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Online Measures of Basic Language Skills in Children with Early Focal Brain Lesions

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Twenty children with early focal lesions were compared with 150 age-matched control subjects on 11 online measures of the basic skills underlying language processing, a digit span task, and 6 standardized measures. Although most of the children with brain injury scored within the normal range on the majority of the tasks, they also had a disproportionately high number of outlier scores on the reaction time tests. This evidence for a moderate impairment of the basic skills underlying language processing contrasts with other evidence suggesting that these children acquire normal control of the functional use of language. Furthermore, these children scored within the normal range on a measure of general cognitive ability, suggesting that there is no particular sparing of linguistic functions at the expense of general cognitive functions. Using the MPD procedure (Valdés-Pérez & Pericliev, 1997), we found that the controls and the five clinical groups could be best distinguished with two measures of online processing (word repetition and visual number naming) and one standardized test subcomponent (the CELF Oral Directions subtest). The 12 children with left hemisphere lesions scored significantly lower than the 8 other children on the CELF-RS measure. Within the group of children with cerebral infarct, the nature of the processing disability could be linked fairly well to site of lesion. Otherwise, there was little relation between site or size of lesion and the pattern of deficit. These results support a model in which damage to the complex functional circuits subserving language leads to only minor deficits in process efficiency, because of the plasticity of developmental processes. © 2000 Academic Press

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Children with focal brain lesions face the challenge of learning language in the absence of an intact cerebral cortex.[1] If the injured area includes some of the left hemisphere (LH) areas that are typically considered essential for language functioning, we might expect that these children would have serious problems learning to speak. However, the fact is that, despite having what would appear to be serious obstacles to language learning, many of these children succeed in acquiring full, normal conversational control over their native language. In order to explain this seeming paradox, we need to examine three basic issues: 1. What is the overall level of competence that these children show in comparison to children with no apparent brain injuries? 2. Do these children demonstrate relative strengths and deficits for particular language processing skills? 3. Is there a demonstrable relation between particular language deficits and damage to particular cortical areas?

In this paper we use online methodologies to measure some of the basic skills underlying language processing. In all of the children we are studying, neurological damage occurred before the 2nd month of infancy, prior to any explicit language learning. Our measures and experiments are designed to evaluate the ways in which the type, size, and site of lesion influence the nature of the resulting language strengths and deficits.

STRENGTHS AND DEFICITS IN LANGUAGE LEARNING

Previous studies (Banker & Larrouche, 1962; Feldman, Holland, Kemp, & Janosky, 1992; Feldman, 1994; Lenneberg, 1967; Thal et al., 1991; Woods & Carey, 1978) have shown that children with early focal lesions have a remarkably favorable prognosis for normal language acquisition. As a result, researchers often view these children as providing evidence for the plasticity of human brain structures. If it is true that these children acquire a fully normal use of language, it becomes difficult to argue that any particular area of the brain or module is somehow crucial for normal language functioning.

On the other hand, many studies have also described deficits (Aram, Ekelman, & Whitaker, 1986; Aram & Ekelman, 1987; Aram, Meyers, & Ekelman, 1990b) or delays (Keefe, Feldman, & Holland, 1989; Marchman, Miller, & Bates, 1991; Thal et al., 1991) in the language abilities of children with focal lesions. These studies provide evidence in support of the view that the left hemisphere plays a central role in the control of language functioning. When this neural substrate in the left hemisphere is damaged, children appear to recruit alternative cortical areas for language processing. Al-

[1] Our thanks to the 20 families who participated in this study, as well as to the teachers and child control subjects in the Mt. Lebanon Montesorri School, the Cathedral School, the Carnegie Mellon Child Care Center, St. Edmund's Academy, and the Seton Center School.

though these alternative patterns of organization may succeed in providing an effective level of language functioning, they can also produce measurable language deficits.

HOW DOES THE BRAIN ORGANIZE FOR LANGUAGE AFTER EARLY LH INJURY?

Over the years, researchers have offered five major hypotheses regarding the ways in which the brain may organize for language after early LH injury. These hypotheses are not mutually exclusive. In fact some are conceptually dependent on each other. Previous research has provided at least some empirical support for each of these hypotheses.

1. *Language sparing and cognitive crowding.* It has often been suggested that the processes of neuronal organization work in a way that tends to spare language at the expense of other cognitive facilities. This observation has been supported by comparisons of verbal and nonverbal intelligence scores in children with focal lesions (Fawer, Diebold, & Calame, 1987; Milner, 1974; Nass, Peterson, & Koch, 1989) and hydrocephalus (Fletcher, Francis, Thompson, Brookshire et al., 1992). The idea is that language is spared because it takes over tissue normally reserved for other cognitive functions. The resultant ‘‘cognitive crowding’’ leads to a deficit in nonlinguistic abilities (Aram & Eisele, 1994; Levine, Huttenlocher, Banich, & Duda, 1987; Nass et al., 1989; Nass, Sadler, & Sidtis, 1992; Strauss, Satz, & Wada, 1990). In cases of children who have lost an entire cerebral hemisphere as a result of a hemispherectomy, cognitive crowding would result from the imposition of two major tasks upon a single hemisphere. For example, if a lesion to Broca’s area shifts some language control processes to the homologous right hemisphere (RH) area, we might expect a certain decline in aspects of nonverbal behaviors that would otherwise be controlled by Brodmann areas 44 and 45 in the RH.
2. *Late rigidity.* A further consequence of cognitive crowding might be that children with focal lesions might be unable to acquire full competence for skills learned later in life. In particular, the skills of reading (Aram & Ekelman, 1988; Aram, Gillespie, & Yamashita, 1990a), narrative discourse (Reilly, Bates, & Marchman, 1998), and mathematics are not encountered until the middle school years. Acquiring these skills may be difficult for these children, because their brains are already ‘‘committed’’ in ways that block the flexible acquisition of these new tasks.
3. *Contralateral recruitment.* A second consequence of cognitive crowding could be a pressure toward contralateral recruitment. To the extent that the brain provides two equipotential systems (Lenneberg, 1967), the loss of language-related processing areas on the left can be compen-

sated for by recruitment of homologous areas on the right. Evidence that there are anatomical and functional differences between the two hemispheres at birth (Dennis & Whitaker, 1976; Kinsbourne & Hiscock, 1983; Molfese & Hess, 1978; Molfese, Freeman, & Palermo, 1975; Molfese & Betz, 1987; Wada, Clarke, & Hamm, 1975; Witelson, 1977; Witelson & Pallie, 1973; Woods & Teuber, 1977) argues against strict equipotentiality. However, more recent evidence points to strong plasticity and reorganization abilities for the right hemisphere in both children with focal lesions (Muter, Taylor, & Vargha-Khadem, 1997; Vargha Khadem, Isaacs, & Muter, 1994) and adult aphasics (Weiller et al., 1995).

4. *Local recruitment.* Another proposed mechanism of brain reorganization involves recruitment of areas adjacent to a lesion (Pons et al., 1991; Ramachandran, 1993, 1995). In the case of children with focal lesions (Papanicolaou, DiScenna, Gillespie, & Aram, 1990), this might mean that a lesion to an area such as superior temporal cortex would lead to a reorganization of function into adjacent temporal and parietal regions, rather than a shift of function to the RH. In their work with induced lesions of the visual memory processing area in infant monkeys, Webster, Bachevalier, and Ungerleider (1995) report exactly this pattern of organization. They find that infant monkeys are able to compensate for the excision of area TE by shifting processing to alternative nearby pathways, whereas adult monkeys cannot organize in this way. If a processing area is damaged bilaterally in adults, recovery of function will depend on making use of areas that may have played only a secondary role in the intact processing system. A PET study of recovery from auditory agnosia in an adult by Engelien et al. (1995) shows that recovery of function after bilateral damage can involve just such a process. In children with bilateral focal lesions, there may be pressure to organize language along fairly atypical patterns.
5. *White matter commitment.* It may be more difficult to accommodate to damage to white matter than damage to gray matter. Although damage to a cortical processing area can be compensated for by recruitment of other cortical areas, it is more difficult to recruit or reorganize the ‘‘connecting wires’’ of subcortical white matter pathways. Dennis and colleagues (Barnes & Dennis, 1992; Dennis & Barnes, 1993) have applied this hypothesis in their studies of children with hydrocephalus. This same factor may also have important implications for the study of children with periventricular hemorrhage or leukomalacia, since these conditions involve damage to white matter areas such as the corona radiata.

The fact that there is some evidence in support for each of these five proposed mechanisms suggests that the actual process of brain organization in a given child will be influenced by a complex set of factors. Our goal in this work is to understand the various ways in which the brain can organize for language processing. This study will not examine all five of these hypotheses, instead focusing primarily on evidence for the initial claims regarding language sparing and cognitive crowding. However, related studies of this same population using fMRI methodology (Booth et al., 1999) provide further relevant data regarding the remaining four issues.

