value	t Statistic (df)	p Value	
SB4 composite score	2.90 (41)	0.0030	1.79 (41)	0.0403	0.272
Letter-Word Identification score [†]	3.65 (41)	0.0004	2.60 (41)	0.0065	0.394
Applied Problems score [‡]	3.38 (41)	0.0008	NS	NS	0.239

* NS = not significant.

[†]Woodcock-Johnson III reading subtest.

[‡]Woodcock-Johnson III math subtest.

TABLE 5
Neurological predictors of cognitive and academic scores for the TBI group

Variable	Predictors						Model R ²
	GCS Score		No. of Lesions		p Value	Model R ²	
	t Statistic (df)	p Value	t Statistic (df)	p Value			
SB4 composite score	NS	NS	-2.42 (19)	0.0138	0.378	0.378	
Letter-Word Identification score	1.86 (19)	0.0391	NS	NS	0.173	0.173	
Applied Problems score	NS	NS	-2.02 (19)	0.0288	0.345	0.345	