

The Neurobiology of Sensory and Language Processing in Language-Impaired Children

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Abstract

■ Clinical, behavioral, and neurophysiological studies of developmental language impairment (LI), including reading disability (RD), have variously emphasized different factors that may contribute to this disorder. These include abnormal sensory processing within both the auditory and visual modalities and deficits in linguistic skills and in general cognitive abilities. In this study we employed the event-related brain potential (ERP) technique in a series of studies to probe and compare different aspects of functioning within the same sample of LI/RD children. Within the group multiple aspects of processing were affected, but heterogeneously across the sample. ERP components linked to processing within the superior temporal gyrus were abnormal in a subset of children that displayed

abnormal performance on an auditory temporal discrimination task. An early component of the visual ERP was reduced in amplitude in the group as a whole. The relevance of this effect to current conceptions of substreams within the visual system is discussed. During a sentence processing task abnormal hemispheric specialization was observed in a subset of children who scored poorly on tests of grammar. By contrast the group as a whole displayed abnormally large responses to words requiring contextual integration. The results imply that multiple factors can contribute to the profile of language impairment and that different and specific deficits occur heterogeneously across populations of LI/RD children. ■

INTRODUCTION

Current formulations of the underlying deficits characteristic of language-impaired (LI) and reading-disabled (RD) children differ in the relative emphasis they place on the linguistic versus sensory/cognitive mechanisms presumed to be necessary for normal language development. For example, recent reviews have variously proposed major deficits in (1) the ability to integrate rapidly presented nonlanguage auditory stimuli (Tallal, 1987), (2) the functions of the transient visual system (Lovegrove, 1991; Lovegrove, Martin, & Slaghuis, 1986; Lovegrove, Garzia, & Nicholson, 1990), (3) specific deficits in syntactic processing (Byrne, 1981), and (4) deficits in verbal short-term memory (Shankweiler & Crain, 1986). However, most studies have not compared these different aspects of processing within a single sample of children. Similarly, the few electrophysiological studies of LI or RD children have tended to focus on a specific aspect of processing, within a single sensory modality (e.g., Mason

& Mellor, 1984; Holcomb, 1986; Harter, Anllo-Vento, Wood, & Schroeder, 1988a; Harter, Diering, & Wood, 1988b; Solan, Sutija, Ficarra, & Wurst, 1990). Thus there is very little behavioral or neurobiological evidence pertinent to the issue of whether the several deficits that LI/RD children have been reported to display arise from a single underlying impairment, or even whether they tend to co-occur. What is needed are behavioral and neurobiological studies of language and nonlanguage processing in the same subjects. These data would also provide evidence on longstanding issues such as the relation between language and nonlanguage skills in neurobehavioral development.

In this endeavor it would be advantageous to investigate the timing and organization of neurophysiological processes within and between the hemispheres while normal and impaired children process sensory, cognitive, and language information. Recording of event-related brain potentials, or ERPs, from the scalp is one of few currently available approaches to the study of the neural

events associated with information processing in healthy human subjects (see Callaway, Tueting, & Koslow, 1978; Hillyard & Kutas, 1983; Hillyard & Picton, 1987; Regan, 1989 for reviews). The power of ERPs lies in that they provide information about the sequence, timing, and, in some cases, the location of neural activity elicited by particular stimuli well before subjects produce an overt response. This approach bypasses some of the limitations associated with behavioral measures, which may reflect relatively late, response-related aspects of processing. From recent reviews of the contributions that ERP studies have made to the understanding of sensory, cognitive, and language processes it is evident that the utility of this technique is greatest when used in conjunction with behavioral measures so that the interpretation of behavioral and neurophysiological data constrain each other.

Recent studies report reliable ERP indices of hemispheric specialization, and of specific and different aspects of language processing (Hillyard & Kutas, 1983; Rugg, 1984; Holcomb, 1988; Holcomb & Neville, 1990, 1991; Neville, Kutas, Chesney, & Schmidt, 1986; Neville, Nicol, Barss, Forster, and Garrett, 1991; Neville, Mills, & Lawson, 1992; Osterhout & Holcomb, 1992; Van Petten & Kutas, 1987). For example, it has been shown that semantic manipulations, such as presenting a target word following an appropriate context versus an inappropriate context or less constraining context modulates the amplitude of the N400 component—N400s are larger to words after an inappropriate or less constraining context. The N400, which typically has a peak latency near 400 msec poststimulus-onset, has a broad scalp distribution, but is usually largest at more posterior sites. Syntactic manipulations, on the other hand, have been shown to affect a number of different ERP components, several of which have a distinctly different time course, scalp distribution, and polarity from the N400 (Neville et al., 1991; Osterhout and Holcomb, 1992). A recent study reports that distinct ERP components are elicited by open and closed class words in normal adults, and that these display different sensitivities to altered early language experience (Neville et al., 1992).

A few recent studies have examined developmental changes in language-sensitive ERPs across the childhood years. Holcomb, Coffey, and Neville (1992) studied subjects aged 5–26 years as they listened to and read (7–26 years) sentences that ended either with an appropriate and highly expected or a semantically inappropriate word. ERPs to sentence final words displayed effects of contextual priming in both modalities in all age groups. Both the early and the late ERP components displayed large decreases in amplitude and latency with age. These changes necessitated normalization procedures so that overall changes in amplitude with age could be assessed separately from changes in the amplitude of the differences between semantically appropriate and anomalous words. A central result was that there were significant reductions in the semantic priming effects with age. The

results suggest that as children acquire better language skills they rely less on semantic context for language comprehension.

ERPs and Developmental Disorders

A number of studies have used ERPs to study children with various reading and language disabilities. Most of these have compared the disabled children to an age-matched cohort of developmentally "normal" children. However, among studies that have examined earlier sensory processes there has been a lack of consistency of findings. For example, Mason and Mellor (1984) recorded brainstem, middle latency, and cortical ERPs to auditory stimuli in LI, motor speech-impaired (MSI), and normal control children. Although they reported that the amplitude of certain brainstem responses were reduced in LI and MSI children they did not find significant differences between the groups in the latencies of these components (the typical measures reported for brainstem potentials) or in the amplitudes or latencies of middle latency components. However, the LI children displayed early cortical sensory potentials (N1 and P2) that were larger over the left than the right hemisphere regardless of the ear of stimulation, while the controls revealed contralateral dominance for stimulation in both ears.

In studies using visual stimuli, Solan et al. (1990) reported smaller P100s in RD than control children using pattern reversal stimuli. May, Lovegrove, Martin, and Nelson (1991), using visual gratings of several frequencies, reported that poor readers had significantly lower amplitudes and significantly shorter latencies for components elicited by stimulus offsets when low spatial frequency stimuli were used.

A relatively large number of studies have focused on so-called cognitive deficits in RD children. Most of this work has involved comparing the amplitude and/or latency of the P300 ERP component of RD subjects to controls (e.g., Holcomb, Ackerman, & Dykman, 1985, 1986; Harter et al., 1988a,b; Taylor & Keenan, 1990). The typical finding has been smaller and/or later P300 responses from the clinical children. Two studies have departed from this norm. Holcomb et al. (1985) reported a dissociation of findings between RD and other types of clinical children. They found that while P300 amplitude to low-frequency target items differentiated controls and attention-deficit-disordered (ADD) children (controls > ADD), RD and control children were better differentiated by the amplitude of the P300 when nontarget word stimuli were contrasted with nonlinguistic symbols. Since symbols elicited larger P300s than words in RD children while the two kinds of stimuli elicited equivalent amplitudes in controls, the results were interpreted as displaying a selective deficit in the RDs when processing word stimuli.

Studies by Harter et al. (1988a,b) also reported a some-

what different pattern of effects. They found that RD boys produced a larger occipital-central N1 component to selectively attended lateral visual stimuli than did normal controls. They concluded that RD children, while deficient in their ability to select a target stimulus (as indexed by smaller P300 components), nevertheless had enhanced spatial attention abilities.

The Current Study

Recent studies utilizing sensory and language tasks in the study of different populations (congenitally deaf adults and hearing offspring of deaf adults) have provided evidence that altered early sensory and language experience can have marked and specific effects on human brain development (Neville et al., 1992; Neville, 1990). Results from these studies suggest that aspects of semantic and grammatical processing are mediated by different neural systems in normal adults and that the acquisition of the grammar of a language is a major determinant in stabilizing a specialized role for the left hemisphere in mediating that language. Additionally, data from these studies suggest that the development of grammatical skills and related brain systems is more sensitive to and dependent on early language experience than is the development of aspects of semantic processing. Therefore, in the current study we employed a paradigm similar to the one in those studies to test specific hypotheses about the organization of language-relevant brain systems in both normal and language-impaired children. Subjects read a series of sentences ending with either an appropriate or anomalous final word and ERPs were recorded to each word in the sentences. This task permitted both the examination of the effects of context on the N400 to sentence final words and the comparison of ERPs to different categories of words (open and closed class) within sentences.

We also employed nonlanguage auditory and visual paradigms utilized in previous research with normal and neurologically impaired adults (Neville, Schmidt, & Kutas, 1983; Knight, Hillyard, Woods, & Neville, 1980) in order to study the development of simple sensory processing in normal and LI/RD children. In particular we assessed the effects of rate of stimulus presentation (200, 1000, and 2000 msec interstimulus intervals—ISI) on the amplitude and latency of the early (100–200 msec) modality-specific sensory ERP components. In both visual and auditory sessions subjects were presented with stimuli at left, right, or central locations. Their task was to detect occasional target events (10%) interspersed among more frequent (90%) standard events. In normal adults the amplitudes of such components are reduced as the stimulus repetition rate is increased. This variation in responsiveness with ISI, known as the relative refractory period or recovery cycle, has been regarded as a measure of the excitability of cortical neurons under

stimulation and may reflect the rate of sensory processing in different cortical areas (Gastaut, Gastaut, Roger, Corriol, & Naquet, 1951). The distribution and recovery cycles of the N1 and P2 components are different for central and peripheral visual stimuli and the systems that mediate these responses to peripheral visual stimuli are more vulnerable to altered early experience (Neville et al., 1983). It has also been reported that lesions to the temporoparietal junction severely diminish these responses to auditory stimulation (Knight et al., 1980).