Paradigms for Studying Children with LH Brain Injury

The first studies of language in children with focal lesions and hemispherectomies (Basser, 1962) relied on clinical data accompanied by neurological diagnoses. During the 1970s and 1980s, researchers increased their reliance on standardized testing and cross-sectional designs (Aram & Ekelman, 1987; Dennis & Kohn, 1985). More recently, researchers have shifted to a longitudinal design accompanied by sampling from naturalistic behaviors (Thal et al., 1991). These research methods may overestimate the extent to which children with focal lesions achieve fully normal language usage. This is because the measures being used—vocabulary growth, MLU, morphological markers, and even narrative structures—are heavily overdetermined by the language learning process (MacWhinney, 1996a, 1996b, 1997). This overdetermination can arise from well-structured parental input, good educational support, and nurturant family environments. Given these support factors, children with focal lesions may be able to acquire a normal control of language, when measured in overall functional terms. However, if we are able to look underneath the successful skills these children have acquired, we may still find evidence for certain residual information-processing deficits.

One way of ‘‘getting under the hood’’ to study potential language deficits is to make use of reaction-time methodology. Kail (1988; 1991; 1992) has shown that reaction-time speed increases throughout childhood. Reaction time methods such as self-paced reading have been shown to be sensitive to fine-grained differences in verbal ability between college students (King & Just, 1991) and school-aged children (Booth, MacWhinney, & Harasaki, under review). These patterns of individual differences suggest that we might be able to detect differences in online language processing between normal children and children with early focal lesions.

Methodology: Group Studies vs. Profiling

The extreme diversity of lesion etiologies, sizes, and sites found in the population of children with early brain injury makes the application of standard group methodology inappropriate. Instead of focusing on the attempt to form large groups, the alternative we prefer is to administer a test battery that provides a large number of measures for each individual subject. If these measures are properly constructed, they can provide us with an informative profile of the child's strengths and weaknesses across the various components of the language processing system. This method of psychometric profiling elaborates the tradition developed by Galton (1883), Swets (1961), Massaro (1987), and many others.

We have used two approaches to the psychometric characterization of our experimental subjects. The first method compares the performance of children with early brain injuries to the performance of a reference sample of age-matched, normally developing children to determine if the experimental subjects' scores fall within or outside the normal range of scores. This procedure is akin to comparing the height of an individual child against the norms that have been established from measurements of a large age-matched sample.

A second method for examining relations among individual profiles uses maximally parsimonious discrimination (MPD), developed by Valdés-Pérez and Pericliev (1997). This analytic tool is designed to extract a set of features that distinguishes a number of clinical groups from each other. The goal is to extract the smallest number of distinctive features that still serve to contrast the groups. In our case, the possible feature set includes scores on standardized tests and scores on reaction-time tests, whereas the groups being distinguished are defined neurologically.

METHODS

Subjects

Control group. The first step in this work involved the construction of a normal processing profile against which we could compare the performance of our experimental group of children with focal lesions. To do this, we recruited 150 children ranging in ages from 5 through 10 years to serve as controls. This group was composed of 25 children at each age of the six age levels. All of the control children were functioning at grade level. They were recruited from parochial and private schools in the greater Pittsburgh area and were tested at their schools. The sample was composed of 86 males and 64 females of varying socioeconomic levels. Eighty-nine percent of the children were Euro-Americans, 9% were African American, and 2% were of Asian origin. This distribution is comparable to the demographics of the region and was also comparable to the distribution for the experimental group. Parental consent was obtained for all participants.

Experimental group. A group of 20 children ages 5 to 11 were recruited through referrals from local hospitals, rehabilitation centers, and previous research studies. The group included 12 boys and 8 girls. Two of the subjects were African Americans. Two children with right-sided lesions and two children with hydrocephalus were included to extend the range of clinical types.

Scans

All of these children were evaluated with a MRI scan to determine the nature, size, and site of their neurological injury. MRI scans for 19 of the 20 children were obtained in the MRI Research unit at Presbyterian University Hospital at the University of Pittsburgh Medical Center. One child, who had a good previous MRI scan, was not scanned again, because she could not tolerate being in the scanner. Parents were asked to read and sign a detailed informed consent statement.

Scans were performed on superconducting magnetic resonance imaging units operating at 1.5 T. The imaging protocol included. 1. a sagittal series with 5-mm-thick spin-echo (SE) 500–600 ms/20 ms/2 (TR/TE/excitations), 2. an axial series with 5-mm SE 3000–3500/30, 90–120 (TR/TE/excitations), 3. a coronal series with 5-mm IR (inversion recovery) 2000/20/800 (TR/TE/TI), and 4. a second coronal series with 1.5-mm SE 3000–3500/30, 100–120/2 (TR/TE/excitations). Scanning was done without sedation and without the use of a bite block. During the scan, the children were in visual and verbal contact with the adults in the operations room. Each scan took about 50 min to complete.

The experimental group can be divided into those who had cerebral infarct (CI), those who had periventricular hemorrhage (PVH), and those who had hydrocephalus (HYD). Cerebral infarct (CI) or stroke is a vascular accident similar to stroke in adulthood. It damages those areas of the brain that are fed by a particular cerebral artery. These areas include discrete or focal areas of cortical gray and white matter. Strokes may be associated with ischemia, asphyxia, hypoxia, hypotension, or certain procedures in early infancy such as cardiac catheterization (Barmada, Moossy, & Shuman, 1979). Children were assigned to the CI category if the MRI scan showed focal damage to the cerebral cortex and adjacent white matter and/or deep basal ganglion structures in the distribution of one or more major cerebral vessels, such as the middle cerebral artery.

PVH is an injury that sometimes arises in children who are born prematurely. In these children, the maturation of the pathways surrounding the ventricles is not yet complete at the time of premature birth. The result can be an injury to the deep subcortical white matter that tends to spare the cortical mantle (Banker & Larrouche, 1962; Schuman & Selednick, 1980). With the advent of high-resolution bedside cerebral ultrasonography (Fawer et al., 1987), these lesions are now detectable *in vivo* in the neonatal intensive care unit. Children were assigned to the PVH category if there was a cavitary lesion adjacent to or communicating with the ventricular system (Grant, Kernerm, & Schellinger, 1982).

HYD is a disorder that arises from a failure in absorption of the cerebral fluid that normally flows through the ventricles. As fluid builds up, it extends the size of the ventricles and compresses the cortical mantle, leading to possible loss of a particular area of cortical material or of subcortical areas, such as the basal ganglia and the corona radiata. Although hydrocephalus does not produce an overt lesion, it does lead to the loss of cortical material. Children were assigned to the HYD category, if the scan showed marked thinning of the cortical mantle with an expanded ventricular area.

Table 1 describes the code name, age, sex, and MRI findings for all the children. Within CI and PVH, we further distinguished children with primarily left lesions from children with primarily right lesions. Because we had only 3 children with primarily right lesions, we grouped these three subjects together into a RIGHT group. Subjects 1 through 12 were the cases of clear left hemisphere lesions, from either PVH or CI. Subjects 13 to 15 were cases of clear right hemisphere lesions. Subjects 16 to 18 were children who were diagnosed as having left hemisphere lesions during infancy, but whose MRI scan at the time of this study revealed only minimal damage. Subjects 19 and 20 were cases of HYD.

Lesion Size and Site Analysis

The raw image data from the MRI scans were quantified using the Alice image processing program. A volumetric analysis for the left and right cerebral cortex was computed from the 22 image axial series. Semiautomatic segmentation was done using a custom plug-in to the Alice program developed by Rob Lewis and Gordon Harris of the New England Medical Center. The goal of this segmentation process was to quantify the volume of remaining healthy tissue and the volume of the lesion in each cerebral hemisphere. We did not attempt to further quantify tissue by lobes.

Segmentation required clicking the mouse inside and outside of candidate regions of interest (ROIs) that were then fit adaptively by a curve which was propagated to the rest of the slices. Sometimes it was necessary to reset the borders of the area being segmented after they had propagated across several slices. The segmentation process yielded three volume estimates: the lesion volume, the volume of the remaining tissue in the lesioned hemisphere, and the volume of the nondamaged hemisphere. Only cortical tissue was included in the volumetric analysis.

From these volumetric estimates, we computed a single index based on the ratio of the left hemisphere volume over the right hemisphere volume. These ratios are given in the last column of Table 1. For children with minimal damage, this ratio was close to 1.000. For the child with the greatest amount of left hemisphere damage, this ratio was 0.441.

Standardized Tests

Each experimental subject was given a set of standardized measures to allow comparison of their outcome on all measures with other studies and normative populations. The standardized tests that were used were as follows: 1. The Peabody Picture Vocabulary Test-Revised (PPVT-R) (Dunn & Dunn, 1981) is an untimed test of receptive vocabulary. 2. The Leiter International Performance Scale (Leiter, 1979) is an untimed tested of nonverbal intelligence. 3. The Clinical Evaluation of Language Function-Revised (CELF-R) (Semel & Wiig, 1994) is a standardized measure of language functioning. All children were tested on the subtest entitled Recalling Sentences (RS), a test that evaluates the ability to recall and reproduce sentence surface structure of varying lengths and syntactic complexity. 4. Of the 20 children, 19 were assessed using two additional CELF subtests. The first was the CELF-OD (Oral Directions) that evaluates the ability to interpret, recall, and execute oral directions of increasing length and complexity. The second was the CELF-FS (Formulating Sentences) that assesses the ability to formulate compound and complex sentences from words provided by the examiner. 5. Nine children were given the CELF-LC (Linguistic Concepts) subtest that evaluates the ability to interpret oral directions which contain linguistic concepts requiring logical operations such as ‘‘and,’’ ‘‘either’’ . . . or,’’ and ‘‘if . . . then.’’ This test is appropriate only for children aged 5 to 7, so it could not be given to all children.

