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IQ decline following early unilateral brain injury: A longitudinal study

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Abstract

We examine whether children with early unilateral brain injury show an IQ decline over the course of development. Fifteen brain injured children were administered an IQ test once before age 7 and again several years later. Post-7 IQ scores were significantly lower than pre-7 IQ scores. In addition, pre-7 IQ scores were lower for children with larger lesions, but children with smaller lesions and higher pre-7 IQ scores showed a greater IQ decline over time. These findings suggest that the cognitive outcomes of children with early lesions, particularly those with relatively small lesions, change over the course of development.

Keywords: Early focal lesion; Congenital; Perinatal; Functional plasticity; Hemiparesis; Unilateral; Laterality; Seizures; Longitudinal; IQ

1. Introduction

As early as 1938, Kennard's studies of motor functioning in primates revealed delayed effects of early lesions of the motor and premotor cortex (Kennard, 1938). Monkeys with infantile lesions initially displayed only mild motor problems but by 3 years of age their symptoms increased in severity. A number of subsequent animal studies are consistent with these general findings, reporting instances where deficits change over time following early frontal lesions (e.g., Goldman, 1971, 1974; Goldman-Rakic, Isseroff, Schwartz, & Bugbee, 1983; Kolb & Whishaw, 1985). Despite this evidence of changing patterns of deficit after early lesions from the animal literature, the majority of studies examining cognitive functioning in children with early focal brain injuries have not been longitudinal in design.

The paucity of longitudinal data on children with early brain injury represents a gap in our knowledge about functional plasticity, as the magnitude and nature of deficits may change over time, particularly when a lesion is superimposed on a developing brain (e.g., Banich, Levine, Kim, & Huttenlocher, 1990; Bishop, 1997; Karmiloff-Smith, 1997, 1998; Thomas & Karmiloff-Smith, 2002). The common practice of assessing the cognitive strengths and weaknesses of children with early brain injury on the basis of data collected at a single time may be a source of significant discrepancies in the literature. For example, some studies report that children with early unilateral brain injury have IQ scores that are significantly different from controls or at least one standard deviation below the population mean (e.g., Riva & Cazzaniga, 1986 (left-lesioned participants only), Banich et al., 1990; Levine, Huttenlocher, Banich, & Duda, 1987; Perlstein & Hood, 1955; St. James-Roberts, 1981; Woods, 1980). Other studies report that IQ level in

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children with early unilateral brain injury is comparable to controls or within one standard deviation of the population mean (e.g., Aram & Ekelman, 1986; Bates, Vicari, & Trauner, 1999; Nass, Peterson, & Koch, 1989; Riva & Cazzaniga, 1986 (right-lesioned participants only) and Vargha-Khadem, O'Gorman, & Watters, 1985; Woods & Carey, 1979). Of note, Vargha-Khadem et al. (1985) eliminated four participants with IQ scores below 75, Nass et al. (1989) eliminated one low and one high outlier, and the mean FIQ of participants in the Woods and Carey (1979) study was 86.5, only slightly above the one standard deviation demarcation. In addition, Bates et al. (1999) report a particularly high average IQ of 93.3 in their sample, but they assessed children at 3–9 years of age, earlier than most other studies. The different IQ levels reported for children with early unilateral lesions may reflect variations in the lesion characteristics of the children included in each study, but they may also reflect a relationship between age of children at test and IQ. That is, it is possible that IQ deficits in children with early unilateral lesions vary as a function of age.

In fact, several cross-sectional studies suggest that IQ level decreases over time in children with early (mainly pre- and perinatal) focal lesions. One such study, carried out in our laboratory, revealed a negative correlation between age at assessment and Full Scale IQ. That is, the older the child at the time of assessment the lower was IQ. This fall-off in IQ appeared to begin at about 6–8 years of age. In contrast to children with early lesions, children with lesions acquired later in childhood did not show this IQ decline (Banich et al., 1990). Consistent with these findings, Bates et al. (1999) report a marginally significant negative correlation between IQ and age at test in children with early lesions ($p < .06$).

Although these cross-sectional findings suggest that IQ may decline over time in children with early focal lesions, the evidence provided is not conclusive because these studies cannot rule out the possibility that different groups are being sampled at different cross-sectional time points. That is, it could be the case that the apparent fall-off in IQ reflects the inclusion of more severely affected children at later than earlier time points. These children might be more likely to continue seeing a pediatric neurologist, the source of referrals for many studies. A longitudinal study is needed to determine whether the fall-off in IQ over the course of development actually occurs or whether it is an artifact of a cross-sectional sampling bias. With a longitudinal design, it is possible to examine whether individual children with early focal lesions have higher IQ levels when they are assessed at younger ages than when they are assessed at older ages.