The subjects in this study were a group of children who were identified as language impaired (LI) when they were 4 years of age and who have been followed since that time both as part of the San Diego Longitudinal Study of the Outcomes of Early Language Impairments (Tallal & Curtiss, 1979–1988) and under the Center for Neurodevelopmental Studies (NIH Center Grant 1985–1996). These children displayed both expressive and receptive language problems as described in Methods. At the time of ERP testing these children were 9 years of age and were also reading disabled (RD) (Tallal, 1987). While most investigators typically study either LI subjects or RD subjects, considerable evidence suggests that most (i.e., above 85%) LI children become RD children, and many RD children had delayed early language development (Tallal, 1987; Stark, Bernstein, Condino, Bender, Tallal, & Catts, 1984). In fact the report of the Interagency Committee on Learning Disabilities to the U.S. Congress (Tallal, 1987) suggested that to continue to separately classify these disorders, which may primarily be distinguished by the age of the diagnosis of the child, may ultimately impede progress toward their eventual treatment and prevention.

RESULTS

Data Analysis

Mixed design analyses of variance (ANOVAs—BMDP2V) were used to analyze all measures (see below). Repeated measures factors included Electrode Site (Frontal vs. Anterior Temporal vs. Temporal vs. Parietal vs. Occipital) and Hemisphere (Right vs. Left) for all analyses. Analyses of the standards in the mapping task data included ISI (short vs. medium vs. long) and location (left vs. center vs. right) variables. ANOVAs on target data included either location or ISI. However, perhaps in part due to poor signal-to-noise ratio, there were no significant group effects for the target ERPs so these are not reported in the Results. In the sentence task the final word analyses included a Sentence Type variable (Appropriate vs. Anomalous Completions) and the middle word analyses included a Word Class variable (Open vs. Closed). The correction recommended by Geisser and Greenhouse (1959) was applied to all repeated measures variables with more than two levels (reported as corrected *p* values). There were also between-subject factors in the

analyses. In some analyses Clinical Group (LI vs. Cls) was included. In other analyses subjects within a group were separated based on their scores on a behavioral test (median split). These included subgroups formed based upon scores on the Tallal Repetition test ("low" rep group score 15 and less, "high" rep group score > 15) and another subgrouping based on the syntax scores (low syntax < 3, high syntax ≥ 3). For all between-subject ANOVAs the standard parametric model for analysis of unequal *n* designs was used (Herr, 1986) when necessary. For the auditory recovery cycle data the ERPs were quantified by taking the latency, peak amplitude, and mean area within 50–200, 200–350, and 350–600 msec. For the visual paradigm the windows were, for the occipital sites 100–200, 150–300, and 300–400 msec, and for sites anterior to the occiput, 50–250 and 150–350 msec.

In the sentence task the ERPs to the middle and final words were quantified in several ways. First, the peak latency and amplitude of the P100 (100–200 msec, occipital sites only), N100 (50–250 msec, except 150–350 msec occipital sites), and P200 (150–350 msec, except 250–400 msec occipital sites, visual ERPs) components were measured using a standard computer algorithm (i.e., the largest value in a latency window relative to the average of the preword baseline).

Second, the average amplitudes between 350 and 700 msec and between 280 and 700 msec were calculated (relative to the average prestimulus baseline).

Finally, to better isolate the effects of priming, "difference waves" were computed by subtracting the final word ERPs in the Best Completion sentences from those in the Anomalous Completion sentences. The peak latency of the N400 (200–1200 msec window) was calculated from the difference waves. Also the mean amplitudes between 300 and 600 and between 600 and 900 msec were computed.

Auditory Recovery Cycle

LIs vs. Controls

Behavior. The LI children were less accurate [$F(1,31) = 8.7, p < 0.006$] and slower [$F(1,31) = 10.4, p < 0.002$] than the control children in deciding whether a tone was or was not a target (see Table 1). These results did not vary as a function of prior ISI.

ERPs to Standards. The ERPs to the standard tones were of similar latency and morphology in the LI and control groups (see Fig. 1) and were characterized by a negative peak around 140 msec (N140) followed by additional negative peaks at about 260 msec (N260) and 440 msec (N440). Each of these peaks was largest from anterior temporal and frontal recording sites, and was absent or very small over occipital sites [electrode effect $F(4,108)$ $N140=54.0, N260=57.3, N440=28.1$, each $p < 0.0001$]. Each component displayed larger amplitudes following longer ISIs [ISI $F(2,54)$ $N140=39.3, N260=56.6, N440=116.3$, each $p < 0.0001$]. Both N140 and N260 were larger from over the hemisphere contralateral to the ear stimulated [side × hemisphere $F(2,54)$ $N140=55.7, N260=9.9$, both $p < 0.0003$]. Additionally, N260 latency was earlier from the contralateral hemisphere. However, N440 was larger from the left than the right hemisphere across all stimulus types [hemisphere $F(1,27) = 8.6, p < 0.006$]. The latencies, amplitudes, distributions, and recovery cycle of each of these components were not significantly different for the LI and control groups (all effects n.s.; see Fig. 1).

In view of the overall lack of differences in the auditory sensory ERP results between LI and control children, we subclassified subjects into two subgroups based on their behavioral performance on the rapid sequencing subtest of the Tallal Repetition Test, using a median split. LI subjects performing within the normal range (i.e., a score of 16–20) were classified as "high" rep while those scoring between 0 and 16 were classified as "low" rep. Since our hypothesis that LI children would show abnormal ERPs on the auditory recovery cycle was based on previous reports of auditory temporal processing deficits (see Tallal, Sainburg, & Jernigan, 1991), we reanalyzed the ERP data based on this classification. There was not enough variability of the normal subjects' scores to permit a correlation with ERPs.

High vs. Low Repetition Test

Behavior. As seen in Figure 2 both LI groups were less accurate than the control group in reporting the targets. However, only the low repetition LI group displayed an effect of ISI in responding to the targets: In these subjects the percent correctly detected targets was significantly lower at the shorter ISIs [group × ISI $F(2,38) = 4.1, p < 0.04$; group effect $F(1,19)$ short ISI = 5.5, $p < 0.03$,

Table 1. Auditory Recovery Cycle

	Correct (%)			Reaction Time (msec)		
	Short	Medium	Long	Short	Medium	Long
CL	98	97	100	614	620	621
LI	87	88	91	789	766	752

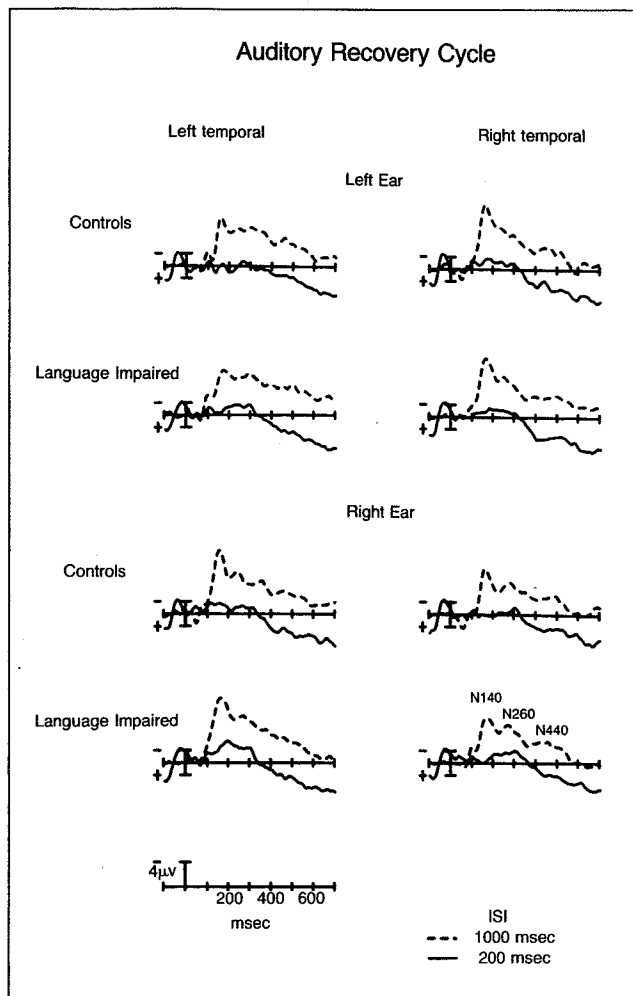


Figure 1. ERPs to standard tones recorded over left and right temporal regions following 200 or 1000 msec ISI, from language-impaired and control subjects.

medium ISI = 4.5, $p < 0.04$, long ISI n.s.]. There were no significant group differences in reaction times.

