

Below-Average, Average, and Above-Average Readers Engage Different and Similar Brain Regions While Reading

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Abstract

Event-related potentials (ERPs) were recorded from 27 children (14 girls, 13 boys) who varied in their reading skill levels. Both behavior performance measures recorded during the ERP word classification task and the ERP responses themselves discriminated between children with above-average, average, and below-average reading skills. ERP amplitudes and peak latencies decreased as reading skills increased. Furthermore, hemisphere differences increased with higher reading skill levels. Sex differences were also related to ERP amplitude variations across the scalp. However, ERPs recorded from boys and girls did not differ as a function of differences in the children's reading levels.

The role of phonological processing in the development of language and reading abilities has received a great deal of attention over the past half-century. Phonological processing refers to the ability to discriminate phonetic contrasts, and includes the discrimination of speech sounds as well as the ability to segment and manipulate phonemes and larger units. Some phonological skills that are important for analyzing the sound patterns in spoken words are present at or shortly after birth, whereas others develop in early infancy. Young infants discriminate between speech sounds that contain phonetic contrasts characteristic of their language environments, and they also appear to be sensitive to phonetic contrasts characteristic of other languages (Eilers, 1977; Eilers, Wilson, & Moore, 1977; Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Molfese & Molfese, 1979, 1980, 1985). With further development, preschool children are able to segment spoken monosyllabic words into onsets and rimes

and, thus, to play nursery rhyme games (Vellutino & Scanlon, 1987). As they continue to develop, children learn to segment polysyllabic words into syllables as they approach kindergarten age and monosyllabic words into phonemes around first grade (Lieberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). Over the past decade, a consensus has emerged among researchers that phonological processing skills are fundamental to language development and to subsequent reading abilities (Brady, 1991; Fletcher, Foorman, Shaywitz, & Shaywitz, 1999; Wagner, Torgesen, & Rashotte, 1994). Children with better phonological skills generally appear to develop into better readers.

The question that concerns the present article is whether event-related potential (ERP) techniques can be used to assess differences in reading skill levels. The ERP is a portion of the ongoing electroencephalogram (EEG) that is repeatedly time-locked to the beginning of a stimulus presentation

(e.g., sound, picture). This time lock allows variations in the brain response to be linked to variations in the evoking stimuli and directly mapped onto other, co-occurring behaviors. The brain responses to repeated stimulus presentations are then averaged together to remove random and non-stimulus-related background electrical activity that is inherent in the ongoing EEG.

Because the ERP technique does not require a planned and overt behavioral response from individuals, it is particularly well suited for the study of early infant and child development. Moreover, as the ERP provides latency as well as amplitude information, it can provide information concerning the rapidity with which the brain processes information (*latency*) as well as the level of neural discharges associated with the processing of information (*amplitude*). Finally, the ERP provides some degree of spatial resolution capabilities that permit a basis for speculations concerning the distribution of processing mechanisms across

different brain regions that are engaged in the relevant cognitive functions. Additional information on ERP techniques useful for studying cognitive processes was included in Molfese, Molfese, and Kelly (2001).

Research has demonstrated that the ERP technique can effectively study both general and specific aspects of the brain's response to stimuli in the external (e.g., speech sounds) as well as the internal environment (Molfese, 1978a, 1978b). For example, the ERP can be used to study an individual's perceptions and decisions during tasks or following a learning situation (Molfese, 1983; Nelson & Salapatek, 1986; Ruchkin, Sutton, Munson, & Macar, 1981), to reflect learning across a brief period of time, such as a 15-min study period, or during an interactive session lasting 10 minutes per day for a week (Molfese, 1989; Molfese, Morse, & Peters, 1990).

ERPs have been found to be sensitive to virtually all dimensions of the reading process, from phonology (Molfese, 2000) through syntax (Brenzitz & Leikin, 2001; Leikin, 2002) to semantics (Schulte-Korne, Deimel, et al., 2004), and to related skills such as rhyming (Lovrich, Cheng, Velting, & Kazmerski, 2003). Although work has advanced on these issues, surprisingly little ERP work has investigated how differences in brain processing relate to differences in reading skills. Proverbio, Vecchi, and Zani (2004) were among the first to address this question.