A few longitudinal studies have examined changes in IQ over time in children with unilateral brain injury but a number of factors make the results of these studies difficult to interpret. One such study assessed children with congenital lesions when they were between ages 3 and 7 years and found no change in IQ scores (Muter, Taylor, & Vargha-Khadem, 1997). Because the assessments in this study were carried out at relatively early ages, these results do not preclude the possibility that changes in IQ become apparent at later ages. In fact, Banich et al.'s cross-sectional study indicates that the decline in IQ-level does not become apparent until 6–8 years of age.

A second longitudinal study, carried out by Aram and Eisele (1994), reported a non-significant decrease in IQ over time for the right but not the left lesion group. Close examination of their sample reveals that some of their participants had acquired rather than congenital lesions. Thus, Aram and Eisele's findings may not be discrepant with Banich et al.'s (1990) study, which specifically showed an age-related decline in IQ among children with congenital lesions.

In the present study, we examine the stability of IQ over time in children with perinatal unilateral brain injury. Importantly, the study is longitudinal in design, and thus avoids the possible confound that exists in cross-sectional studies. Using Banich et al's findings as a starting point, we test each child twice, once before age 7 and once after age 7, to examine whether IQ declines over time. We also re-examine Aram and Eisele's (1994) data to determine whether the subset of children in their sample with lesions that were incurred early in life show a significant decline in IQ over developmental time.

In addition to examining change in IQ over time, we use our longitudinal data to examine the relation of seizure history, lesion laterality, and lesion size to IQ, and ask whether these relations differ at our two testing time points. Prior studies indicate that seizures are a negative predictor of IQ in children with early lesions (Bates et al., 1999; Muter et al., 1997; Vargha-Khadem, Isaacs, van der Werf, Robb, & Wilson, 1992). With respect to lesion laterality, prior studies have not provided consistent evidence that Verbal IQ deficits are more marked after early left hemisphere lesions and Performance IQ deficits are more marked after early right hemisphere lesions (e.g., Bates et al., 1999; Muter et al., 1997; Vargha-Khadem, Isaacs, & Muter, 1994). Previous research is also somewhat inconsistent about the relation of lesion size and IQ. In particular, a review of animal studies indicates a curvilinear relationship such that both small and large lesions were associated with better outcomes than medium size lesions (Irle, 1990). In studies of children with early lesions, some investigators report results consistent with these animal findings (Bates et al., 1997) whereas others report that cognitive outcomes are inversely related to lesion size (Levine et al., 1987). These studies have not examined whether the relation between lesion size and IQ changes over time.

Increasing our knowledge about the effects of early focal lesions on cognitive development and how these effects may change with age has important theoretical implications concerning the limits and extent of

functional plasticity after early focal brain injury. In addition, this knowledge may have important practical implications for planning interventions for children with early lesions, even for those who appear to be functioning well at early ages.

2. Methods

2.1. Participants

Fifteen children and young adults (6 males and 9 females) with congenital hemiparesis and unilateral lesions participated in the study. Participants were patients at the Pediatric Neurology Clinic at The University of Chicago Children's Hospital, and were diagnosed with infantile hemiparesis by Dr. Peter Huttenlocher, pediatric neurologist. Inclusion in the study was based on neurologic findings of unilateral dysfunction and on evidence of unilateral lesions from an imaging study (MRI or CT scan). Diagnostic imaging studies, either MRI scans or CT scans, revealed that 10 of the participants had left hemisphere lesions and 4 had right hemisphere lesions. The lesion laterality of the participant with an apparently normal MRI was diagnosed on the basis of hemiparesis.

IQ tests were administered to participants at two time points. At the first testing, participants ranged in age from 4 years 3 months to 6 years 10 months (average 5 years, 10 months) and at the second testing they ranged in age from 7 years 6 months to 21 years 7 months (average 14 years 0 months). The time elapsed between the two testing points ranged from 1.5 years to almost 15 years, with an average of 8 years 2 months and standard deviation of 4.0 years.

As is typical in children with hemiparesis, some of our participants had a history of seizures whereas others were seizure free (Ingram, 1964; Levine et al., 1987; Perlstein & Hood, 1955). Children who had a history of recurrent seizures as documented in the clinical pediatric neurology records were placed in the seizure group. Children who had no history of seizures or only one infantile seizure with no recurrence were placed in the no-seizure group. Based on these criteria, there were 7 children in the seizure group and 8 children in the non-seizure group. In the seizure group, 4 children had left hemisphere lesions and 3 had right hemisphere lesions. In the non-seizure group, 7 children had left hemisphere lesions and only 1 had a right hemisphere lesion.