ERPs to Standards. As seen in Figure 3 the morphology of the ERP components was similar in the high and low repetition groups. However, each of the components was significantly reduced in the low compared to the high repetition group over anterior regions of the right, but not the left hemisphere [hemisphere \times electrode \times group $F(4,60)$ N140 = 6.4, $p < 0.006$; N260 = 2.8, $p < 0.07$; N440 = 6.4, $p < 0.002$; see Fig. 3 and Table 2]. This effect was equivalent for each stimulus location and each ISI for the N260 and N440 components (n.s. group interaction effects with location of stimulation or ISI). However, for N140 these group differences were only apparent following the shortest ISI [ISI \times hemisphere \times group $F(2,30)$ = 3.3, $p < 0.06$; at 200 msec ISI, hemisphere \times group $F(1,15)$ = 8.1, $p < 0.01$: N140 right hemisphere low repetition = $-3.1 \mu\text{V}$, high repetition = $-4.4 \mu\text{V}$; left hemisphere low repetition = $-4.5 \mu\text{V}$,

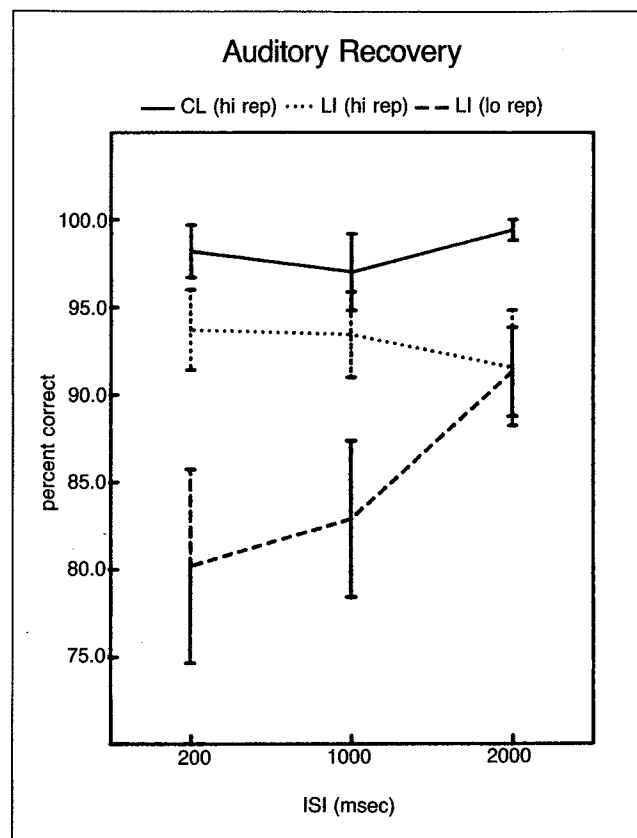


Figure 2. Percent correctly detected targets on the Auditory Recovery Cycle Task in control subjects and in language-impaired subjects who scored high and low on the repetition task.

high repetition = $-4.2 \mu\text{V}$]. In addition, the latency of the N140 component was significantly delayed in the low repetition group [group $F(1,15)$ = 9.1, $p < 0.008$] especially over temporal and parietal regions of the left hemisphere [hemisphere \times electrode \times group $F(4,60)$ = 3.1, $p < 0.05$; see Table 3].

Visual Recovery Cycle

LIs and Controls

Behavior. As seen in Table 4 LIs and controls did not differ significantly in the speed or accuracy of responding to targets.

ERPs to Standards: Occipital Sites. As seen in Figure 4 the stimuli elicited ERPs of similar morphology in LI and control subjects. Over occipital regions the response was characterized by a positivity around 150 msec (P150), a negativity around 230 msec (N230), and a positivity around 350 msec (P350). For all subjects the P150 elicited by central stimuli was larger than that elicited by peripheral stimuli [side $F(2,56)$ = 27.0, $p < 0.0001$]. Both groups displayed larger P150 amplitudes following longer than shorter ISIs [ISI $F(2,56)$ = 30.0, $p < 0.0001$], and in each

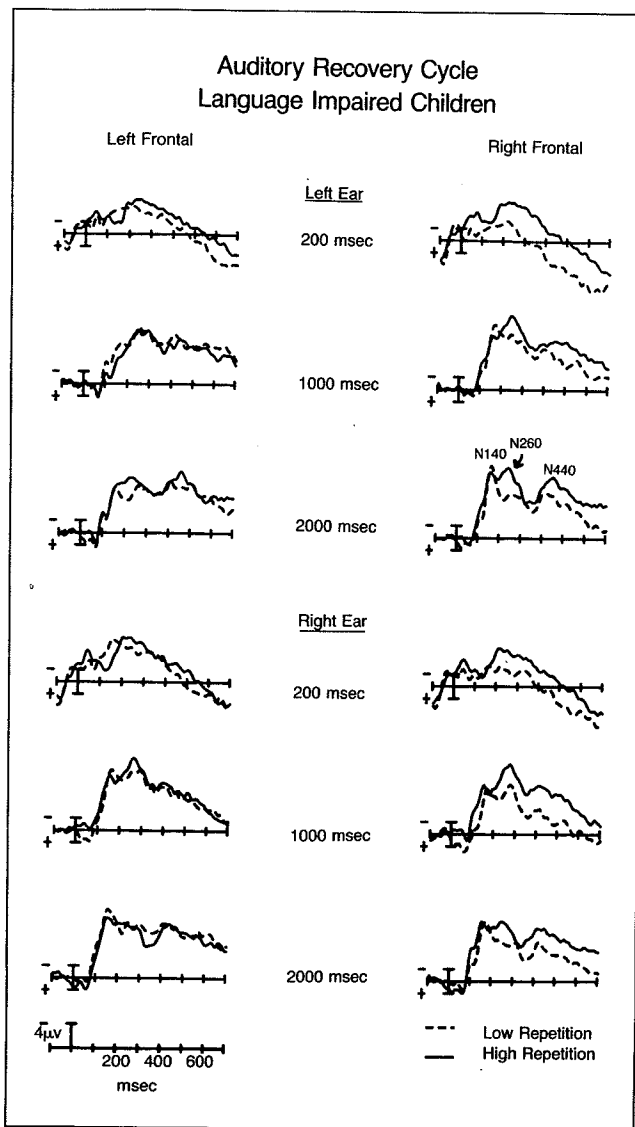


Figure 3. ERPs to standard tones recorded over left and right frontal regions from LI children who performed poorly (low repetition) and within normal limits (high repetition) on the Repetition Task.

group P150 was larger over the hemisphere contralateral to the eliciting stimulus [side \times hemisphere $F(2,56) = 16.1, p < 0.0001$] and was of longer latency following the shortest ISI [ISI $F(2,56) = 3.6, p < 0.04$]. The N230 also was later following shorter ISIs [ISI $F(2,56) = 3.5, p < 0.04$] and its amplitude tended to be contralateral [side \times hemisphere $F(2,56) = 2.8, p < 0.07$]. P350 amplitude was larger with increasing ISI [ISI $F(2,56) = 15.9, p < 0.0001$] and displayed a contralateral distribution [side \times hemisphere $F(2,56) = 8.9, p < 0.0007$].

GROUP EFFECTS. All mean latency and amplitude values for the two groups are presented in Tables 5 and 6. P150 latency did not differ in the two groups. However, P150 amplitude was significantly smaller in the LI than the control children [mean μV LI = 3.8, Control 5.7; group

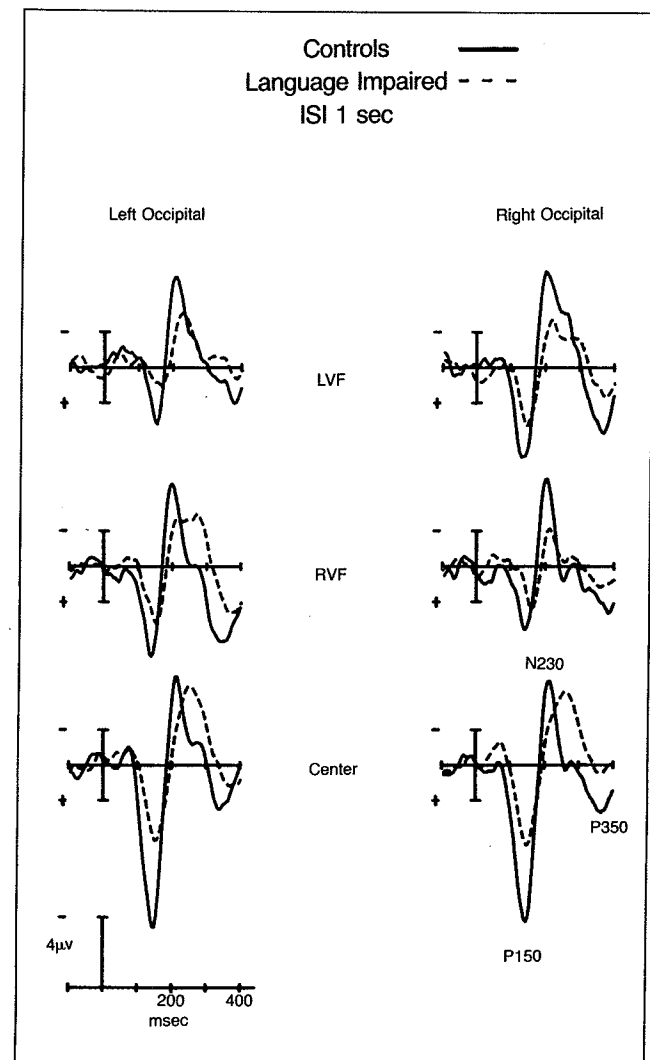


Figure 4. ERPs to standard visual stimuli in the visual recovery cycle paradigm. Recordings from over left and right occipital regions from control and language-impaired subjects.

$F(1,28) = 7.8, p < 0.009$]. This effect occurred across all stimuli at all ISIs.

N230 latency was significantly longer in the LI than the control children [mean msec 241 vs. 229; group $F(1,28) = 4.3, p < 0.04$]. N230 amplitude was not significantly different in the two groups.