There is little agreement among scientists about the identification of specific brain structures involved in different stages of reading and word processing. Unfortunately, we know even less about the order in which these different brain structures become active in the reading process. To address these points, Proverbio et al. (2004) recorded ERPs from 28 scalp sites of 10 Italian university students while they processed meaningful and meaningless Italian words in a phonemic/phonetic decision task. Visual ERPs were recorded to different orthographic stimuli, half of which were Italian

words (high vs. low frequency of occurrence) and half of which were meaningless strings of letters (legal pseudowords and letter strings). Participants were instructed to decide if a "phone" was present or not in a word (e.g., "Is there a /k/ in cheese?"). Proverbio et al. reported that ERPs changed as a function of changes in both lexical frequency and orthographical regularity during the first 150 ms following stimulus onset. The centroparietal P150 amplitude was larger in response to high-frequency words than in response to low-frequency ones and larger in response to words and pseudowords than in response to letter strings. P150 amplitude was the same in response to well-formed meaningful words as in response to meaningless words when the latter had a low lexical frequency, suggesting to Proverbio et al. that highly familiar words are recognized as meaningful unitary visual objects at very early stages of processing, through a visual route to an orthographic input lexicon. Subsequent negative ERP amplitudes between 250 and 350 ms were larger over the left occipital-temporal electrode sites during the presentation of words and pseudowords, but larger over the left frontal regions during the reading of letter strings. Proverbio et al. speculated that such spatial differences indicated a "dissociation in accessing the phonemic representation of well- or ill-formed strings of characters." Thus, at the beginning of the ERP waveform detected at anterior electrode locations, an automatic process occurs that facilitates the recognition of very familiar words—or at least familiar letter strings that are pronounceable. Immediately following this event, a related process triggers several patterns of lateralized responding. In other words, word recognition and processing continue for some period of time as different brain regions become engaged to process different aspects of the stimuli.

A number of recent ERP studies investigated differences in reading skill levels in adults and children. In one study, Lovrich, Cheng, Velting, and

Kazmerski (1997) reported that ERPs, reaction time (RT), and response accuracy differed between 14 adults with average or impaired reading abilities. Participants engaged in the phonological and semantic categorization of spoken words. Participants with a reading impairment made significantly slower and less accurate responses than average readers on both tasks. When the ERP data were analyzed, participants with a reading impairment generated a larger negative peak at approximately 480 ms during a rhyme processing task. However, no differences were noted between reading groups for the semantic processing task. Clearly, ERPs appear sensitive to differences in reading skill levels, at least as far as phonological processing is involved. Given the rich history of findings that mark a close relationship between phonological processing skills and reading skills, this finding is not surprising. However, it is surprising that Lovrich et al. found no effect for semantic processing. It was our speculation that intersubject variability contributed to the lack of semantic findings, because semantic factors played a more variable role in reading levels due to the more prominent role played by mapping phonology onto orthographic characters. If this was the case, a larger range of reading skills, which included not only below-average and average readers but above-average readers as well, could yield some indication that ERPs were sensitive to semantic processing skills.

To address the issue of semantic and phonological processing as a function of reading skill level, the present study tested three groups of children who differed in their reading skills. Based on the work of Lovrich et al. (1997) and Proverbio et al. (2004), we anticipated that ERP differences would occur between these three groups. More specifically, by Hypothesis 1, it was expected that the early portion of the ERP—specifically, the N1-P2 complex—would show the fastest latencies for above-average readers and the slowest latencies for below-