2.2. Procedure

IQ testing was carried out at the University of Chicago at both time points with the exception of one participant whose first testing was administered elsewhere. Depending on the age of participants and the time of testing, either the WPPSI, the WPPSI-R, the WISC-R, or the WAIS-R was administered (Wechsler, 1967, 1974, 1981, 1989). MRI data from 12 out of 15 participants were acquired close to the second IQ assessment time point. MRI image analysis was carried out on 0.5 mm contiguous coronal sections through the brain. The volume of each hemisphere and the location of lesions were ascertained from these sections. It was not possible to directly measure lesion size in all participants because many of them had generalized atrophy rather than circumscribed lesions. Thus, we obtained a measure of extent of injury by tracing the area of intact brain regions in each T1-weighted coronal section and by adding these areas (Banich et al., 1990). This yielded volumetric measures of the intact and lesioned hemispheres.

3. Results

Table 1 summarizes the following data for each participant: age at each test time, sex, lesion laterality,

Table 1
Participant information and IQ scores

ID	Age (T1)	Age (T2)	Sex	Lesion laterality	Seizure status	VIQ 1	PIQ 1	FIQ 1	VIQ 2	PIQ 2	FIQ 2	Test 1	Test 2
1	5.92	7.5	F	L	No	87	72	78	96	90	92	WPPSI-R	WISC-R
2	5.58	13.67	M	L	No	87	86	86	84	91	86	WPPSI	WISC-R
3	6.5	15.08	M	L	No	98	81	89	81	65	71	WPPSI	WAIS-R
4	6.25	12.58	M	L	No	86	102	92	79	81	78	WISC-R	WISC-R
5	4.25	14.00	F	L	No	100	101	101	97	87	91	WPPSI	WISC-R
6	6.75	21.58	M	L	No	94	77	84	88	75	80	WISC-R	WAIS-R
7	5.42	17.33	F	L	No	111	119	116	97	87	92	WPPSI	WAIS-R
8	4.25	17.50	F	L	Yes	107	111	110	93	99	94	WPPSI	WAIS-R
9	4.58	8.33	F	L	Yes	101	110	106	87	101	92	WPPSI	WISC-R
10	6.42	13.67	M	L	Yes	87	111	98	77	101	87	WISC-R	WISC-R
11	6.92	20.50	F	L	Yes	80	85	81	72	75	73	WISC-R	WAIS-R
12	6.83	11.83	M	R	No	106	88	97	105	81	92	WISC-R	WISC-R
13	5.92	12.58	F	R	Yes	78	77	76	78	85	80	WISC-R	WISC-R
14	6.25	14.67	F	R	Yes	118	126	124	102	105	103	WISC-R	WISC-R
15	6.17	9.17	F	R	Yes	87	74	80	50	95	71	WISC-R	WISC-R

Table 2
Participant lesion information

ID	Lesion laterality	Lesion type	Etiology (if known)	Lobes involved	Non-lesioned hem (cm^3)	Lesioned hem (cm^3)
1	L	Porencephaly	Pre-/perinatal infarct	F, P	532.3	303.8
2	L	Porencephaly	Pre-/perinatal infarct	F, T, P, O, BG, IC	—	—
3	L	Diffuse atrophy	Pre-/perinatal infarct	F, T, P	542.2	333.3
4	L	Porencephaly	Pre-/perinatal infarct	F, T, P	606.6	380.7
5	L	Porencephaly	Perinatal Asphyxia pre/perinatal infarct	P	456.6	374.86
6	L	Porencephaly	Pre-/perinatal infarct	F, T, P, O, BG	596.1	229.3
7	L	Diffuse atrophy	Prenatal infarct	P, T, BG	577.2	520.1
8	L	Porencephaly	Pre-/perinatal infarct	T, BG	489.1	398.9
9	L	Normal MRI	Unknown	—	—	—
10	L	Porencephaly	Pre-/perinatal infarct	F, T, P, BG, IC	680.3	249.1
11	L	Porencephaly	Pre-/perinatal infarct	F, BG	456.4	430.2
12	R	Porencephaly	Perinatal infarct	F, P	621.2	389.6
13	R	Porencephaly	Pre-/perinatal infarct	F	—	—
14	R	Porencephaly	Intracerebral neonatal thrombo-cytopenia and cerebral hemorrhage	F, P, BG	468.3	449.8
15	R	Diffuse atrophy	Postnatal infarct at 7 months	F, T, P, O	481.4	283.4

seizure status, Verbal, Performance, and Full Scale IQ at each test time, and the type of test administered. Table 2 summarizes lesion type, etiology, regions involved, and volume of the normal and abnormal hemispheres. Two-tailed t tests examined whether the Verbal IQ, Performance IQ, Full Scale IQ, and amount of IQ change over time differed significantly for individuals who received different IQ measures (e.g., WPPSI & WISC-R, WISC-R & WAIS-R) vs. those who had the same IQ scale (WISC-R) at both time points. Because there were no systematic differences ($p > .30$ in all cases) the IQ measures were considered as equivalent, regardless of the test type or edition used.