P350 latency was similar in the two groups, but P350 amplitude was significantly smaller in the LI children, especially at medium and long ISIs [ISI \times group $F(2,56) = 5.5, p < 0.01$; see Table 6].

ERPs to Standards: Sites Anterior to Occiput. P150 was small or absent anterior to the occiput and was not measured. A negative component was present in this time region (N150) and was followed by a positivity at 250 (P250). For both groups N150 amplitude increased with prior ISI [ISI $F(2,56) = 65.0, p < 0.0001$], was contralateral [side \times hemisphere $F(2,56) = 6.9, p < 0.004$], but

Table 2. Auditory Recovery Cycle (Mean Microvolts)

	<i>Left Hemisphere</i>					<i>Right Hemisphere</i>				
	<i>F</i>	<i>AT</i>	<i>T</i>	<i>P</i>	<i>O</i>	<i>F</i>	<i>AT</i>	<i>T</i>	<i>P</i>	<i>O</i>
N140										
Hi rep	-3.78	-3.49	-3.80	-2.75	-0.93	-4.48	-3.72	-3.29	-1.62	-0.32
Low rep	-4.28	-3.88	-3.59	-2.40	-0.56	-3.43	-2.84	-2.77	-1.44	-0.27
N260										
Hi rep	-7.61	-5.50	-4.97	-2.48	-0.81	-7.98	-5.73	-4.29	-1.74	-0.47
Low rep	-6.90	-5.32	-3.99	-2.10	-0.66	-5.13	-3.63	-2.83	-0.96	-0.16
N440										
Hi rep	-5.14	-2.78	-2.24	-0.90	-0.59	-5.00	-3.03	-1.68	-0.19	-0.11
Low rep	-4.63	-2.73	-1.88	-1.01	-0.21	-2.08	-0.75	-0.80	-0.33	0.08

Table 3. Auditory Recovery Cycle: N140 Latency, 200 msec ISI

	<i>Frontal</i>	<i>Anterior Temporal</i>	<i>Temporal</i>	<i>Parietal</i>	<i>Occipital</i>
High Rep Subjects					
LH	150	142	149	139	121
RH	141	152	150	141	113
Low Rep Subjects					
LH	153	160	162	164	131
RH	159	158	157	150	121

Table 4. Visual Recovery Cycle

	<i>Correct (%)</i>			<i>Reaction Time (msec)</i>		
	<i>Short</i>	<i>Medium</i>	<i>Long</i>	<i>Short</i>	<i>Medium</i>	<i>Long</i>
CL	99	96	98	597	587	593
LI	95	94	96	640	630	629

also displayed a standing right hemisphere asymmetry [hemisphere $F(1,28) = 11.9, p < 0.001$]. P250 amplitude increased with increasing prior ISI in both groups [ISI $F(2,56) = 27.7, p < 0.0001$].

GROUP EFFECTS. N150 latency was earlier in the controls than the LIs over frontal and anterior temporal sites [electrode \times group $F(3,84) = 3.9, p < 0.03$], and at the medium and long ISIs [ISI \times group $F(2,56) = 3.4, p < 0.04$]. N150 amplitude was reduced in the LIs for central stimuli [side \times group $F(2,56) = 4.5, p < 0.02$].

LIs: High and Low Auditory Repetition Test

LI children that were within and below the range of control values on the Repetition Test were compared, for the sake of comparability with the auditory data.

There were few significant effects. Over the right occipital region the low repetition LIs displayed larger P150 amplitude than the high repetition subjects, while over the left occiput the high repetition subjects P150 responses were larger than the low repetition [hemisphere \times group $F(1,16) = 6.1, p < 0.02$]. Anterior to the occiput over the left hemisphere the amplitude of N150 was decreased in low repetition compared to high repetition LIs [hemisphere \times group $F(1,16) = 7.9, p < 0.01$].

Visual Sentence Processing

Behavior

The LI subjects were less accurate in judging whether or not the sentence made sense [group $F(1,22) = 61.5, p < 0.0001$; see Table 7].

Table 5. Visual Recovery Cycle Occipital Sites: Latency (msec)

	<i>LVF</i>		<i>Center</i>		<i>RVF</i>	
	<i>CL</i>	<i>LI</i>	<i>CL</i>	<i>LI</i>	<i>CL</i>	<i>LI</i>
P150						
Short	143	154	145	151	156	157
Medium	145	150	140	146	139	148
Long	148	144	144	151	142	146
N230						
Short	238	238	239	240	235	258
Medium	225	239	232	240	215	234
Long	224	235	232	253	221	232
P350						
Short	330	354	350	360	334	358
Medium	355	359	359	355	350	352
Long	363	354	337	352	359	355

Table 6. Visual Recovery Cycle Occipital Sites: Peak Amplitude (μV)

	<i>LVF</i>		<i>Center</i>		<i>RVF</i>	
	<i>CL</i>	<i>LI</i>	<i>CL</i>	<i>LI</i>	<i>CL</i>	<i>LI</i>
P150						
Short	1.99	0.75	3.82	3.43	1.88	1.76
Medium	5.34	3.30	10.60	5.87	5.08	4.02
Long	6.28	3.83	10.75	7.07	5.23	4.02
N230						
Short	-6.39	-4.43	-8.10	-4.34	-5.30	-4.23
Medium	-7.51	-5.05	-8.62	-7.46	-6.65	-5.05
Long	-7.32	-5.42	-7.04	-6.97	-7.49	-6.29
P350						
High	1.02	1.19	-0.64	2.74	1.14	1.72
Medium	4.53	2.67	5.19	2.52	5.36	3.09
Low	4.45	3.00	5.82	3.83	5.32	3.33

Open and Closed Class Words

Only a subset of the LI children could read well enough to participate in the reading task ($N=12$). Nonetheless, as for the nonlanguage stimuli, the amplitude of the P150 component to words was significantly reduced in LIs compared to control subjects [14.8 vs. 8.9 μV , group $F(1,22) = 15.1, p < 0.0008$]. Neither the amplitude nor

the latency of occipital N230 component to words was different in the two groups. The P350 amplitude over occipital regions was markedly reduced in the LI subjects [5 vs. 11.5 μV , group $F(1,22) = 11.7, p < 0.002$]. Anterior to the occiput the N150 and P250 components did not differ in the two groups (see Figs. 5 and 6).

As seen in Figures 5 and 6, following the P350 re-

Table 7. Visual Sentences

	Correct (%)	
	CL	LI
Appropriate	98	89
Anomalous	98	89

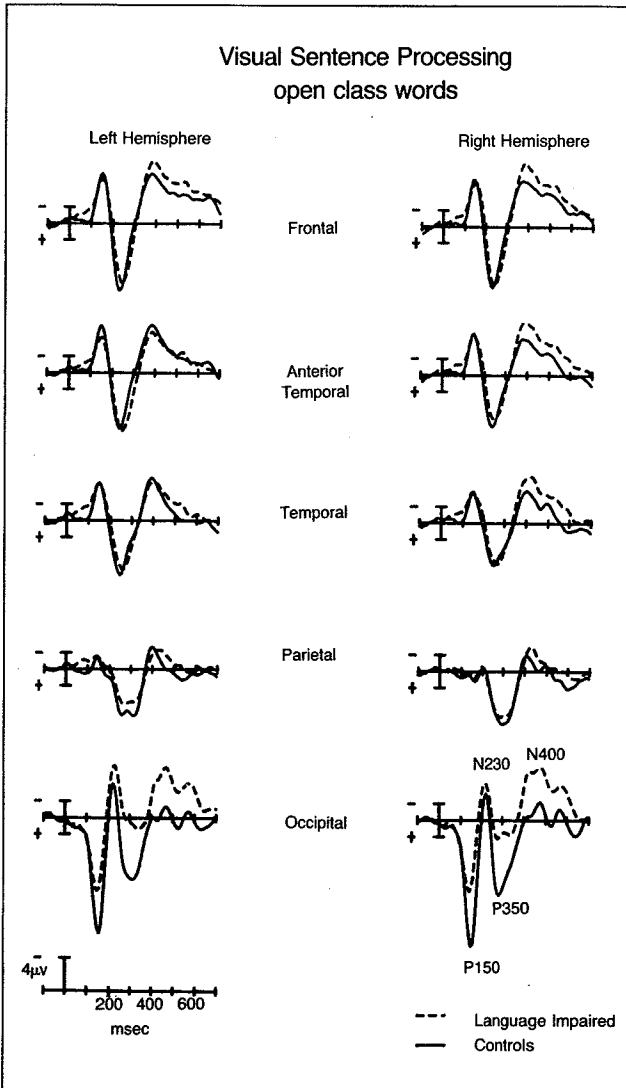


Figure 5. ERPs to open class words in the middle of sentences from left and right frontal, anterior temporal, temporal, parietal, and occipital sites of control and LI children.

response, ERPs to words (in contrast to the ERPs to non-language stimuli) elicited a negative component around 450 msec. As seen in Figures 5 and 6 this response was larger for open than closed class words [word class \times electrode \times hemisphere $F(4,88) = 4.6, p < 0.006$]. These characteristics have been reported previously in descriptions of the expectancy-sensitive N400 response to open class words and the asymmetrical N280 response to closed class words in normal adults (Neville, 1991; Neville et al., 1992; Van Petten & Kutas, 1991).