average readers, with average readers falling between these two groups. Moreover, by Hypothesis 2, it was expected that hemisphere differences would occur between the three groups. Given the findings reported by Proverbio et al., it was anticipated that above-average and average readers would generate larger left-hemisphere amplitude responses than the below-average readers. Given the expectation that semantic factors would interact with phonological factors, Hypothesis 3 anticipated that children at different reading levels would respond differently to words than to pronounceable nonwords, and that they would also respond in a different fashion to these two types of stimuli than they would to orthographically incorrect but phonologically correct words. If the children were using a phonological strategy to discriminate words from other orthographic items, ERPs should respond similarly to words and to the orthographically incorrect but phonologically correct words (e.g., *kat*). If, on the other hand, the children used a word recognition strategy that allowed them to access semantic information more directly, the ERPs were expected to discriminate the words from the pronounceable nonwords and the ortho-

graphically incorrect but phonologically correct words.

Method

Participants

Twenty-seven children (14 girls, 13 boys) between 9 and 12 years of age ($M = 10.7$ years, $SD = 9$ months) participated in this study. All children participated in two phases of testing: (a) an ERP test of word classification, during which they indicated their word-nonword decisions behaviorally while their brain responses to visual stimuli were recorded; and (b) a behavioral assessment test session, which measured cognitive and language abilities, and a test of oral reading skills, on which their group membership was based. Children were required to pass a visual screening test for corrected vision for each eye of at least 20/30. Children were divided into three different reading ability groups based on their word recognition and reading skills using Slosson scores (Slosson & Nicholson, 1994). The three groups differed significantly from each other ($p < .001$). Participant characteristics for the three different groups are summarized in Table 1.

Measures

Behavior Measures. Each child completed standardized assessments of word reading, rhyme detection, and phonological processing. Furthermore, a handedness test (Oldfield, 1978) was administered to all children to determine their hand preferences.

The *Slosson Oral Reading Test-Revised* (SORT-R; Slosson & Nicholson, 1994) was administered by the school and was used as a screening tool to assess each child's word recognition and reading skills. The SORT-R has good internal consistency and test-retest stability, all yielding coefficients above .95. Passage Comprehension from the *Woodcock-Johnson Test of Achievement* and Reading Comprehension from the *Peabody Individual Achievement Test* correlate with the SORT-R .68 and .83, respectively.

Rhyme Detection is one of eight subtests of the *Phonological Abilities Test* (PAT; Muter, Hulme, & Snowling, 1997). The PAT is a rapid assessment of phonological awareness skills. The Rhyme Detection subtest has 3 demonstration items and 10 test words. Children are shown a page with four pictures. A target picture appears above three test pictures. The child is

TABLE 1
Means and Standard Deviations of Demographic and Behavior Measures by Reading Ability Group

Group	n	LQ		Grade		SORT-R		Age		NEPSY		PAT	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Above-average readers													
Girls	4	.88	.14	5.50	0.58	9.28	2.43	10.50	0.85	10.25	2.06	10.00	0.00
Boys	4	.81	.12	5.25	0.96	8.80	1.66	10.44	1.11	11.25	4.03	10.00	0.00
Both sexes	8	.85	.13	5.38	0.74	9.04	1.94	10.47	0.91	10.75	3.01	10.00	0.00
Average readers													
Girls	5	.84	.16	5.60	0.55	5.96	1.09	11.13	0.64	7.00	2.55	9.80	0.45
Boys	4	.68	.33	5.50	0.58	5.60	0.81	10.63	0.70	8.75	1.71	10.00	0.00
Both sexes	9	.76	.25	5.55	0.53	5.80	0.94	10.91	0.68	7.78	2.28	9.89	0.33
Below-average readers													
Girls	5	.81	.24	5.40	0.55	3.82	1.01	10.45	0.69	8.00	2.55	9.40	1.34
Boys	5	.86	.13	5.60	0.55	3.02	0.77	11.25	0.81	5.60	2.41	9.80	0.45
Both sexes	10	.84	.18	5.50	0.53	3.42	0.94	10.85	0.82	6.80	2.66	9.60	0.97