Reaction Time Tests

Equipment. All of the reaction-time tests were administered on the computer. We used a Macintosh 660AV with a 15-in. monitor. All of the experiments were built using the PsyScope experiment generator system (Cohen, MacWhinney, Flatt, & Provost, 1993). Responses were registered by presses on the PsyScope button box or on small buttons glued directly onto the computer screen. Auditory stimuli were presented across stereo headphones with a separate headset for the child and the experimenter. Vocal responses were recorded using a microphone, which triggered a voice-activated relay circuit in the PsyScope button box.

All experimental subjects and control children were tested individually in two sessions lasting approximately 30 min each. Each of the experiments was presented in a game format. Before each experiment, the subject was presented with both oral and written directions for the task and was given the opportunity to complete a few practice trials. Subjects were instructed to listen carefully and to respond as fast as they could. After the tester was confident that the subject understood the instructions and had successfully completed the practice trials, the actual experiment was presented. After each session, the subject was rewarded with his or her choice of a small prize.

Reaction time tasks. There were 11 reaction-time tasks, including two detection tasks, three recognition tasks, three choice tasks, and three naming tasks. In all of the tasks, there was a stimulus that appeared for 300 ms. Visual stimuli were presented on a computer screen. Audi-

TABLE 1
The 20 Experimental Subjects

Number	Code	Age	Sex	Group	MRI findings	L/R ratio
1	BRAS	7	M	Left PVH	Enlargement of the L ventricle with minor reduction of L white matter.	0.969
2	MAG	10	M	Left PVH	Enlargement of the L ventricle including damage to the interior part of the motor strip, somatosensory strip and the adjacent parietal area.	0.981
3	DES	10	F	Left PVH	Enlargement of L ventricle. White matter loss underneath the entire L cortex, with some retrograde white matter loss.	0.949
4	DUP	7	M	Left PVH	Enlargement of both lateral ventricles L $>$ R. Reduction in white matter in L periventricular region, in the areas anterior and posterior to the ventricle.	0.961
5	TID	10	F	Left PVH	Enlargement of the L lateral ventricle into posterior cortical areas.	0.998
6	ELS	6	F	Left CI	Previous scan showed small lesion in the left parietal white matter.	n.a.
7	JOR	6	M	Left CI	Damage to L DLPFC and nearby areas, including Broca's area; enlarged L ventricle.	0.809
8	JUS	9	M	Left CI	Near complete loss L parietal lobe; some insular loss; 50% loss of occipital, mostly anterior; significant frontal loss with only some anterior frontal preserved.	0.441
9	KAM	9	F	Left CI	L lateral/posterior/inferior frontal loss, adjacent to insula, sparing motor strip; L lateral/anterior parietal loss and some loss of the left insula.	0.696
10	MAM	7	F	Left CI	Enlargement of the L ventricle centrally with thinning of left white matter (cororna radiata, centrum semiovale, corpus callosum).	0.926
11	RYB	7	M	Left CI	L lateral inferior anterior frontal loss, affecting Broca's area and DLPFC; enlargement of the L lateral ventricle, probable compensation for volume loss.	0.821
12	STEW	5	F	Left CI	Loss along the L central sulcus involving the posterior L frontal cortex and anterior L parietal area.	0.932

TABLE 1—*Continued*

Number	Code	Age	Sex	Group	MRI findings	L/R ratio
13	EMF	7	F	Right PVH	Enlargement of the R ventricle centrally and in the parental region.	1.104
14	JOD	8	M	Right PVH	Right frontal encephalomalacia involving prefrontal cortex.	1.116
15	KAD	7	F	Right CI	Right frontal parietal encephalomalacia.	1.051
16	MIB	9	M	Minimal	No obvious damage.	0.956
17	MID	7	M	Minimal	Apparent cortical thinning in the occipital lobes bilaterally, but no evidence of large focal tissue loss.	1.033
18	NIM	9	M	Minimal	No obvious damage.	0.986
19	DAC	8	F	HYD $L > R$	Enlargement of L lateral ventricle engulfing most of parietal and much of occipital lobe. A thin parietal mantle remains, along with a somewhat larger occipital mantle. Some enlargement of R lateral ventricle.	0.864
20	WIG	10	M	HYD $R > L$	Extremely large right lateral ventricle with appearance of moderate pressure and an enlarged left lateral ventricle.	1.300

tory stimuli were presented over headphones. The subject’s task was to press a red button to indicate detection or recognition of the stimulus. The reaction time was the duration between the onset of the stimulus and the pressing of the button. In each experiment the stimulus appeared at a lag of 1000, 1500, or 2000 ms after the previous trial. Because this duration was varied randomly, subjects could not predict when the stimulus would appear. For all these tasks the children were instructed to respond as quickly as possible. The time of the button press or the onset of the vocal response was measured using the voice-operated relay built into the button box. 1. Visual detection. In this task, the child pressed a red button whenever a star appeared on the computer screen. 2. Auditory detection. In this task, children used headphones to listen for a pure 1-kHz tone. In both the visual and auditory detection tasks, trials were not counted if the reaction time was less than 200 ms, on the assumption that the child must have been have begun response initiation prior to the stimulus presentation. Trials that lasted longer than 2000 ms were excluded on the assumption that these long response times indicated that the child might have missed the presentation of the stimulus. 3. Visual recognition. Trials consisted of the display of either a star or a square. Children were asked to press the red button when a star appeared. Trials were terminated if the child failed to push the button within 2000 ms. In addition to the response timing errors that are possible for the detection tasks, this task can produce errors when children press the button for the incorrect stimulus. 4. Auditory recognition. Trials consisted of the presentation of either a 1-kHz tone or a higher pitched 5-kHz tone. Children were instructed to press the button when they heard the lower tone. Trials were terminated if the child failed to push the button within 2000 ms. 5. Word recognition. Trials consisted of the auditory presentation of either the word ‘‘dog’’ or the word ‘‘cat.’’ Children were instructed to press the button when they heard the word ‘‘dog.’’ 6. Visual choice. The stimuli for the three choice tasks were the same as those for the three corresponding recognition tasks. In the choice tasks, the children had to choose between two possible buttons to press. Small gummed labels were attached above the buttons to remind children which button corresponded to which stimulus. In the visual choice task, one button was for the star and one for the square. 7. Auditory choice. In the task, the red button was for the low tone and the green for the high tone. These choices were labeled with a down-arrow for the low tone and a picture of an up-arrow for the high tone. 8. Word choice. In this task, children heard either the word ‘‘dog’’ or the word ‘‘cat.’’They were asked to press the red button for ‘‘dog’’ and the green button for ‘‘cat.’’ The buttons were labeled with pictures of the animals. 9. Word repetition. Over headphones, children heard a randomly selected digit from the numbers between 1 and 9. They were asked to repeat the number verbally. The onset of their response was measured using the voice-activated response key built into the button box. The reaction time was computed from the beginning of the number word. 10. Visual number naming. Here children saw a number visually and then named it. As soon as the child named the number, it disappeared from the screen. 11. Picture naming. In this task, children were asked to name line drawings of basic objects. Many of the line drawings were taken from the stimuli of Snodgrass and Vanderwart (1980). There were a total of 96 pictures, from which the PsyScope program randomly selected 20 for each child. Before the practice section for this experiment, the subject was asked to name all 96 pictures, as they were presented in flash card form. Pictures that the child had difficulty naming were repeated until all pictures were named accurately.

Auditory Digit Span

We also included one nonspeeded information-processing task. This was a digit span measure for evaluating working memory. Digit span is defined as the largest number of digits that can be accurately recalled 50% of the time. In our version of this measure, the numbers from 0 to 9 were digitized and presented through headphones in various orders. There were eight trials at each level. If the subject was correct five or more times of eight, the computer would advance to the next level. The subject was instructed to listen carefully and to repeat the numbers aloud in the correct sequence when a question mark appeared on the screen. The tester then entered the subject’s response into the computer by using the keyboard. The subject would advance through the levels until less than five of the eight digits were correct.

Z-Score Analysis

For each child (20 experimental and 150 control) on each of the 12 experimental tasks, we computed a *z*-score based on the means and standard deviations for the control group at each age level. Under Results, we describe several analyses based on these scores.