An analysis of variance examining both seizure status and lesion laterality simultaneously was precluded by the fact that there was only one subject who had a right hemisphere lesion and no seizures. Thus, we examined the impact of seizures and lesion laterality on IQ scores in two separate analyses, an approach that allows main effects of these variables to be detected.

Our first analysis of variance examined the effects of seizure status on Verbal and Performance IQ at the two testing points. IQ Subscale (Verbal IQ, Performance IQ) and Time of Test (pre-7, post-7) were within-subjects variables and Seizure Status was a between-subjects variable. There was a significant main effect of Time of Test $F(1,13) = 10.98$, $p = .0056$, such that IQ scores were higher at the pre-7 than the post-7 test point. (Mpre-7 Verbal IQ $= 95.13$, $SD = 11.87$; Mpost-7 Verbal IQ $= 85.73$, $SD = 13.96$; Mpre-7 Performance IQ $= 94.67$, $SD = 17.73$; Mpost-7 Performance IQ $= 87.87$, $SD = 11.29$; see Fig. 1). There were no main effects or interactions involving Seizure Status or IQ Subscale, suggesting that the decrease was not affected by seizure status and that it did not differ for Performance and Verbal subscales. Moreover, Verbal and Performance IQ did not significantly differ at either time point, even as assessed by uncorrected paired-sample t tests, (pre-7 $t = .139$, $p = .89$; post-7 $t = .482$, $p = .64$, $P < .05$).

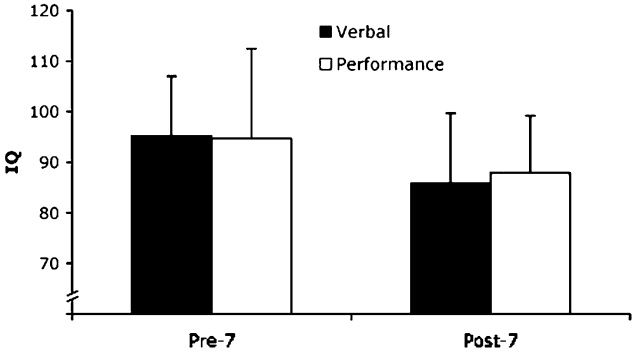

Fig. 1. Pre- and post-7 verbal and performance IQs.

A second analysis of variance was carried out to examine the effects of lesion laterality on Verbal and Performance IQ at the two testing points. IQ Subscale and Time of Test were within-subject variables and Lesion Laterality was a between-subjects variable. Again, the only significant finding was a main effect of Time of Test $F(1,13) = 8.05$, $p = .014$, such that IQ scores were higher at the pre-7 than the post-7 testing. There were no main effects or interactions involving Lesion Laterality or IQ Subscale, indicating that the pattern of Verbal and Performance Scores did not differ by laterality of lesion. As in the first analysis, there were no differences between Verbal and Performance IQ scores at either time point.

Next, we considered the IQ change over time for individual participants. Twelve of the fifteen participants showed decreases in IQ, two showed increases, and one showed no change Fig. 2. The significance of this downward trend was also assessed using the

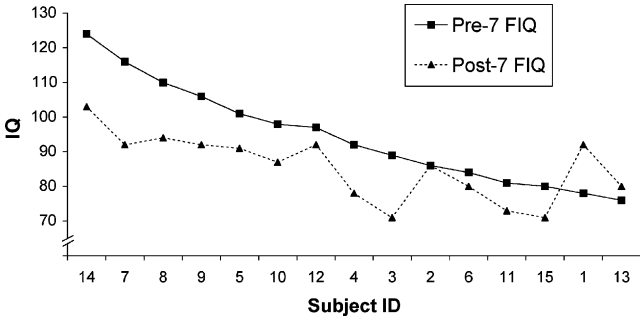

Fig. 2. Full-scale IQ scores at pre- and post-7 test times for individual participants ranked by pre-7 IQ scores.

non-parametric Wilcoxen matched pairs signed-rank test. Consistent with our ANOVA results, this test showed a significant decrease in IQ over time $T = 10.5$, $p < .01$, two-tailed, with the ranks for decreases in IQ totaling 94.5 and the ranks for increases totaling 10.5. This test shows that the ANOVA results are not attributable to a few extreme cases.