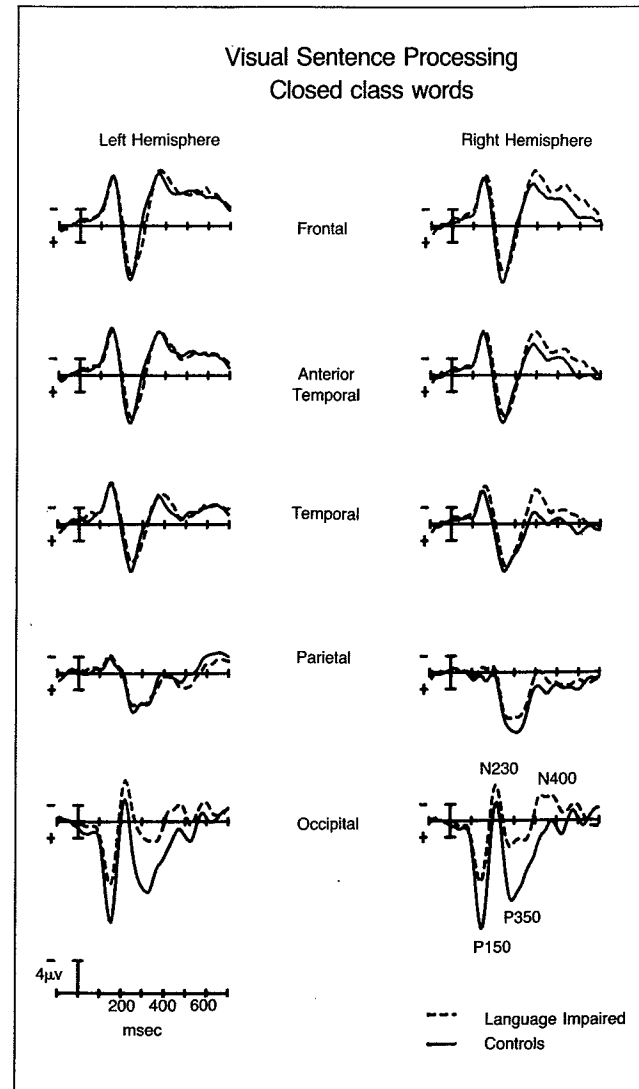


Figure 6. ERPs to closed class words in the middle of sentences from left and right frontal, anterior temporal, temporal, parietal, and occipital sites of control and LI children.

The N400 response was significantly larger in the LIs than control children, especially in ERPs to open class words recorded from over the occipital regions [word class \times electrode \times group $F(4,88) = 3.6, p < 0.02$]. This negativity was symmetrical in response to open class words in both groups (hemisphere effect n.s.). By contrast, in response to closed class words the control children displayed an asymmetry similar to that observed in normal adults, i.e., anterior regions of the left hemi-

sphere were more negative than the right [hemisphere $F(1,11) = 14.4, p < 0.003$; hemisphere \times electrode $F(4,44) = 7.5, p < 0.001$; see Figs. 6 and 7). In contrast the LI children showed a symmetrical response to closed class words (n.s.). These effects were not different for LIs who scored high and low in the auditory repetition task. Since we have reported that the anterior negativity to closed class words and the asymmetry it displays are linked to performance on tests of English grammar (Neville, 1991; Neville et al., 1992) we assessed these effects as a function of the LI children's performance on the syntax subtest of the Cycle Test of Language Abilities (Curtiss, Katz, & Tallal, 1992). On this test LI children performed with considerable variability (1.40–4.33) compared to controls (4.2–4.86). We divided the LI group into those scoring 3 or above (high syntax) or below 3 (low syntax). It is important to note that the LI children who performed poorly on the repetition task were not necessarily those who scored poorly on the test of syntax (correlation = 0.02). Figure 8 displays the ERPs to open and closed class words from the two hemispheres of control children and LI children that scored high and low on the Cycle Test of Syntax. Over frontal and anterior temporal sites in response to open class words the groups displayed similar, symmetrical responses (n.s.).

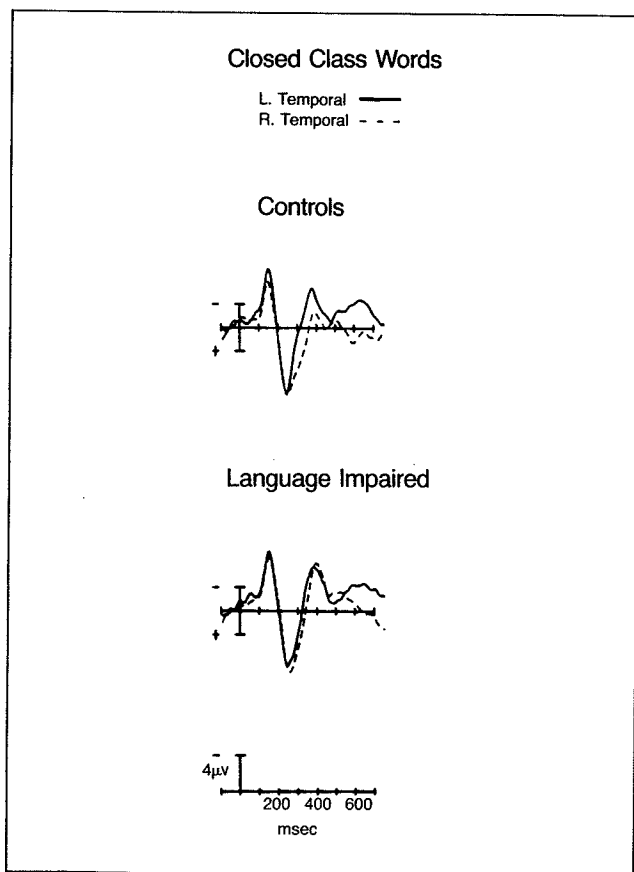


Figure 7. ERPs from left and right temporal regions to closed class words from control and LI children.

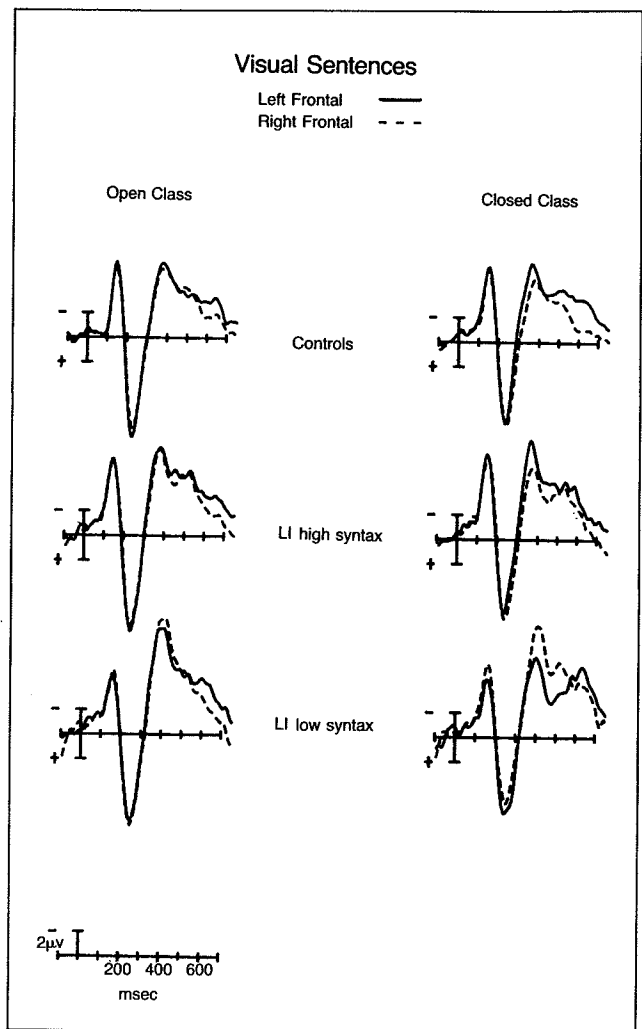


Figure 8. ERPs to open and closed class words from controls and LI children that performed well and poorly on the Cycle Test of Language Abilities.

By contrast in response to closed class words the high syntax group displayed an asymmetry similar to that of the controls, while the low syntax group displayed an opposite pattern [hemisphere \times group, frontal sites $F(1,10) = 5.3, p < 0.04$; anterior temporal $F(1,10) = 3.5, p < 0.09$].

Final Words

ERPs to the sentence final words displayed group differences in the early components similar to those observed in the previous comparisons, i.e., over occipital regions P150 and P350 amplitudes tended to be reduced in LIs compared to control children [P150 group $F(1,22) = 6.0, p < 0.02$; P350 group $F(1,22) = 2.9, p < 0.10$].

Following P350 both groups displayed an enhanced N400 component over posterior scalp in response to the semantic anomalies [see Fig. 9; word type $F(1,22) = 66.1, p < 0.0001$; word type \times electrode $F(4,88) = 9.0, p < 0.001$]. The effect tended to be larger in the LI than

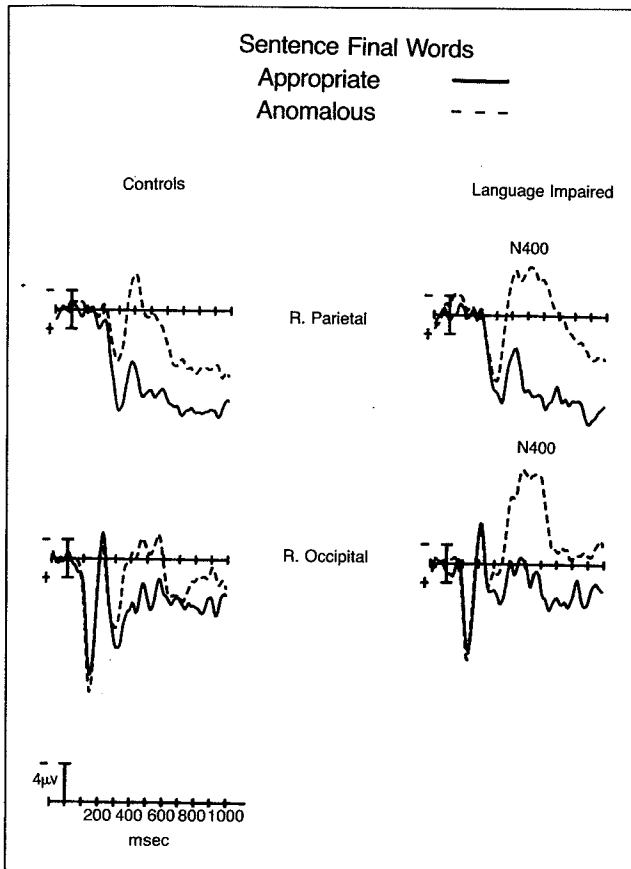


Figure 9. ERPs to semantically appropriate or anomalous sentence final words from right parietal and occipital regions of control and LI children.