RESULTS

Formal Tests

Table 2 presents the scores on the standardized tests for the children with brain injury. The mean score for the children with brain injury on the Leiter was 95.45 (SD 17.71); on the PPVT it was 96.05 (SD 15.0). Both of these means are solidly within the normal range. On the Leiter, three children scored greater than 2 SD below the mean. None of the children scored more than 2 SD below the mean on the PPVT. The correlations between the Leiter and the PPVT for the group of experimental children was moderate at $r =$

TABLE 2
Scores on the Standardized Tests

		Leiter	PPVT	CELF-RS	CELF-FS	CELF-OD	CELF-LC
Left lesions							
1	BRAS	114	82	7			
2	MAG	66	125	11	4	5	
3	DES	62	75	5	4	4	
4	DUP	117	108	9	3	4	12
5	TID	94	110	13	17	11	
6	ELS	110	101	9	7	5	13
7	JOR	93	91	3	3	6	10
8	JUS	103	100	3	3	7	
9	KAM	107	97	6	6	8	
10	MAM	121	95	7	6	9	12
11	RYB	92	98	7	4	3	9
12	STEW	96	77	6	7	9	8
	Mean	97.9	96.6	7.2	5.8	6.4	9.7
	SD	18.6	14.3	3.0	4.0	2.5	2.1
Other lesions							
13	EMF	111	125	12	12	11	12
14	JOD	79	92	8	6	6	
15	KAD	107	98	11	4	12	12
16	MIB	81	88	11	10	7	
17	MID	106	72	5	12	7	
18	NIM	93	93	9	7	7	6
19	DAC	95	81	11	6	8	
20	WIG	62	113	16	8	6	
	Mean	91.8	95.3	10.4	8.1	8	10
	SD	16.8	17	3.2	2.9	2.3	3.5

Note. Difference between groups approaches significance at $p = .075$.

.50. DES scored poorly on both these measures, suggesting a global problem with intellectual and language skills. WIG and MAG scored 2 SD below the mean on the Leiter and almost 2 SD above the mean on the PPVT, suggesting a selective problem in nonverbal intelligence or visual processing. We also compared the performance of the 12 children with specifically left hemisphere damage to the other 8 experimental children. We found no significant differences between these two groups on the Leiter or the PPVT.

In contrast to their nearly normal performance on the PPVT and Leiter, the experimental subjects performed more poorly on the language processing tasks of the CELF. For these tests, the mean is 10 and the standard deviation is 3. The mean for the experimental subjects on the CELF-FS was 6.79, which was more than 1 SD below the mean. The mean score on the CELF-OD was 7.11, close to 1 SD below the mean. The experimental children did somewhat better on the CELF-RS and CELF-LC, though only 9 children took this last measure, because it is appropriate for use only with children between ages 5 and 7. On the CELF-RS, the 14 children with clear left hemisphere damage had a mean of 6.79, which was significantly ($p < .01$) worse than the mean of 10.37 for the other 8 subjects. The PPVT correlated with the CELF-RS at $r = .691$ ($p > .05$), with the CELF-LC at $r = .559$ (n.s.), with the CELF-FS at .439 (n.s.), and with the CELF-OD at .091 (n.s.).

The two standardized measures of language processing that most clearly distinguish the children with brain injury from the normal controls are the CELF-OD and CELF-FS. On these measures, the mean for the children with brain injuries is in the bottom 5% of the standardized distribution. The CELF-FS correlated moderately with the CELF-OD at $r = .508$.

It appears that these tasks cluster into two groups. The first group includes those tasks that demand a good control of words. These are the PPVT, the CELF-RS, and the CELF-LC. The PPVT is a test of vocabulary size that directly tests word-based knowledge. In the CELF-RS, knowledge of words is used to facilitate the short-term recall or repetition of sentences. In the CELF-LC, knowledge of operators such as quantifiers and conjunctions is used to follow the instructions to demonstrate linguistic comprehension. In contrast, the CELF-FS and the CELF-OD fall into a second group that relies on nonlexical language processing. In the CELF-FS the child must apply syntactic, semantic, and pragmatic abilities to compose a complex sentence structure based on the words provided. In the CELF-OD, the child must store, elaborate, and execute a complex plan to follow oral directions. These two tasks emphasize language planning, as opposed to the use of lexicon and basic syntax. The fact that the experimental children have more problems with this second group of tasks and fewer with the first group underscores their weakness on planning tasks and their relatively good control of the basic elements of language.

Processing Tasks—Group Analysis

Figures 1 to 11 display the mean reaction times and the standard deviations for each task at each age level for the control subjects as a group. Figure 12 displays mean digit span length and standard deviations at each age level for the control subjects. These 12 figures also have asterisks to mark the scores of the experimental subjects, whenever they fell above the 90% confidence interval. The number of scores of control subjects that fell above the 90% confidence interval is indicated on the bar for each age group. We used the 90% confidence interval, rather than the 90% confidence interval, since we were primarily interested in studying the 5% of scores that correspond to the slowest reaction times. The 12 figures also include the regression line that best fits the distribution of scores for the controls, as well as a second regression line for the experimental subjects.

All of the figures show that the mean reaction times or span scores for the tasks decreased steadily across the age range for both control and experi-

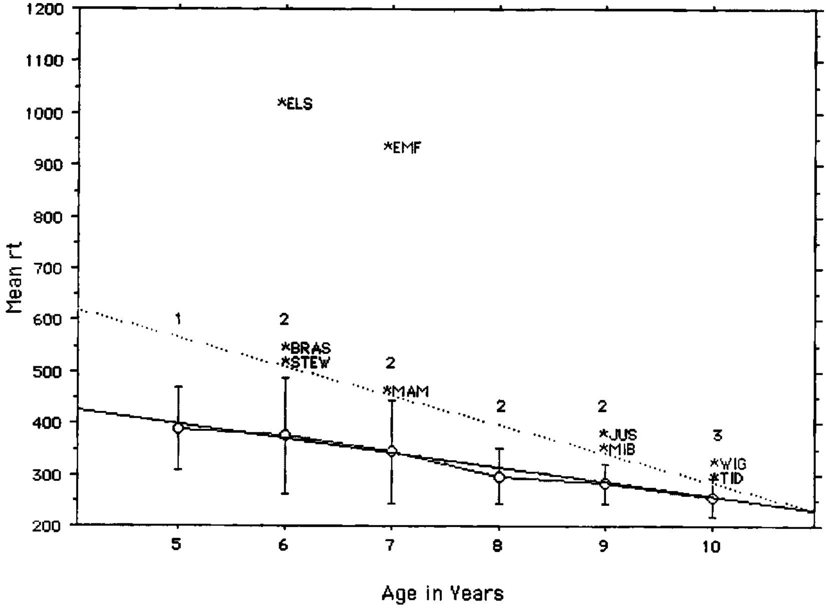

FIG. 1. Reaction times for visual detection from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (45% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (8% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group with a slope of -27.138 and an r^2 of .46. The dotted line is the regression line for the experimental group, with a slope of -52.563 and a r^2 of .297.

mental subjects. These results support the finding of constant development in processing speed reported by Kail (1988, 1991, 1992). In all of the timed tasks, the means reaction times for the controls were faster than the mean reaction times for the experimental subjects. For the digit span task, the number of digits recalled increases with age. For all of the tasks, except word recognition and digit span, the regression lines for the two groups converge with age, although this convergence is stronger for some tasks than for others. The two tasks that showed the weakest r^2 values were the auditory recognition task and the word repetition task. This was due to a higher variability at all ages for these tasks.

Outlier Score Analysis

We also conduct comparisons between the tasks in an attempt to discover clear dissociations. For example, we looked for clustering of auditory tasks as opposed to visual tasks. We also looked for evidence that naming or choice could be impaired separately from recognition. However, there was no evidence of any clear patterns of task dissociations. Instead, we saw that the

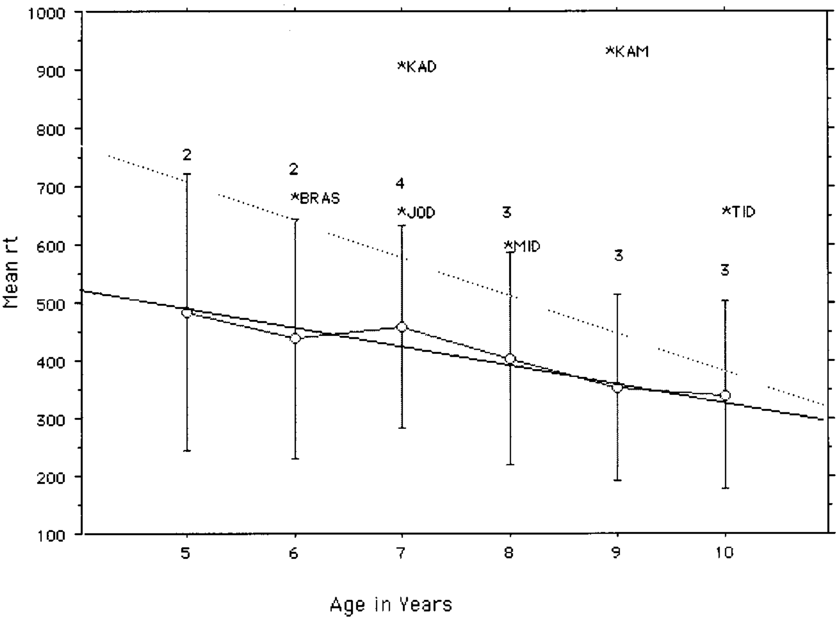

FIG. 2. Reaction times for auditory detection from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (30% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (11% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of -27.774 and an r^2 of .145. The dotted line is the regression line for the experimental group, with a slope of -60.481 and a r^2 of .207.

children in the experimental group displayed weaknesses scattered across the tasks. Following an analytic logic suggested by Bishop (1983), we wanted to know whether these patterns could be characterized as falling within the normal range of variation. In particular, we wanted to know how often the experimental children achieved test scores that were outliers in the overall *z*-score distribution. Figure 13 examines this issue by tabulating the number of times that each child had an outlier score. Outlier scores here are defined as scores that are more than 1.5 standard deviations above or below the mean.