We also examined changes in particular subtest scores over time. Subtests that appeared across the different IQ tests administered (WPPSI, WPPSI-R, WISC-R, and WAIS-R) were selected for analysis. These included several Verbal IQ subtests (Information, Similarities, Arithmetic, Vocabulary, and Comprehension) and several Performance IQ subtests (Picture Completion, Block Design). The one participant who was tested elsewhere at the first testing point was not included in these analyses as there was no record of individual subtest scores. For the fourteen remaining participants, two-tailed t tests were performed on pre-7 and post-7 scores. There were declines in subtest scaled scores over time for all of the subtests examined, most of which were statistically significant: (Arithmetic ($t = 2.74$, $p < .01$), Vocabulary ($t = 5.43$, $p < .001$), Comprehension ($t = 4.33$, $p < .001$), Picture Completion ($t = 2.63$, $p < .03$), Block Design ($t = 3.58$, $p < .01$); Similarities ($t = 1.59$, $p = .1358$); Information ($t = .99$, $p = .34$)).

Because all participants in the study had some degree of hemiparesis we examined the role of motor impairment in IQ subtest performance. Thus, our next analysis examined performance on two Performance IQ subtests, one requiring motor dexterity in manipulating pieces (Block Design) and another with minimal motor demands (Picture Completion). A repeated-measures ANOVA with Task and Time of Test as within-subjects factors revealed a main effect of Time of Test ($F(1,13) = 7.06$; $p = .0197$), corroborating the earlier reported decline in scores over time for other IQ and subtest scores. However, there was no significant main effect of Task ($F(1,13) = 1.37$; $p = .138$) or Task × Time of Test interaction ($F(1,13) = .35$; $p = .57$), suggesting that motor impairment was not a significant factor in subjects' subtest performance level or score decline.

Correlational analyses addressed several additional questions. First, we examined whether pre- and post-7 IQ scores were correlated in this population as they are in the population as a whole. As summarized in Table 3, we found a significant positive relationship between Full Scale IQ scores at different ages, such that a higher pre-7 IQ was associated with a higher post-7 IQ (Pearson's $r = .67$, $p = .0063$). Verbal IQ was highly positively correlated between the two time points (Pearson's $r = .78$, $p = .0005$), and Performance IQ was marginally positively correlated between the two time points (Pearson's $r = .49$, $p = .06$). Second, we examined the relation between pre-7 IQ scores to the magnitude of the decline in IQ. Pre-7 IQ was positively associated with decline in IQ scores, indicating that subjects with a higher IQ tended to lose more points than subjects with lower IQ scores (Pearson's $r = .81$, $p = .0002$). The relationship between post-7 IQ and amount of decline was not significant (Pearson's $r = .25$, $p = .38$). The correlation between pre-7 IQ and magnitude of the decline does not reflect regression towards the mean which would yield worse performance for above-average children and better performance for below-average children over time, with no net main effect of time. Instead, we found a decrease for the majority of the children with perinatal lesions, but a steeper decline for those whose early IQ scores were higher. We also examined whether the time elapsed between pre-7 and post-7 IQ tests was associated

Table 3
Intercorrelations between IQ and time of test

	1	2	3	4	5	6
1. Pre-7 IQ	—	.67 (.006)[a]	.81 (.0002)[b]	.28 (.31)	.59 (.045)[c]	.04 (.90)
2. Post-7 IQ		—	.25 (.376)	−.023 (.93)	.49 (.11)	−.003 (.99)
3. Decline (Pre-Post)			—	.29 (.29)	.56 (.06)	−.041 (.90)
4. Time between Tests				—	.24 (.46)	−.25 (.43)
5. Lesioned hemisphere (cc)					—	−.34 (.28)
6. Non-lesioned hemisphere (cc)						—

Note. These values represent r values. p statistics are given in parentheses.
[a] $p < .01$.
[b] $p < .001$.
[c] $p < .05$.

with the amount of decline, and this was not a significant relation (Pearson's $r = .29$, $p = .90$).

Additional analyses examined the relation between volume of the lesioned hemisphere (our index of lesion size) and IQ scores at each testing point. We used the volume of the lesioned hemisphere as our index of lesion size rather than number of lobes involved as it provides a more direct measure of lesion size and was fairly normally distributed. In addition, the volume of the lesioned hemisphere and the number of lobes involved were significantly correlated (Pearson's $r = -.64$, $p < .05$), suggesting that these measures are both tapping the extent of anatomical damage. Pre-7 IQ scores were positively correlated with the volume of the lesioned hemisphere (Pearson's $r = .59$, $p = .045$; Fig. 3) and post-7 IQ scores showed this same relation but the correlation did not reach significance (Pearson's $r = .49$, $p = .11$). There was no relation between pre- or post-7 IQ and the volume of the non-lesioned hemisphere (Pearson's $r = .042$, $p = .90$ and $r = -.003$, $p < .99$, respectively). Interestingly, the amount of IQ decline was marginally significantly correlated with volume of the lesioned hemisphere, i.e., more decline for children with larger lesioned hemispheres, i.e., smaller lesions (Pearson's $r = .56$, $p = .06$).