Table 8. N400 Amplitude (μV)

	Parietal		Occipital	
	Controls	LIs	Controls	LIs
Appropriate	1.6	0.6	-2.1	-5.1
Anomalous	-7.3	-9.2	-6.2	-14.4

control children over posterior sites [word type \times electrode \times group $F(4,88) = 2.4, p < 0.08$; see Table 8]. Additionally, LI children tended to have larger N400 responses to both appropriate and anomalous endings [group $F(1,22) = 3.7, p < 0.06$]. Also the posterior N400 to anomalous endings occurred later in the LI than the control children [group \times word type \times electrode $F(4,88) = 4.1, p < 0.009$].

The difference waves, shown in Figure 10, display the tendency for the N400 to be larger in the LI children, especially over posterior regions of the right hemisphere [hemisphere \times electrode \times group $F(4,88) = 2.7, p < 0.06$]. There were no significant differences in N400 latency or amplitude between the high and low syntax LI

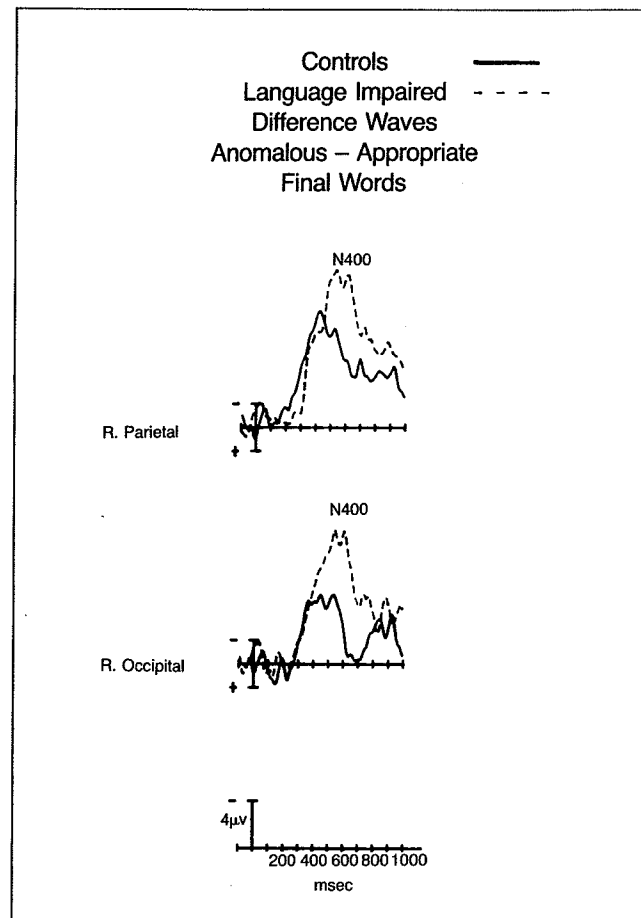


Figure 10. Difference ERPs, formed by subtracting ERPs to semantically appropriate from semantically anomalous sentence final words from control and LI subjects.

children, nor between the children who scored high and low on the auditory repetition task.

DISCUSSION

These results imply that a single-factor account of the deficits of LI and of RD children is not adequate. Multiple aspects of processing were affected in the LI/RD group but not homogeneously across the sample. Rather the pattern of results is consistent with a multiple-factor and multiple subtypes LI/RD framework.

The results suggest that specific aspects of sensory and language processing were abnormal in this LI/RD group as a whole, while other aspects were aberrant only in (different) subsets of the LI/RD sample. More specifically ERPs during auditory sensory processing were abnormal only in those LI/RD children whose performance on the Tallal Repetition Task was abnormal. By contrast, early responses of visual ERPs to both language and nonlanguage stimuli were markedly reduced in amplitude in the LI/RD group as a whole. Abnormal organization of ERPs linked with grammatical processing were evident only in a subset of the LI/RD group (and this was not the

subset that displayed abnormal auditory processing). On the other hand the LI/RD group as a whole displayed abnormally large ERP responses (N400) to sentence-medial open class words and to sentence-final words. Below we discuss each of these patterns of results in turn.

Auditory Sensory Processing

Research by Tallal and colleagues (see Tallal et al., 1991 for review) has documented that young LI children are specifically impaired in their ability to discriminate and sequence rapidly presented nonverbal stimuli. For example, whereas normal children can correctly report the temporal order of different tones presented at ISIs of 8 msec, LI children require over 300 msec to perform at the same level of accuracy. Significantly, this result has been observed in the auditory, visual, and tactile modalities and has been interpreted as showing that even simple sensory processing is considerably slower in LI than in normal children. These authors and Di Lollo, Hanson, and McIntyre (1983) reported that LI/RD and dyslexic children show a similar deficit. The present results showing that subjects who display this type of deficit also show reduced ERP amplitudes and increased ERP latencies to tone stimuli provide neurophysiological evidence that is consistent with the hypothesis that a significant percentage of developmental language disorders may represent a "final common path" that arises from an inability to perceive the changing acoustic spectra that characterize ongoing speech perceptions.

The present results suggest that an early auditory ERP component, N140, was delayed in latency and was most reduced in amplitude following short ISIs in LI/RD subjects who scored poorly on the repetition test. N140 thus displayed a pattern similar to the behavioral data from this task (the correct detection of targets) and to results on the repetition task. The N140 response in these subjects is likely to be equivalent to the N100 response in adults. Several lines of evidence, including studies of magnetic evoked responses (Pantev, Hoke, Lehnertz, Fahrendorf, & Stoher, 1990; Hari & Lounasmaa, 1989), source localization algorithms (Scherg, Vajsar, & Picton, 1989), and clinical evidence suggest that the N100 response is not a unitary process but may consist of as many as six components (Näätänen & Picton, 1987). The anterior and contralateral distribution of the N140 response in the present study make it likely that it includes activity generated in the cortex of the supratemporal plane, including the primary auditory cortex on Heschel's gyri. The pattern of results suggests that in some LI/RD children (i.e., the low repetition subjects in the current sample) reduced and slowed activity within primary and association auditory areas contributed to their language impairment. The subsequent N250 and N440 responses were also reduced in the low rep subjects, and this effect occurred at all ISIs. These results imply that auditory sensory processing may be abnormal even at moderate

rates of stimulus presentation in a subset of the LI/RD population, but that this only affects performance on the repetition test and on target detection in the current task at the highest rate of presentation. N250 also displayed an anterior and contralateral distribution and in addition was earlier over the contralateral hemisphere and may thus represent continued activity of superior temporal gyrus (Näätänen and Picton's component 2). N440 displayed a left hemisphere asymmetry and may represent an area-specific response linked to the task demands.

The reduction in amplitude of each of the auditory ERP components occurred over anterior regions of the right hemisphere. This asymmetry is of interest in view of MRI studies of these same children that show subcortical volumes in the right diencephalon and caudate were significantly reduced in these LI/RD children compared to controls (Jernigan, Hesselink, Sowell, & Tallal, 1991). In view of the hypothesized role of such structures in mediating attention and in view of the sensitivity of early auditory ERPs to attention (Hansen & Hillyard, 1980; Näätänen & Picton, 1987; Hillyard, Hink, Schwent, & Picton, 1973; Woldorff & Hillyard, 1991) it will be important for future research to explore behavioral and neurophysiological systems during tasks requiring focused auditory attention in LI/RD children.

Visual Sensory Processing

The present results clearly point to abnormalities in the early stages of nonlanguage visual processing of LI/RD subjects. Both the P150 component and the P350 were markedly reduced in the LI/RD group as a whole. Moreover these effects were equivalent for peripheral and foveal stimuli and for all rates of stimulation employed here. This effect is important when considering the hypothesis put forward initially by Lovegrove (1986, 1991) that the visual processing deficit of dyslexics arises primarily from abnormalities of the "transient" visual subsystem that arises within the periphery of the retina and is most sensitive to low spatial and high temporal frequencies. By contrast, the "sustained" visual system that processes primarily central visual information and is most sensitive to high spatial and low temporal frequencies has been reported to be normal in dyslexic subjects. These parallel subsystems have also been described as the "where" and "what" subsystems (Held, 1968; Ingle, 1967; Newcombe & Russell, 1969; Schneider, 1969; Trevarthen, 1968; Ungerleider & Mishkin, 1982). Considerable anatomical evidence in animals and clinical data from humans lends support to this functional distinction. Thus the pathway from the retina to the lateral geniculate, striate cortex, and inferior temporal cortex, (the "ventral" visual pathway) is critical in pattern discrimination, while lesions to the pathway that projects to striate, extrastriate, and parietal cortex (the "dorsal" visual pathway) lead to deficits in orientation toward and localization of peripheral visual stimuli (Denny-Brown & Chambers, 1958;

DeYoe & Van Essen, 1988; Humphrey, 1970; Keating, 1980; Livingstone & Hubel, 1987; Schneider, 1969; Trevarthen, 1968; Ungerleider & Mishkin, 1982). Data from normal adults (Neville & Lawson, 1987a) are in agreement with these proposals and further suggest that attention to central and peripheral visual space is mediated by separate neural systems. In addition, results from animals and from studies of deaf adults raise the hypothesis that the peripheral or transient visual system develops later and may be more vulnerable to developmental abnormalities than is the focal or sustained system (Neville & Lawson, 1987b,c; Neville et al., 1983).