When summing these outlier scores, a reaction time on a particular task that was slower than the mean for that task was given a value of -1. A reaction time on a particular task that was faster than the mean for that task was given a value of $+1$. This means that a value of $+1$ would cancel out a value of -1. However, for the experimental group, there were only 4 positive individual outlier scores of a total of 240 possible scores (20 children times 12 tasks). These 4 positive outlier scores were distributed across 4 different experimental children. This means that, for the experimental children, the

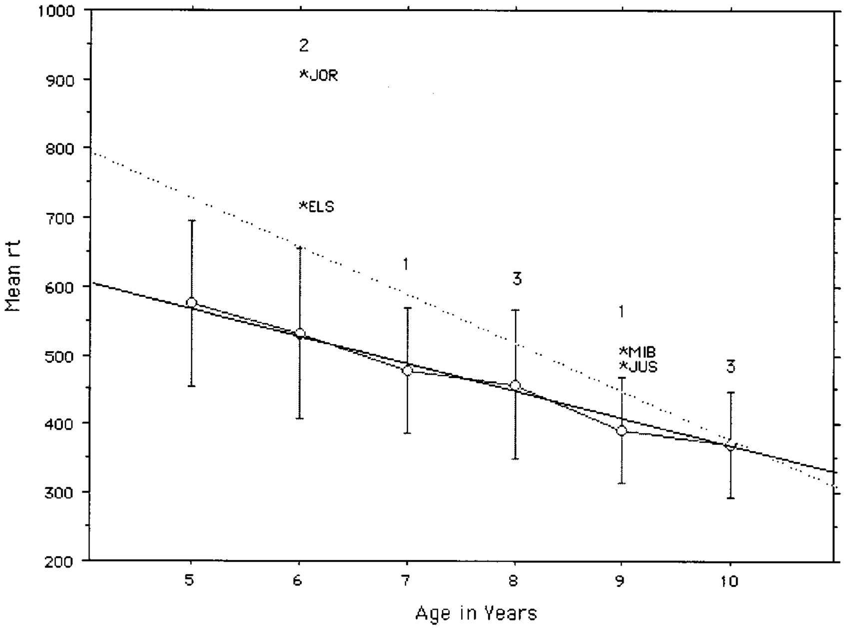

FIG. 3. Reaction times for visual recognition from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (20% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (7% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of -40.048 and an r^2 of .50. The dotted line is the regression line for the experimental group with a slope of -63.905 and a r^2 of .576.

total summed outlier score is largely a function of the number of times they scored substantially below the mean of the control subjects.

The top panel of Fig. 13 gives the percentages of these summed outlier scores for the control group subjects. For example, the largest bar in that panel represents the fact that 45% (68) control subjects had a summed outlier score of 0, and 19 (28%) had a summed outlier score of +1. The bottom panel in Fig. 13 gives a similar histogram for the 20 experimental subjects. All of the experimental children, except for DAC and TID, had one or more outlier scores.

Figure 13 summarizes a general result that is present in each of the previous figures 1–12. This figure shows that the children with focal lesions were markedly slower on the reaction time tasks than were the control children. Within the control group, there were 2 children who were so slow on the tasks that they were indistinguishable from the focal lesion children. However, the overwhelming majority of the 150 control children obtained no more than one low outlier score.

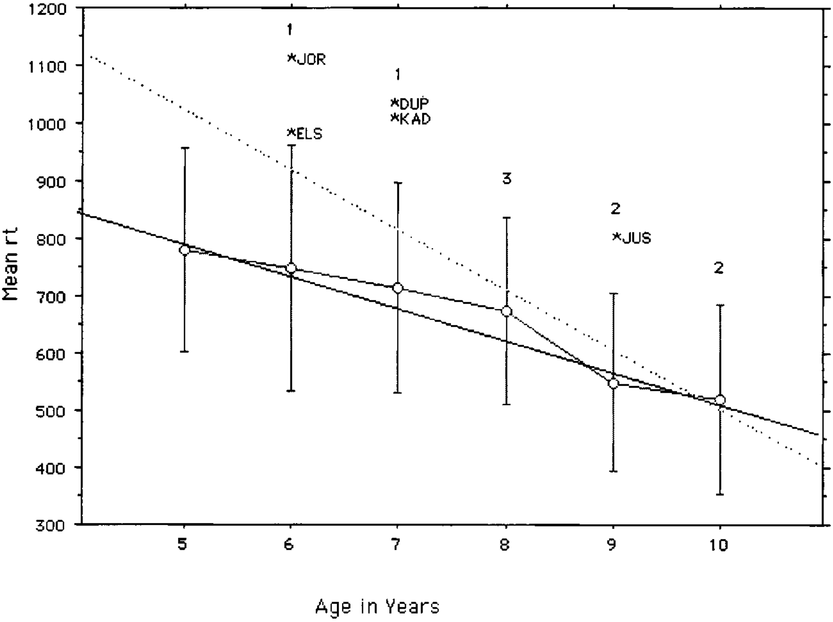

FIG. 4. Reaction times for auditory recognition from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (25% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (6% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of −55.24 and an r^2 of .401. The dotted line is the regression line for the experimental group with a slope of −92.86 and a r^2 of .65.

Classification of Profiles

In order to better understand the extent to which lesion type affects developmental outcome, we applied the MPD analysis framework of Valdés-Pérez and Pericliev (1997). This analysis takes as input a series of measures across a set of subjects who have been preclassified into groups. In this case, the groups were 1. L-PVH: Children with left focal lesions resulting from periventricular hemorrhage. The five subjects here were TID, DES, MAG, DUP, and BRAS. 2. L-CI: Children with left focal lesions resulting from cerebral infarct. The five subjects here were STEW, JOR, RYB, MAM, and JUS. 3. RIGHT: Children with right focal lesions or bilateral lesions. The three subjects here were KAD, JOD, and EMF. 4. HYD: Children with hydrocephalus. The two subjects here were DAC and WIG. 5. MIN: Children with minimal damage. The three subjects here were NIM, MIB, and MID. 6. Control: Age-matched control children. Data from all 150 control children are included in this group.

For each child, the data included in the model were age group-referenced

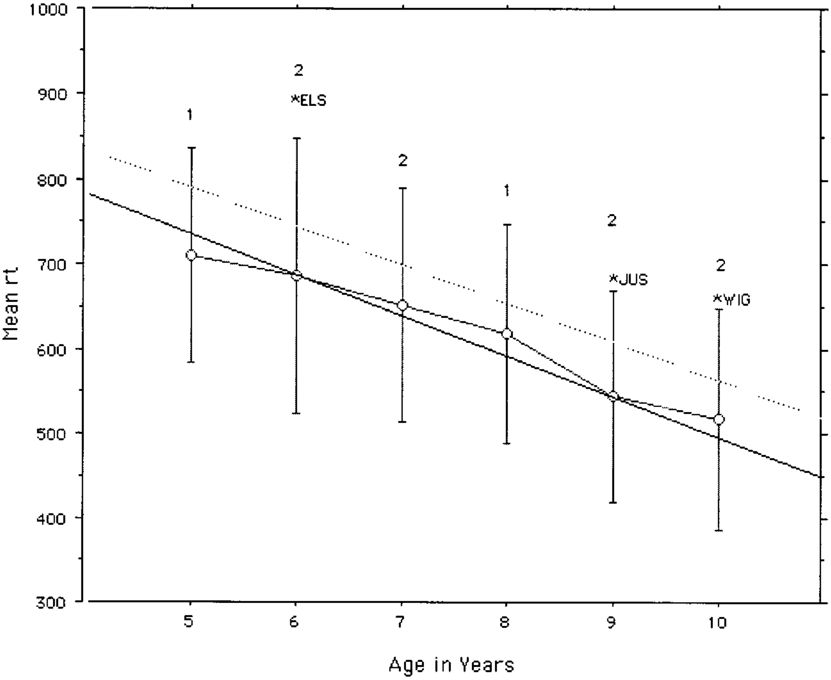

FIG. 5. Reaction times for word recognition from age 5 to age 10. Circles indicate control group means with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (15% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (7% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group with a slope of −40.166 and an r^2 of .379. The dotted line is the regression line for the experimental group with a slope of −36.366 and a r^2 of .459.

z-scores for the 12 experimental measures and for five standardized tests (PPVT, CELF-OS, CELF-RS, CELF-FS, and Leiter). Because of its restricted age range, the CELF-LC was not included. All scores were continuous numeric variables, although the MPD procedure can also handle Boolean variables.