Our correlational analyses revealed significant pairwise relationships between pre-7 IQ and post-7 IQ, between level of IQ scores and lesioned hemisphere volume, and between amount of IQ decline and lesioned hemisphere volume. A stepwise regression was carried out to determine which of these variables accounts for a significant portion of the variance in IQ decline. The separate contributions of pre-7 IQ, post-7 IQ, and lesioned hemisphere volume to the variance of the IQ decline were examined. It was found that pre-7 IQ accounted for 50% of the variance in decline scores, and that lesioned hemisphere volume was not a significant regressor ($p > .15$). Rather, the volume of the lesioned hemisphere is significantly related to pre-7 IQ, which in turn is related to the decline in IQ. Thus, larger lesions (as indexed by size of the lesioned hemisphere) are associated with a lower pre-7 IQ scores, which are in turn associated with a milder decline in IQ over time. Although a regression analysis with a small sample size is not ideal, additional tests are consistent in showing a relation between lesion size and IQ decline. The IQ scores of children with smaller and larger lesions, compared on the basis of a median split of abnormal hemisphere volume, are farther apart at the earlier testing point than the later testing point average difference = 15 points for pre-7 IQ (two-tailed $t(10) = 1.96$, $p = .077$) and 6.67 for post-7 IQ (two-tailed $t(10) = 1.11$, $p = .29$). This is because the children with higher pre-7 IQ scores show a steeper decline in IQ than those with lower pre-7 IQ scores.

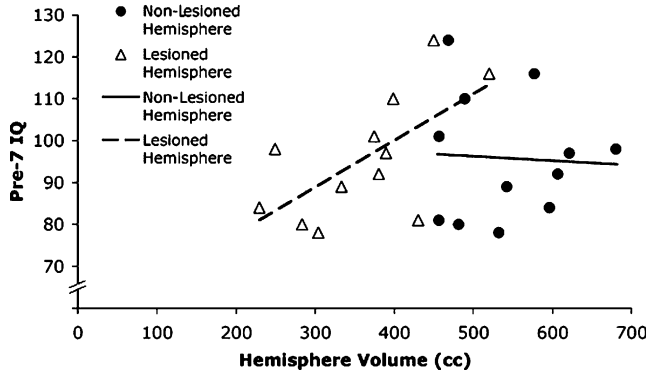

Fig. 3. Correlation of pre-7 IQ and volume of the lesioned and non-lesioned hemispheres.

3.1. A re-examination of Aram and Eisele's data (1994)

Aram and Eisele's sample consisted of children with congenital and acquired lesions, all of whom had no history of seizures. As in the current study, Aram and Eisele tested children's IQ twice. To compare Aram and Eisele's findings to our findings, we re-examined the portion of their sample most similar to ours. We selected those children who had lesions prior to the age of 2. Of these eleven children, eight children had IQ tests both before the age of 7 and after the age of 7. Of the remaining three children, one had a second testing time at 6 years 2 months, 10 months shy of the 7th birthday, and two had their first testing time just after age 7, at 7 years 4 months and 7 years 7 months. The average age of these eleven children at the first testing point was 6 years 0 months (range 4 years 7 months to 7 years 7 months) and the average age of children at the second testing point was 10 years 3 months (range 6 years 2 months to 13 years 3 months). Testing of this sub-sample of children occurred an average of 4 years 4 months apart (range 1 year 3 months to 5 years 11 months).

A repeated-measures analysis of variance with Time of Test (pre and post-7) and Test Type (Verbal and Performance IQ) on this sub-sample from Aram and Eisele's study revealed a nearly significant main effect of Time of Test ($F1, 10) = 4.94$, $p = .051$, attributable to higher IQ scores at the pre-7 test point (Mpre-7 VIQ = 109.6, $SD = 14.51$; Mpost-7 VIQ = 107.3, $SD = 12.81$; MPre-7 PIQ = 107.3, $SD = 9.37$; MPost-7 PIQ = 98.4, $SD = 8.98$). Although the decrease for participants in their study was larger for PIQ than VIQ, there was no main effect of Test Type ($F(1, 10) = 2.05$, $p = .18$) and the interaction of Test Type and Time of Test did not reach significance ($F(1, 10) = 2.58$, $p = .14$). Thus, Aram and Eisele's results are similar to the current findings as the sub-sample of children in their study with early lesions showed lower IQ score at the post-7 than at the pre-7 test point.