In recent reviews, Lovegrove et al. (1986, 1991) presented a series of persuasive arguments against the prevailing view that RD subjects do not differ from normal children in visual processing (Benton, 1975; Vellutino, 1979 a,b). Lovegrove et al.'s argument focuses on the fact that most researchers do not distinguish between the transient and sustained visual systems. Their review reveals that at least 75% of reading disabled subjects (most of whom were also LI) displayed large and consistent deficits in the functions of the transient visual system, but did not differ from controls in the functioning of the sustained system. The authors discuss the central role of the transient system in reading, by permitting the integration of information from successive fixations and by producing good temporal resolution. Thus a deficit in this system may diminish the integration of information across visual fixations and the integration of foveal and parafoveal information within a fixation.

A few recent studies have compared the P100 component of the visual evoked response to reversing checkerboards in normal and dyslexic children. Each of these studies reports decreased amplitude in dyslexic children (Mecacci, Sechi, & Levi, 1983; Solan et al., 1990). These studies presented stimuli only to the foveal region. In view of recent evidence showing an increased representation of the fovea along the ventral pathway, and of the periphery along the dorsal pathway (Baizer, Ungerleider, & Desimone, 1991) the present results, showing reduced visual ERPs to both peripheral and foveal stimuli, implicate deficits along both pathways. Alternatively, the very brief stimulus duration (50 msec) of the visual stimuli may have placed greater processing requirements on the transient system, and therefore deficits within this system in the LI subjects may have been amplified by this short duration. Of interest with respect to this hypothesis is the fact that the group difference in the latency of N230 (LIs slower) was not evident in the language task in which stimulus durations were 300 msec and therefore more likely to activate primarily the sustained system.¹ An alternative hypothesis for the different results in the two tasks is related to the fact that only a subset of the LI children (i.e., those who could read well enough) participated in the language task. It may be that children in whom the latency delay is largest are the poorest readers and therefore did not contribute data to the sentence

processing task. However there were no significant differences in N230 latency in the nonlanguage task between subjects who could and could not read the sentences.

A few studies have attempted to link particular early visual ERP components with the different visual pathways. Previc (1988) postulated, on the basis of their different spatial frequency and contrast sensitivities, that an early visual negativity (50 msec) and P100 reflect the outputs of the parvocellular and magnocellular pathways, respectively. Livingstone, Rosen, Drislane, & Galaburda (1991) report that the magnocellular layer of the LGN is small in dyslexics as compared to a control sample, but the parvocellular layer was similar in the two groups. In addition they report that both the N50 and P100 responses were delayed in latency in dyslexics in response to low contrast checkerboard stimuli only. They suggest these results are compatible with a magnocellular deficit in dyslexia. They also propose that the dorsal or transient visual system arises from the magnocellular pathway, and that their results are consistent with Lovegrove's hypothesis.

On the other hand, recent studies by Mangun and Hillyard and colleagues (Mangun & Hillyard, 1990; Mangun, Hillyard, & Luck, 1992) employed current source density analyses of ERP activity and have linked these data to MRI images of the same subjects to localize the sources of the P100 and N180 visual responses. Their results led them to suggest that the P100 may be generated in lateral prestriate cortex, along the ventral pathway, while N180 may be generated along the dorsal pathway. Thus, different investigators have alternatively suggested that P100 (which probably corresponds to the P150 in this study) is generated within the magnocellular system (assumed to lead to the dorsal pathway) or along the ventral pathway. These discrepancies may be resolved in part by further evidence on the relationship between the parvo/magno and ventral/dorsal pathways and further evidence on the generators of P100.

In this study the visual processing abnormalities indexed by the ERPs were apparent in the entire LI/RD group independently of performance on repetition tests and thus do not strictly parallel the auditory processing deficits in the ERPs, which were apparent only in the low repetition subjects. Nonetheless, the low repetition group did display reduced visual ERP amplitudes over the left hemisphere in comparison to the high repetition group.

Language Processing

Some of the early visual abnormalities noted above were also observed in the ERPs to visual language stimuli (the amplitude reductions of P150 and P350). This implies that a similar visual abnormality is operating during reading, although the present data do not illuminate the relation between the two. The lack of significant corre-

lations between ERP measures and reading scores may have resulted from the uniformly low scores of the LI children on the reading tasks.

The results of the language study suggest that a subset of LI/RD subjects, specifically those that score poorly on tests of syntax, display abnormal hemispheric specialization of an ERP component that may index aspects of grammatical processing (i.e., an asymmetrical anterior negative component elicited by closed class words). A large literature has been interpreted as showing that the primary deficits of both LI children and LI/RD children are within the domain of language rather than in the development of general cognitive or sensory processing. For example, studies have reported that LI children frequently produce ill-formed sentences that appear to lack "internal syntactic structure" (Morehead & Ingram, 1973; Menyuk, 1964; Lee, 1966). Similarly, studies of poor readers report that the acquisition of specific syntactic structures, particularly those that are inherently more complex and are acquired late in normal development, are further delayed in RD children causing a deficit in their ability to read (Byrne, 1981; Fletcher, Satz, & Scholes, 1981; Vogel, 1975; Chiat & Hirson, 1987). Several recent studies report that many aspects of the acquisition of morphology and syntax are normal in LI children (Leonard et al., 1988) although persistent difficulties with grammatical morphemes have been reported (Loeb & Leonard, 1991; Clahsen, 1989).

On the other hand, several studies have observed basically normal or delayed, but not deviant, acquisition of language structure in language-impaired children, and this has been interpreted as support for the idea that grammatical knowledge is very robust in general and is intact in these children, and that both LI and RD arise from deficits in the processing systems (e.g., memory) required to utilize this knowledge in speech and reading (Shankweiler & Crain, 1986; Curtiss et al., 1992). By this view the task demands and/or restricted time sampling of earlier studies may have led to inaccurate estimates of syntactic knowledge.

The online task utilized here required only that subjects read simple sentences, i.e., it required minimal mnemonic processes. The results suggest that at least some LI/RD children may display abnormalities in processing information that is central to grammatical processing. It is important to note that this subset of children was not the same as that which displayed auditory sensory processing deficits.

All of the LI/RD children displayed abnormally large N400 responses both to open class words in sentence-medial position and to sentence-final words that were semantically anomalous. The behavioral literature on semantic development in LI and RD subjects is characterized by controversy, no doubt in part due to the different methods used to assess the acquisition and representation of and access to the lexicon. Several studies report that the acquisition of meaning relations between words

and of lexical items themselves develop normally in LI children, while others report delays in the utilization of lexical items (Freedman & Carpenter, 1976; Leonard, Steckol, & Schwartz, 1978; Curtiss & Tallal, 1985; Johnston & Kamhi, 1984). Similarly, studies of RD variously report deficiencies in semantic processing (Perfetti & Lesgold, 1978), no deficits in semantic processing (West & Stanovich, 1978), or increased semantic effects in poor readers (Schvaneveldt, Ackerman, & Semlear, 1977; Ceci, 1982).

There is currently considerable discussion about the specific process(es) that N400 may index, but in view of the facts that N400 amplitude is strongly negatively correlated with both word frequency, semantic context and controlled processing (Brown, Hagoort, & Swabb, 1989; Holcomb, 1988; Kutas & Hillyard, 1984; Neville, Pratarelli, & Forster, 1989; Rugg & Doyle, 1992), it is reasonable to assume that it indexes processes invoked in the integration of a word into a context (Holcomb & Neville, 1990; Rugg & Doyle, 1992). Indeed, the marked decline in N400 amplitude across normal childhood has been interpreted as indexing decreasing reliance on context for word recognition and decreased effort required to integrate words into context as children acquire greater reading skills (Holcomb, Coffey, & Neville, 1992). By this interpretation the present results raise the hypothesis that the auditory and visual sensory processing deficits and the syntactic processing deficits evidenced by all or some of the LI/RD children lead to compensatory increases in the effort required to integrate words into context and for greater reliance on context for word recognition than in control subjects. We have observed a similar effect to semantic anomalies during an auditory version of this sentence-processing task (unpublished observations) suggesting that this effect is not solely attributable to the LI/RD subjects' altered experience with reading.

In summary, the present results taken together suggest that early sensory processing deficits are an important feature of the LI/RD profile. Additionally, some LI/RD children display aberrant processing of grammatical information, and this does not appear to be correlated to the sensory deficits. LI/RD subjects as a group place more reliance on and/or require more effort in integrating words into sentential contexts. This effect may be a compensatory strategy in response to deficits in the earlier stages of processing. More generally the current pattern of results clearly indicates that multiple factors contribute to the emergence of language-processing deficits and moreover that these deficits are heterogeneous across populations of LI/RD children.