The MPD procedure works iteratively to extract the smallest feature set that contrasts all cases in the data. Because naturalistic data typically has some class overlap, MPD form clear contrasts by excluding a certain amount of data in the area of overlap between the classes. In the current solution, 38% of the data in the area of overlap was excluded in order to get a perfect class separation. This level of exclusion is typical for naturalistic data. Monte Carlo tests show that one has to go up to an exclusion of 78% of the data in order to distinguish classes that are randomly sampled from the same distribution. On the other hand, if groups were completely non-overlapping in their performance, there would be no need for data exclusion. Thus, the

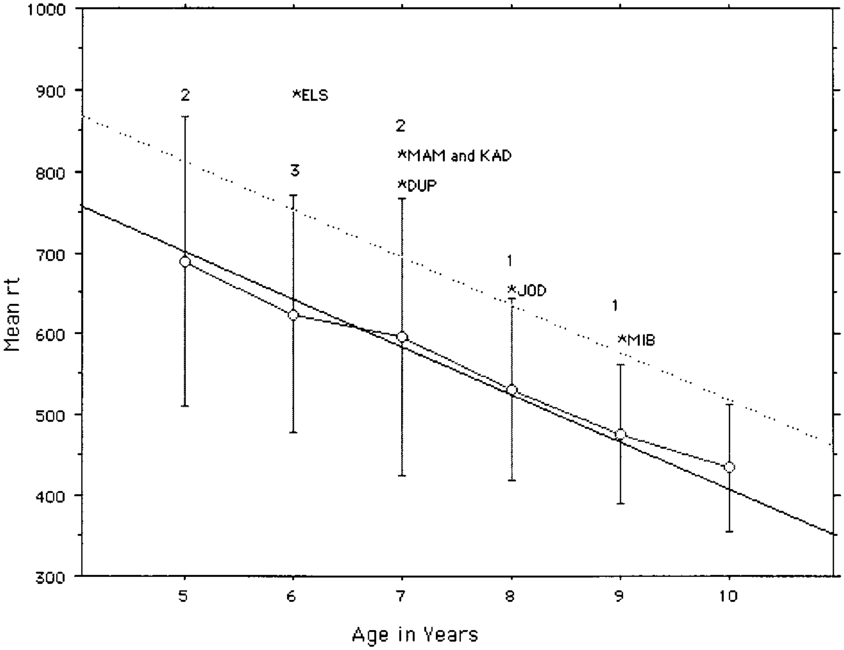

FIG. 6. Reaction times for visual choice from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (30% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (6% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of −49.827 and an r^2 of .487. The dotted line is the regression line for the experimental group, with a slope of −50.742 and a r^2 of .387.

exclusion level for this particular data set lies halfway between perfect discrimination and the classification of random data. The MPD procedure is also capable of working with conjunctions of features, but that mode was not utilized for this analysis.

We wanted the analysis to include scores from both the reaction time measures and the five standardized tests (Leiter, PPVT, CELF-OD, CELF-FS, and CELF-RS). To do this, we assigned scores on the standardized tests to the control children by using the mean and standard deviation appropriate for each test. For the Leiter and the PPVT the mean was 100 and the standard deviation was 15. For the three CELF measures, the mean was 10 and the standard deviation was 3. The goal here was simply to guarantee that the overall distribution of test scores for the control group was distributed normally about the normal mean. Because the MPD analysis did not look at combinations of features within children, there was no need to worry about exactly which control children received which normalized scores.

The optimal MPD solution used three test scores to discriminate the six

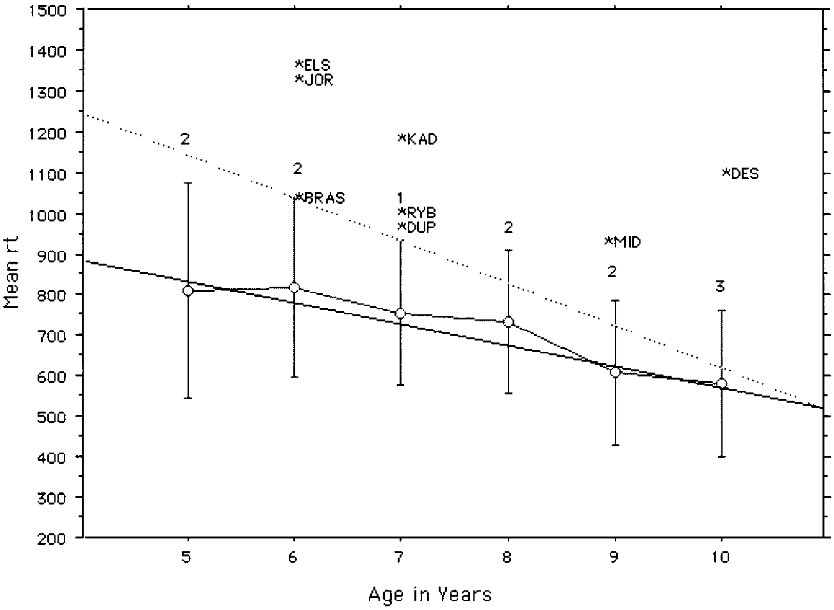

FIG. 7. Reaction times for auditory choice from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (40% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (8% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of -27.138 and an r^2 of .46. The dotted line is the regression line for the experimental group, with a slope of -52.563 and a r^2 of .297.

classes. These were the scores on Word Repetition, Visual Naming, and the CELF-OD. It is interesting that only one of the five standardized tests was included in the three most distinctive measures. Also, the offline digit span measure was not as powerfully distinctive as the two reaction time naming measures. This finding shows that the two reaction time measures of number naming did a good job of tapping into skills that separate the clinical types from each other and from the control group.

Table 3 displays how the three measures worked to distinguish each group from the other five. The first column of this table lists the six target subject groups. For each target group, the MPD analysis delineates comparisons with the other five groups in terms of the three measures in the optimal MPD analysis. Column 2 gives the measures when these comparisons point to strengths for the target group. Column 5 gives the measures when these comparisons point to weaknesses for the target group. Columns 3, 4, 6, and 7 give the details of these comparisons and the percentage overlap in the MPD comparisons.

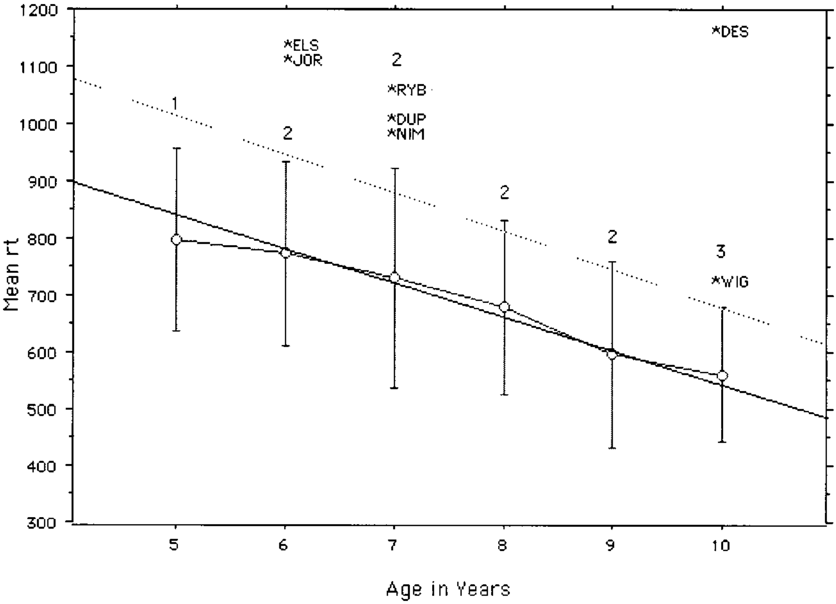

FIG. 8. Reaction times for word choice from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (35% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (8% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of -52.174 and an r^2 of .318. The dotted line is the regression line for the experimental group, with a slope of -90.934 and a r^2 of .324.

The Word Repetition and Visual Number Naming tasks were the measures that provided the clearest distinctions between groups. However, for those cases that could not be distinguished using these two measures, the CELF-OD provided useful additional information to distinguish groups. Additional analyses showed that the Word Choice and Visual Recognition measures were also close to the CELF-OD in terms of their ability to distinguish groups. However, the three-feature set of Word Repetition, Visual Number Naming, and the CELF-OD provides the most parsimonious solution at the 38% overlap tolerance level.

Across these three measures, the MIN and Control groups were the two that included the best performers. The other four groups showed a pattern of strengths combined with weaknesses. Of these, the HYD group stood out as having an extreme strength on the Visual Naming measure and an extreme weakness on the Word Repetition measure. However, since there were only two children in this group, these comparisons may be a result of individual differences, rather than group characteristics.