4. Discussion

Results of the current longitudinal study show that IQ scores of children with early unilateral brain injury decrease over the course of development. This decline seems to occur regardless of seizure status or lesion laterality, and is similar for Verbal and Performance IQ. The finding of a decline in IQ with increasing age is consistent with a re-analysis of Aram and Eisele's (1994) data as well as with a marginally significant finding reported by Bates et al. (1999). The mean IQ level of our sample at the first testing point (FIQ = 94.5) is consistent with the IQ level (FIQ = 93.3) reported by Bates et al. (1999). The lower mean IQ of our sample at the second testing point (FIQ = 85.5) is consistent with the magnitude of IQ deficits reported in studies in which the IQ of children with early lesions was obtained later during childhood or during adulthood (e.g., Duval, Dumont, Braun, & Montour-Proulx, 2002; Perlstein & Hood, 1955; St. James-Roberts, 1981).

We did not find evidence for a curvilinear relation between our index of lesion size (lesioned hemisphere volume) and cognitive outcome at either time point. Rather, we found that larger lesions, as indexed by the size of the lesioned hemisphere, were associated with lower pre-7 IQ scores; however, the magnitude of the IQ decline was greater for children with smaller lesions and higher pre-7 IQ scores. In light of our small sample size, we tentatively conclude that when early lesions are larger, the immediate impact on cognitive functioning is greater, but changes over time are less dramatic. In contrast, when early lesions are small, the immediate impact on cognitive functioning is relatively mild, but the full impact of the lesion on functioning unfolds over time. As a result, the IQ scores of children with smaller and larger lesions become closer over time.

Our study did not reveal any effect of seizure history or lesion laterality on IQ or changes in IQ over time. Based on prior studies, we did not expect to see an effect of lesion laterality on VIQ—PIQ differences or in changes in IQ over time (e.g., Bates et al., 1999). However, we did expect a poorer outcome in the group of children with seizures than in the group with no history of recurrent seizures (e.g., Huttenlocher & Hapke, 1990; Vargha-Khadem et al., 1992). The failure to observe this relation may be attributable to the small size of our sample, and to our exclusion of children with other than mild seizure disorders from the sample of children studied. Further, IQ measures may be too coarse to characterize possible deficits related to seizure status.

An important issue when interpreting the decline in IQ scores is the natural variability that normal children show when tested at different ages. A relevant study (Moffitt, Caspi, Harkness, & Silva, 1993) found a significant correlation between IQ scores of children tested at age 7 and later, at ages 9, 11, and 13 (correlation range .74 to .78), suggesting that most children tend to maintain their scores relative to their peers over several testing points. Taking into account the standard error of measurement within any single testing point, any IQ change between two testing points that exceeds 8.32 WISC-R IQ points may be safely assumed to exceed measurement error, (see Lord & Novick, 1968 for calculations; cited in Moffitt et al., 1993) a pattern that 10 of our 15 subjects show.

Another important point when comparing scores from different IQ scales (e.g. WISC-R and WPPSI) is the relation of performance on the tests. A sample of fifty children was given both the WPPSI and the WISC-R at age 6, when applicable age ranges of the two tests overlap; results showed correlations between VIQ, PIQ and FIQ on the WPPSI and the WISC-R ranging from .80 to .82 (Sattler, 1974). Mean IQ scores on these two tests differed by less than 3 points, and were slightly higher on the WPPSI than the WISC-R. However, our findings were not driven by the five children who were administered the WPPSI (or WPPSI-R) and then the WISC-R. Sattler (1974) also administered the WISC-R and the WAIS, to a sample of 16-year-olds, when the applicable age ranges of the two tests overlap. Cross-correlations between WISC-R and WAIS IQ scores ranged from .83 to .96, depending on subscale. Mean IQ scores on these two tests differed by 5–6 points, and were higher on the WAIS (Sattler, 1974), which is in the opposite direction from our observed IQ decline. Thus, it seems unlikely that our findings can be accounted for by the particular IQ tests administered at the pre- and post-7 time points.

The finding of an IQ decline following early brain injury adds to a growing body of longitudinal studies of developmental disorders, genetic disorders and neurological syndromes with similar conclusions. A decline in IQ over time was observed in a longitudinal study of children with Down Syndrome (Carr, 1988). In this sample, the greatest loss in IQ occurred between 6 months and 4 years of age, although there was still an IQ decline of 8 points between ages 4 and 11 years of age. There is also widespread evidence for a decline in IQ during childhood among both males and females with fragile X syndrome (e.g., Brun et al., 1995; Hagerman et al., 1989). Interestingly, several fragile X studies report the same phenomena that we found—that the children with higher initial scores are at the greatest risk for decline and exhibit more decline than those with lower initial scores (e.g., Brun et al., 1995; Dykens et al., 1989). A recent longitudinal study of children with autism also found significant IQ declines for the cohort tested between ages 5 and 7, and an IQ plateau for the cohort tested between ages 8 and 10 (Fisch, Simensen, & Schroer, 2002). A longitudinal study of children with early developmental delays of unknown etiology showed a pattern of significant decrease in IQ between 3, 6, and

11 years of age (Keogh, Bernheimer, & Guthrie, 1997). These diverse studies emphasize the importance of a longitudinal or follow-up approach when examining cognitive outcomes in children with early brain lesions and a variety of congenital disorders.