METHODS

Subjects

A total of 34 volunteers between the ages of 8 and 10 years of age served as subjects. All were referred by the

Language Research Center at Children's Hospital in San Diego and were part of a longitudinal study. Subjects were paid for their participation. The sample studied was drawn from a larger sample of 95 specifically language-impaired children and 60 age-, IQ-, race-, and socioeconomic status-matched controls, identified at the age of 4 years and studied longitudinally until the age of 8 years. Inclusion in the longitudinal study at the age of 4 years was based on the following criteria for both groups: (1) performance IQ of 85 or greater, (2) normal hearing acuity, no motor handicaps and no oral, structural, or motor impairments affecting nonspeech movement of the articulators, (3) an English language background without significant dialectical or language differences in the home environment, (4) no obvious signs of infantile autism (as defined by *Diagnostic and Statistical Manual of Mental Disorders, Third Edition*), and (5) no known neurological disorders. Language-impaired children were at least 1 year behind their chronological and non-verbal mental age on a battery of standardized receptive and expressive language measures.² Normal control children met the same criteria as the language-impaired subjects except that their speech and language skills had to be within 6 months of their chronological age. A subset of children who completed all 5 years of testing in the longitudinal study were selected to participate in this study. Twenty-two children who continued to demonstrate significant language impairment as well as academic achievement deficits were selected as subjects for these experiments. At the time of this study, when they had an average age of 9 years, they continued to be language impaired, but in addition, many had severe learning disabilities that emerged during the longitudinal study. They may or may not be similar to a group selected solely on reading ability (i.e., developmental dyslexic) although they all did have severe reading impairment when these studies were performed. Twelve matched controls who demonstrated normal language development and academic achievement (reading, spelling, and mathematics) also agreed to participate. One language impaired and one control child were left-handed, all other subjects were right-handed.

Behavioral Tests

All subjects were administered a variety of behavioral tests including the Tallal Auditory Repetition Test in which subjects repeat the sequence of tones of different frequencies presented at different rates (Tallal & Piercy, 1973; Tallal, 1978). The Repetition Test is hierarchical in nature and is comprised of a series of subtests (detection, association, discrimination, sequencing, rate processing and serial memory) that build one on the other. In brief, subjects are trained, using an operantly conditioned two-alternative forced-choice procedure to press the bottom panel of a response box in response to stimulus 1 and the top panel in response to stimulus 2 (discrimination

subtest). Next, binary series of these two stimuli are presented in increasingly longer series at various rates of presentations. Subjects indicate what they perceived by pressing the panels on the response box corresponding to the order of presentation. Subjects were grouped according to scores on this task for some of the analyses. In addition, the Curtiss and Yamada Comprehensive Language Evaluation-Full including the Syntax Subtest (see Curtiss et al., 1992) and the Wide Range Achievement Test (WRAT) were administered. Scores on the Syntax Subtest were used to group subjects for some of the analyses. These items test for knowledge of grammatical relations between phrasal and/or clausal constituents, and other linguistic structures (see Curtiss et al., 1992). At nine years of age (i.e., at the time of the ERP studies) the mean WRAT scores were 7.5 for the control subjects and 2.8 for the LI group ($p < 0.0001$). Scores on each of these tests (obtained at the time of ERP testing) were used to form various subgroups on which further analyses were performed.

Visual and Auditory Mapping

Stimuli and Procedure. There were two stimulus types for these procedures. In the auditory task a 2000-Hz tone (the standard stimulus) and a 1000-Hz tone (designated the target stimulus) were presented over TDH-39P headphones (65 db SL). In the visual task the target was a small white rectangle (6 mm wide, 12 mm tall) and the standard was a larger red square (23 mm per side) displayed on a computer monitor. In both tasks all stimuli were presented for a duration of 50 msec, at one of three interstimulus intervals (ISI; 200, 1000, and 2000 msec) and at one of three locations (left, center, and right). For the auditory task left stimuli were presented only to the headphone speaker over the left ear, right-sided stimuli were presented to the right speaker, and center stimuli were presented to both speakers. For the visual task left stimuli were presented 8.8° to the left of fixation, right stimuli were presented 8.8° to the right of fixation, and center stimuli were presented at fixation. In both tasks subjects were presented with a total of 999 stimuli (99 of which were targets), with equal numbers at each of the three locations. For each of the three ISIs there were 333 trials equally distributed across the three locations. All stimuli were presented randomly intermixed.

During both tasks subjects were instructed to fixate on the center of the screen and monitor the stimulus stream for occasional target events ($p = 0.10$), which were pseudorandomly mixed with the standard stimuli (with the restriction that all targets were followed by a long ISI standard). They were told to press a button on a box with their index finger (hand was counterbalanced across subjects) as quickly as possible whenever they detected a target stimulus at any of the three locations. Subjects were instructed not to move their eyes from a fixation spot affixed to the center of the monitor. Subject's gaze

direction was monitored by an experimenter sitting next to the subject and via a remote closed circuit television system. Subjects were given 50 practice trials before the experimental run in each modality. During the experiment they were given a rest break every 333 trials.

Visual Sentences—Stimuli and Procedure

The stimuli for this experiment were generated from a master list of 160 highly constrained sentences (final word cloze probability > 0.8) ranging from 3 to 13 words in length.³ All words except those in sentence initial or final position were coded and averaged separately according to whether they were within the open class (noun, verbs, and adjectives) or closed class (including articles, pronouns, prepositions, conjunctions, and auxiliaries). Four lists of 80 sentences were formed from the master list such that lists 1 and 3 contained the same sentence stems (the first 80) and list 2 and 4 contained the same (the remaining 80). In each list 40 of the sentences ended with a highly expected, semantically appropriate word (e.g., The boys ate all the chocolate chip cookies) and the other 40 ended with an a semantically anomalous completion (e.g., Giraffes have long scissors). Anomalous words were selected by rearranging the appropriate words (between sentences) such that they no longer fit with the sentence context (for further details see Holcomb et al., 1992). Each subject viewed only one list of 80 sentences. Only 12 of the LI subjects could read well enough to do the visual sentence task.

Sentences were presented in a word-by-word fashion in the center of a video monitor at a comfortable illumination level. The duration of each word was 300 msec and the interstimulus interval was 700 msec. All first words and proper nouns began with an upper case letter and all other letters were lower case. All words were between 0.5 and 2.0° of horizontal visual angle and 0.75° of vertical visual angle.

The experiment was self-paced, each trial beginning when the subject pressed a button. The outline of a white rectangle appeared on a video monitor 1.5 sec later (6 × 3°). The subject was told not to move or blink during the time the rectangle was on the screen. The first word of the sentence was presented 1 sec after the onset of the rectangle, centered in the middle of the rectangle. The rectangle was turned off 3 sec after the onset of the final word in the sentence and was replaced by a visual message to respond YES or NO. The subject responded by pressing a button to indicate whether or not the sentence made sense. Because the response was delayed 3 sec (to prevent the motor response from contaminating the ERP to the final word), accuracy of response, rather than speed, was emphasized. Response hand was counterbalanced across subjects in each age group. Each subject engaged in 10 practice trials prior to the run of 80 experimental sentences.

ERP Recording

The EEG was recorded from 14 scalp electrodes including standard International 10–20 System locations, left and right occipital (O1, O2), frontal (F7, F8), and six nonstandard locations, left and right parietal (30% of the interaural distance lateral to a point 13% of the nasion–inion distance posterior to Cz, roughly Wernicke's region), left and right temporal (33% of the interaural distance lateral to Cz), and left and right anterior temporal [one-half of the distance between F7(8) and T3(4)]. In addition to these sites, we also recorded from the midline sites, Cz and Pz, and two frontal sites, FP1 and FP2. Data from these sites will not be reported here. Recordings at FP1 and FP2 were used for artifact reject purposes. These electrodes were attached to an elastic cap (Electro-Cap) and were referenced to linked mastoids. The electrooculogram (EOG) was recorded from electrodes beneath the left eye and lateral to the right eye (mastoid reference). All impedances were maintained below 5k Ω . Grass 7P511 amplifiers (bandpass 0.01 to 100 Hz) were interfaced to a 16 channel 12 bit A/D converter and the EEG was digitized on line and stored on digital tape.

Offline, separate ERPs (100 msec prestimulus baseline) were averaged for each subject at each electrode site from trials free of EOG and movement artifact (5%).⁴ In the auditory and visual recovery cycle procedures separate ERPs were computed for standard stimuli preceded by each ISI and location (i.e., 3 ISIs × 3 locations = 9 conditions). For targets, only trials with correct responses were included in the averages. Subjects ($N=3$) with fewer than 10 trials in a condition were excluded from the ERP analysis. The small number of target trials precluded averaging according to ISI and location.

In the sentence task separate averages were made for final words of both Sentence Types (Appropriate and Anomalous Completions) from trials on which the subject responded correctly. Also, separate averages were made for the open and closed classes of words in the middle of sentences (i.e., excluding those in the first and final positions of the sentence).

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Notes

1. We are grateful to an anonymous reviewer for this suggestion.
2. Language age is computed from the Sequenced Inventory of Communicative Development (SICD) (Hedrick, Prather, & Tobin, 1979), the Token Test (DiSimoni, 1978), the Northwestern Syntax Screening Test (NSST) (Lee, 1971), the Carrow Elic-

ited Language Inventory (CELI) (Carrow, 1974), and the Curtiss and Yamada Comprehensive Language Evaluation (YCIE-E&R). 3. The sentences used in this study were selected based on extensive testing in several San Diego area elementary schools. Before a sentence could be a candidate for inclusion in the study it had to meet two criteria. First it had to be "readable" by greater than 97% of second grade children ($n=80$). Second it had to have a cloze probability for second and third grade children greater than 0.8 ($n=120$), that is, greater than 80% of the children tested had to fill in the appropriate best completion final word when given the stem sentence ending in a blank.

4. The EOG channels of each subject's raw data were searched (via a software routine) on a trial-by-trial basis for high amplitude activity and these trials were automatically rejected by the averaging program. The criteria for rejection were titrated individually for each subject based on inspection of the eye channels after averaging, and the relative amplitude of the ERPs for that subject (range, 50 to 100 μ V peak to peak).

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