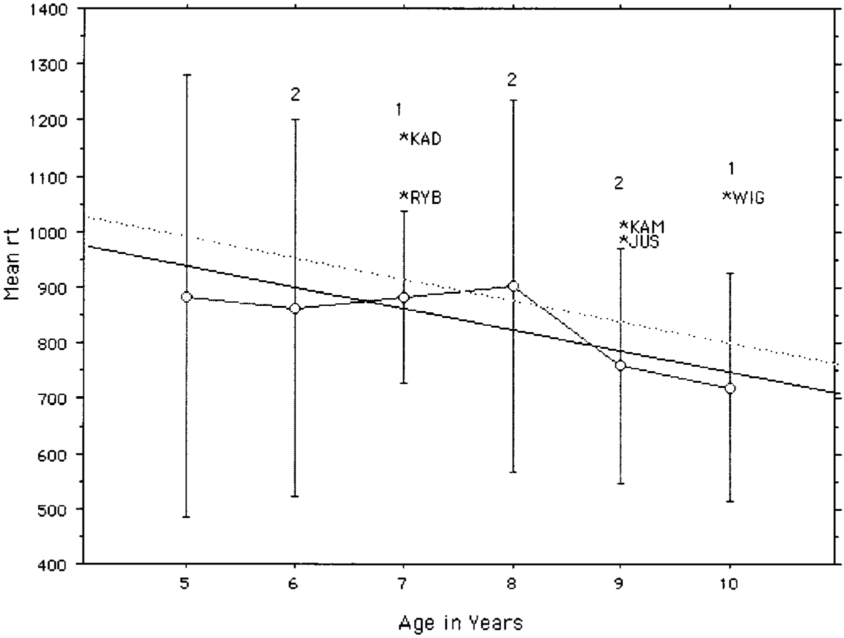

FIG. 9. Reaction times for word repetition from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (25% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (5% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of -34.85 and an r^2 of .091. The dotted line is the regression line for the experimental group, with a slope of -38.89 and a r^2 of .108.

In this analysis, the MIN group appeared similar to the control group. However, an examination of Figs. 1–11 shows that there were eight cases in which the three children in this group obtained low outlier scores on the reaction time tests. This is an outlier score rate of 22.2% (8 of 36 tests) for this group. The outlier score rate for the control group is 7.1% (128 of 1800 tests). The fact that the outlier score rate for this group is still almost three times the rate for the control group suggests that these children with minimal observable lesions on an MRI scan still have a few selective, minimal processing problems.

Once these three groups were distinguished, the task of distinguishing between L-CI, L-PVH, and RIGHT was more difficult. The CELF-OD was useful in distinguishing RIGHT from the two other groups, since the RIGHT group did better on this measure of storing, elaborating, and following oral directions. The Word Repetition task was particularly important in distinguishing L-CI from L-PVH, with the L-PVH children doing better on this task.

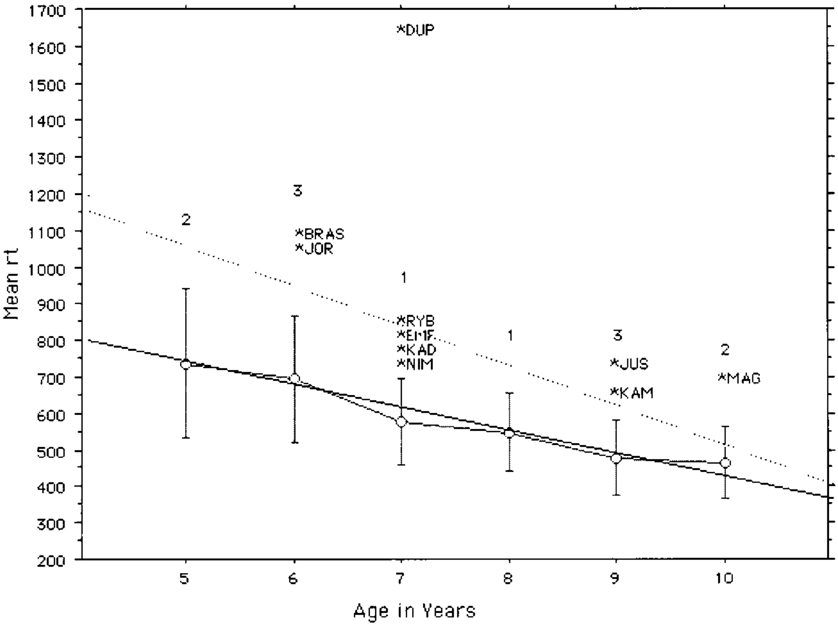

FIG. 10. Reaction times for visual number naming from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (50% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (8% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of -58.649 and an r^2 of .55. The dotted line is the regression line for the experimental group, with a slope of -91.982 and a r^2 of .311.

Lesion Size and Laterality Analyses

The last column of data in Table 1 gives the L/R ratio scores for the 20 experimental children. We found no clear impact of left hemisphere lesion size, as quantified by these L/R ratio scores on performance for our online measures. In fact, the only measure that provided reliable separation between groups in terms of lesion laterality was a contrast between the children with left lesions (L-CI and L-PVH) with the other three groups (R, HYD, MIN) for the CELF-RS (repeating sentences). As noted earlier, an unpaired t test comparison between these two groups was significant at the $p < .01$ level. The mean CELF-RS score for the 14 children with left hemisphere lesions was 6.786, whereas the mean for the other 8 children was 10.375.

DISCUSSION

This study addressed three basic questions about the nature of language learning and language performance in 20 school-aged children who had incurred a focal neurological injury prior to the second month of infancy. 1.

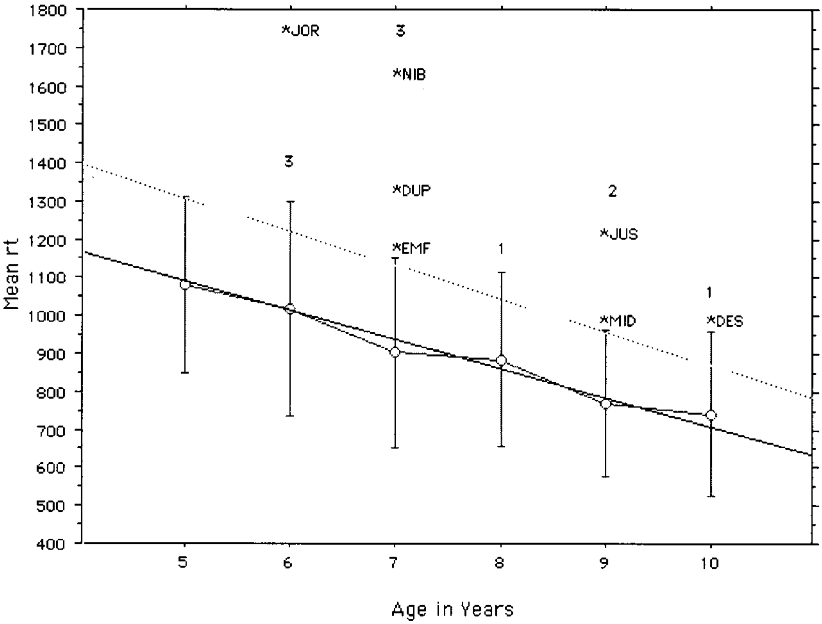

FIG. 11. Reaction times for picture naming from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (35% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (7% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of -69.719 and an r^2 of .378. The dotted line is the regression line for the experimental group, with a slope of -87.238 and a r^2 of .248.

What is the overall level of competence that these children show in comparison to children with no apparent brain injuries? 2. Do these children demonstrate relative strengths and deficits for particular language processing skills? 3. Is there a demonstrable relation between particular language deficits and damage to particular cortical areas? The performance of the 20 experimental subjects was compared to that of age-matched peers using a set of online measures of language processing. The results provided evidence relevant to each of these questions.

To address the first question, we examined the performance of the children with focal lesions on standardized, offline measures of nonverbal intelligence (Leiter) and receptive language (PPVT). On these tests, the experimental subjects as a group performed within the normal range. Only five children had scores on these tests that were more than 1 SD below the mean. MAG and WIG scored below the normal range on the Leiter, but did well on the PPVT. STEW and MID, on the other hand, scored low on the PPVT, but did well on the Leiter. Only DES scored below normal on both tests. This

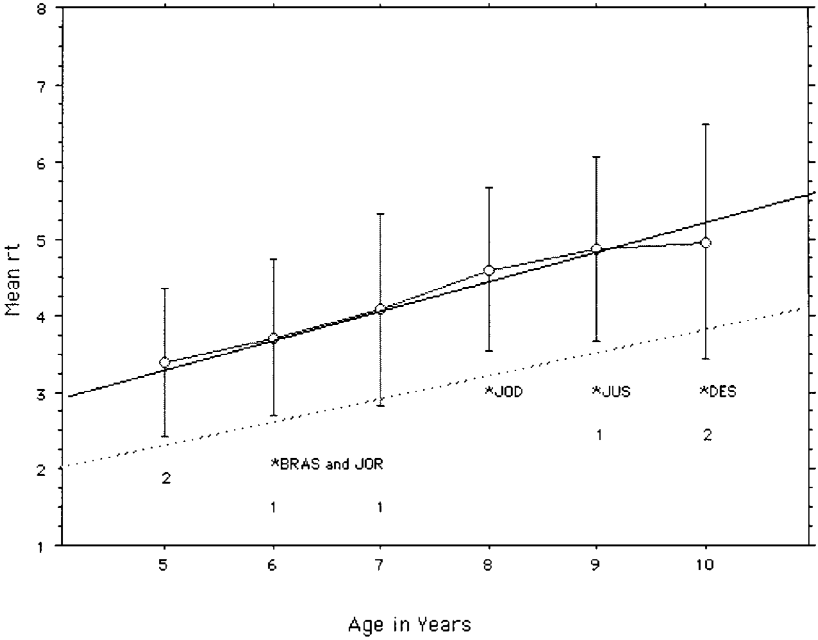

FIG. 12. Mean digit spans from age 5 to age 10. Circles indicate control group means, with bars for 90% confidence intervals. Experimental group subjects with scores above the 90% confidence interval (25% of the total group) are given with asterisks. Numbers above the confidence bars indicate the control group subjects (4% of the total group) at each age who fell above the 90% confidence interval. The solid line is the regression line for the control group, with a slope of +0.333 and anr^2 of .359. The dotted line is the regression line for the experimental group, with a slope of +0.296 and a r^2 of .332.

indicates that, except for DES, there is no evidence in these children of any global cognitive problem.