Studies of other disorders with similar IQ declines over time may illuminate the mechanisms by which IQ loss takes place. Recent work on fragile X syndrome has begun to suggest possible mechanisms for the IQ decline found in that syndrome. In particular, excessive numbers of immature dendritic spines have been found in synapses in human patients and mouse models with a genetic knockout of the FMR1 gene (Grossman et al., 2003). It is theorized that these dendritic spines reflect a failure of the mechanism by which excess and inappropriately located synapses are pruned during child development (Galvez, Gopal, & Greenough, 2003). Importantly, this pruning of excess synapses is a process that takes place throughout early and middle childhood, with variations in timing associated with different brain regions (Huttenlocher, 2002), which coincides with the period in which IQ declines in fragile X patients. It is possible that children with early brain lesions have a similar failure to prune excess early synapses, not because of a genetic anomaly, but simply because reduction of brain tissue may lead to a greater proportion of these synapses receiving the type of reinforcement that prevents pruning.

As mentioned previously, studies of animals with surgically induced focal lesions show that functional deficits vary as a function of age at time of testing. For example, Goldman (1971, 1974) found that monkeys with bilateral lesions of the dorsolateral frontal lobe during infancy do not show deficits on a delayed response task at 12–18 months of age but show marked deficits at 2 years of age. This finding may be explained by normal developmental changes in this brain region. Thus, the dorsolateral prefrontal cortex may not be involved in delayed response tasks at early test times because it is relatively immature. With increasing maturity, this cortical region may become involved in delayed response tasks, leading to the emergence of deficits in monkeys with early damage to this region. Similarly, the fall-off in IQ in children with congenital focal brain lesions may be explained in terms of the time course of development of particular brain regions.

It is also possible to think about the decline in IQ scores over time in terms of the increased processing demands of tasks that must be passed to maintain the same IQ score over time. Early damage may place limits on the brain's computational and/or storage capacities. Assuming that these capacities are increasingly taxed as cognitive skills become more complex, the disparity between children with early brain injury and their non-brain injured peers might be expected to widen with age. This disparity may become particularly evident when IQ tests begin to demand abstract reasoning in middle childhood and beyond (e.g., Hagerman et al., 1989). Alternatively, it is possible that the decline in performance over time is an artifact of the design of IQ tests. That is, the items that young children need to answer to attain an average IQ score at an early age may not tap the kinds of processes with which brain injured children have difficulty. In contrast, to attain this same IQ level at a later age, children may need to correctly answer questions that do tap the kinds of processes that pose difficulty for children with early unilateral brain injury. According to this view, the magnitude of cognitive deficits might appear more stable over time if younger and older children were given tasks that tap similar underlying processes.

Although the mechanisms underlying the IQ decline in children with early brain injury remain an open question, the finding of a decline has theoretical, methodological, and practical implications. Theoretically, the decline suggests that functional plasticity may be insufficient to sustain a normal rate of development on the foundation of a brain with an early injury. The finding that a fall-off in IQ level occurs at around 6–8 years of age raises the important question of why IQ is vulnerable during this time period. Although the answer is currently unknown, we speculate that the timing of the IQ fall off may be associated with crossing a threshold in the number of excess synapses available. For example, once a certain proportion of excess synapses have been pruned by normal developmental processes, there may be less plasticity for later developing skills (Huttenlocher, 2002; Huttenlocher & Dabholkar, 1997). Supporting the hypothesis of a decrease in plasticity at around this time, studies of patients with unilateral lesions report that it is less likely for language functions to reorganize to the right hemisphere if lesions occur after 5–6 year of age (e.g., Muller et al., 1998, 1999; Rasmussen & Milner, 1977; Satz, Strauss, Wada, & Orsini, 1988; Satz, Strauss, & Whitaker, 1990). Methodologically, the IQ decline indicates that it is not possible to understand the effects of early lesions without taking a developmental approach and studying changes in functioning over time. Finally, the IQ decline has practical implications, suggesting that intervention may be useful to young brain injured children, even those who do not exhibit early cognitive deficits, as these services may diminish the severity of future deficits.

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