Note. LQ = laterality quotient (Oldfield, 1971; LQ > .50 indicates high right-hand preference); SORT-R = *Slosson Oral Reading Test-Revised* (Slosson & Nicholson, 1994); NEPSY = *NEPSY Developmental Neuropsychological Assessment*, Phonological Processing subtest (Korkman, Kirk, & Kemp, 1998); PAT = *Phonological Abilities Test*, Rhyme Detection subtest (Muter, Hulme, & Snowling, 1997).

asked to point to the picture whose name rhymes with the target word ("What rhymes with *cat*? *Fish*, *bell*, or *hat*?"). Internal consistency reliabilities (.67-.97) and test-retest reliability (.58-.86) are high. Regarding criterion-related validity, PAT scores correlated .37 to .66 with Single Word Reading from the *British Abilities Scales* (BAS; Elliott, Smith, & McCulloch, 1996).

A subtest was drawn from the *Developmental Neuropsychological Assessment* (NEPSY; Korkman, Kirk, & Kemp, 1998) to assess phonological processing by assessing phonemic awareness, including word identification from a segment and phonological segmentation at the syllable and single-letter level (e.g., the child creates a new word by omitting a phoneme/syllable or substituting a phoneme)

Electrophysiological Testing

Stimuli. The visual stimuli were 15 orthographic items that included three-letter consonant-vowel-consonant (CVC) syllables. Five CVCs were regular words (e.g., *bag*); a second group of 5 CVCs included orthographic items that sounded like words if pronounced but that orthographically were not words (e.g., *bak*); and a final set of 5 items were pronounceable nonwords (e.g., *dak*). Each stimulus was presented seven times in randomly ordered blocks, where each block included one item from each category. Once all CVCs from each category were presented, a new random block order was presented. Each stimulus was presented for 1 s, followed by a varied interstimulus interval (ISI) from 2 to 4 s before the next CVC was presented. The children were instructed to press one button if they saw a word or if they saw letter combinations that if pronounced would sound like a word. A second button was to be pressed if the item was not a word.

ERP Testing Procedures. Each child was tested individually in a sound-attenuated testing room. Prior to the experiment, the child was famil-

iarized with the testing room. Once the child was seated comfortably, his or her head was measured to determine the appropriate electrode net size and the two reference points (Cz, a mid-central position at the top of the head, and *nasion*, a central position at the top of the bridge of the nose) to assist in aligning the electrode net when it was placed on the child's head. Prior to placement, the net was soaked in a warm potassium chloride solution (1.5 teaspoons of KCl, 1 L of distilled water with 3 cc of Johnson's Baby Shampoo) that served as a conductor for electrical currents from the scalp to the electrodes of the net, thereby negating the need for abrading the participant's scalp.

The brainwaves were recorded using a high-density array of 128 Ag/AgCl electrodes embedded in soft sponges and arranged into a net (Geodesic Sensor Net, EGI Inc.). During recording, all electrodes were referenced to Cz and then subsequently re-referenced to an average reference during data analysis. All impedances remained at or below 40 k Ω throughout the test session, as indicated by measures taken before and after the stimulus presentation period. The high pass filter was set to 0.1 Hz and the low pass filter to 30 Hz.

Following electrode net application, the child was instructed to sit quietly and to view the items displayed on a high-resolution monitor positioned 1 m in front of the child at eye level. During stimulus presentation, the child's EEG and electromyography (EMG) were continuously monitored, and behavioral observations were made, to track the child's state and determine when stimulus presentation should occur. During periods of motor activity or inattention, stimulus presentation was suspended. Testing was resumed when the child's alertness and motor activity returned to an acceptable level.

Stimulus presentation was controlled by the Electrophysiological Graphical Imaging System (EGIS), v. 2.2 (EGI, Inc.). Net Station 1.0 (EGI,

Inc.) was used to record the electrophysiological data. The data were amplified 10,000 times and continuously sampled and stored. Subsequent data analyses focused on a subset of this data stream that was sampled every 4 ms over a 1-s period (250 samples/s). For subsequent analyses, the 700-ms period immediately following stimulus onset was selected for further analysis. Based on previous work with a similar age population, the 700-ms period was selected because most of the synchronized activity of the ERP had concluded at the end of the 700-ms post-stimulus onset period.