To address the second question, we used both online and offline measures of language processing. Although there was no evidence for any major overall cognitive deficit in these children, there was strong evidence of deficits in both offline and online language processing. On the four subtests of the CELF that measure offline language processing, all of the experimental subjects, except for TID and EMF, showed subnormal performance. This provides evidence that, despite overall normal cognitive abilities, these children have some problems with language functioning.

We used 11 online measures to examine language processing. The results from these studies indicated that children with focal lesions have deficits in online language processing. Although the children with focal lesions always scored within the normal range on most of the measures, it was also the case that the children who had two or more markedly low scores (Fig. 13) were always children with brain injury, rather than any of the 150 control subjects.

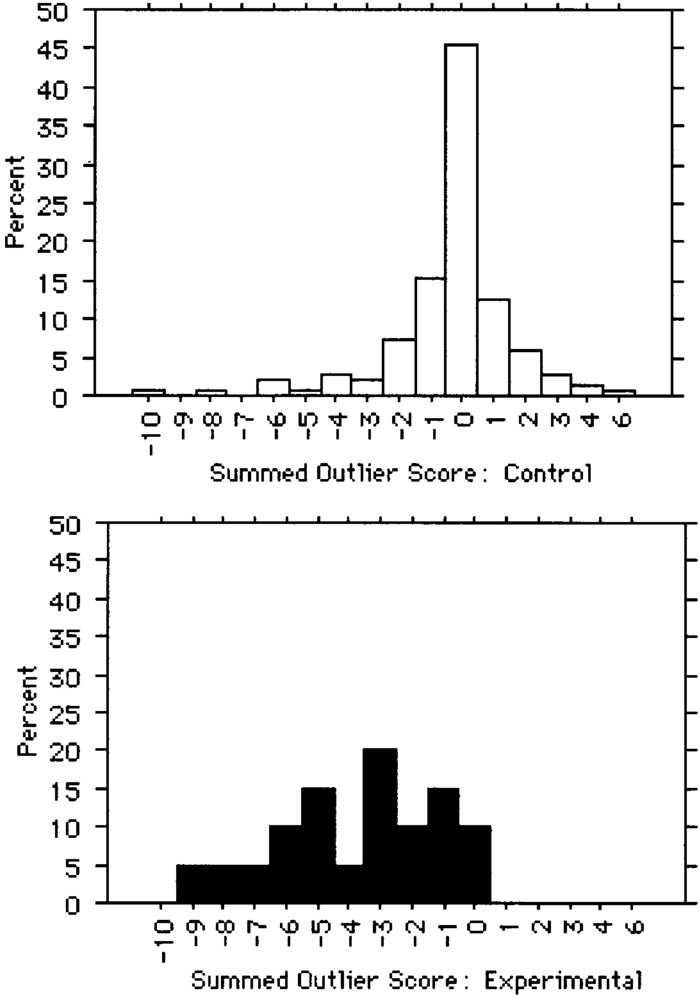

FIG. 13. Percentages of children in each group with a particular summer outlier score. Top is the control group. Bottom is the experimental group.

Moreover, when we applied the MPD technique to group children into classes, we found that two online measures—Word Repetition and Visual Naming—were sufficient to capture most of the distinction among the six groups. The fact that these two online measures were even better than the standardized measures at the group discrimination task suggests that it would be profitable to devote further attention to online measures as a way of studying language deficits in children with focal lesions.

Further evidence of the sensitivity of the online measures came from the four children in the MIN group. These children had been diagnosed at birth

TABLE 3

Results of the MDP Analysis, Listing Relative Strengths and Weaknesses on the Three Critical Indicators (Visual Naming, Word Repetition, and CELF-OD) of Each Target Group in Relation to the Comparison Groups with Percentage of Overlap between Groups on Each Measure

Target group	Strength	Comparison group	Percentage of overlap	Weakness	Comparison group	Percentage of overlap
Control	Visual Naming	MIN	35			
		L-PVH	31			
		RIGHT	21			
	CELF-OD	L-CI	29			
		L-PVH	27			
		HYD	19			
		MIN	10			
MIN	Word Repetition	Right	33			
		Control	29			
		L-PVH	25			
		HYD	00			
RIGHT	CELF-OD	HYD	33	Visual Naming	MIN	33
		MIN	33		Control	21
		L-CI	33		HYD	0
		L-PVH	25			
L-CI	Word Repetition	HYD	0	CELF-OD	RIGHT	33
					Control	33
				Word Repetition	L-PVH	39
					MIN	14
L-PVH				CELF-OD	HYD	25
					MIN	25
					RIGHT	25
					Control	20
	Word Repetition	L-CI	39	Word Repetition	MIN	25
		HYD	0			
HYD	Visual Naming	L-PVH	20	Word Repetition	RIGHT	33
		L-CI	20		Control	1
		Control	1		MIN	0
		MIN	0		L-PVH	0
		Right	0		L-CI	0

as having brain lesions, but showed no evidence of lesions on MRI scans in mid childhood. Although these four children scored in the normal range on the offline measures, they demonstrated a level of outlier scores on the reaction time tasks that was well above that for the control group. This suggests that, although their brain has largely recovered from the early injury, the process of recovery and reorganization may have left some suboptimal patterns of connectivity.

The children with focal lesions did not suffer from any general problem with rapid responding using the button box assembly. In fact, for the Auditory Detection task, which included the most basic motoric and attentional operations involved detection and response, nearly all of the children with brain injury performed in the normal range. Second, it is important to note that most of the online tasks showed an extremely lawful increase in reaction speed with age. This was also true for the digit span measure. The reaction times of the experimental subjects improved as a function of age, as did the reaction times of the control subjects. We found that the regression lines for the experimental subjects were steeper than the regression line for controls in all but two tasks—word recognition and digit span. In other words, as experimental subjects get older, their performance improves relative to the control subjects. This is fairly clear evidence for developmental catch-up and evidence against late rigidity or critical periods for these basic level skills, although we would need to follow these children to older ages to determine if the reaction times fully converge.

The final issue addressed in this work was whether there was a demonstrable relation between damage to particular cortical areas and performance on specific offline or online measures. Although we did find a relation between left hemisphere damage and weak performance on the CELF-RS, there was little overall relation between specific tasks and specific sites. There were some suggestive relations between site and specific tests in the L-CI group. For example, RYB's low scores on the CELF seem to stem from frontal involvement in sentence planning. Or KAM's outlier score on Auditory Detection seems to reflect problems with a temporal lobe lesion to auditory processing areas. Although these relations were suggestive, they were not striking. Using fMRI methodology with these same children, we have been able to discern closer relations between lesion site and language processing, which we have reported elsewhere (Booth et al., 1999). In this sense, the reaction time methodology tends to diagnose problems with language integration without specifying in detail the anatomic localization of specific subcomponents of functional neural networks.

Summarizing these findings, we can say that children with focal lesions have remarkable success in acquiring a solid, functional use of language. This successful acquisition of language functioning is not purchased at the expense of any overall deficit in cognitive processing. However, underneath this functional surface, there appear to be some residual processing deficits. We hypothesize that these deficits result from suboptimal reorganization of neural tissue subsequent to brain injury. However, over time, these initial suboptimalities are further minimized in comparison with normals, as children gain continual practice with rapid language processing.

The study of language organization in children with focal lesions is currently undergoing rapid advances, as we begin to apply new techniques in both imaging and online processing methodologies. In this paper, we have shown how it is possible to study a relatively small and diverse group of children using these new methods. By comparing these children to a larger set of age-matched control children we have derived a fairly accurate measure of their language processing abilities. In fact, the measures we developed were better than standardized measures in terms of their ability to distinguish between subgroups.

These initial results should not be interpreted as denying the potential importance of lesion site and type. There are fundamental differences in the underlying etiologies of cerebral infarct, hydrocephalus, and periventricular leukomalacia. As we learn more about the details of brain organization, and as we refine our online measures, we will begin to understand how marked differences in the brain organizations of these three groups can lead to differential patterns of deficits and successes during online language processing.

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