Procedure

The behavior assessments were administered in the standard manner, with the instrument order varied across children as much as possible while still maintaining the integrity of the standardized assessment procedures. Following behavioral assessments, the children participated in the ERP testing. The ERP and behavioral components of the study were administered independently by researchers who were blind to the child's performance on the behavioral assessments.

Results

Data analyses involved two phases: (a) analyses of children's performance on the behavioral assessment measures, and (b) analyses of the ERP data collected in response to the visually presented CVCs.

Behavioral Assessment Results

Means and standard deviations for the behavioral assessments are reported in Table 1 for the three groups of children—those with reading scores above average, average, and below average. One-way ANOVAs were used to compare group differences on the behavior assessment tasks and screening tasks. Differences were noted between groups only for the SORT-R, $F(2, 24) =$

40.60, $p < .0001$, and the phonological processing measure, $F(2, 24) = 4.22$, $p < .027$.

The number of correct and omitted responses to the words versus nonwords visual stimuli for each condition and participant were analyzed using a two-way, Group (3) \times Condition (2) ANOVA. There were no group or condition differences in the number of omitted responses ($p > .1$). Main effects of group, $F(2, 72) = 17.164$, $p < .001$, and condition, $F(2, 72) = 15.354$, $p < .001$, were identified for the number of correct responses. Post hoc analyses using Tukey's HSD further indicated more correct responses to words than to nonwords that sounded like words ($p < .001$) or to other nonwords ($p = .011$). Furthermore, above-average readers produced more correct responses than average ($p = .005$) and below-average readers ($p < .001$), whereas there were no differences between the latter two groups.

There was also a Group \times Condition interaction, $F(4, 72) = 2.812$, $p = .032$. Post hoc tests noted no group differences in the number of correct responses to words. However, for non-

words that sounded like words, above-average readers produced more correct responses than average ($p = .038$) and below-average readers ($p = .003$). There were no differences between average and below-average readers. For nonwords, above-average readers had more correct responses than below-average readers ($p = .002$), but other group differences were not significant. These effects are illustrated in Figure 1.

Electrophysiological Results

The digitized ERP data from all participants were segmented to include a 100-ms prestimulus interval (baseline) and a 704-ms poststimulus interval. Prior to the statistical analyses, the data were re-referenced to the average of all electrodes. Next, artifact rejection was carried out on the ERP data for each electrode to eliminate ERPs contaminated by motor movements and eye artifacts from further analysis. If an artifact (operationally defined as a shift in the voltage level in excess of $\pm 80 \mu\text{V}$) occurred on any one electrode channel during the 100-ms pre- or 700-ms post-stimulus period on any trial, all of the

ERPs collected across all of the electrode sites for that trial were discarded from subsequent analyses. Rejection rates were comparable across groups and stimulus conditions. Following this, the segmented data were averaged individually for each participant. Electrodes identified as "bad" (i.e., poor signal quality on 10% or more of the trials) were replaced by interpolating their data from immediately adjacent electrodes. Following the baseline adjustment and averaging procedures, all data from individual electrodes were averaged within each of 10 scalp regions (5 anatomical regions for each hemisphere—frontal, central, parietal, occipital, and temporal; see Figure 2). This approach reflected anatomically based boundaries and represented a modification of the clusters initially proposed by Curran (1999). The purpose of this clustering procedure was to reduce the number of variables in order to increase statistical power.

This analysis sequence followed procedures outlined and used successfully in previous studies with a variety of different participant populations. The data set was submitted to a two-step analysis procedure that involved the use first of a principal components analysis (PCA) with varimax rotation to identify major regions of variability in the ERP and then of an ANOVA to determine whether such variability occurred systematically in relation to the variables under investigation. This analysis sequence followed the procedures used by Molfese and others since 1976 (Molfese, Nunez, Seibert, & Ramaiah, 1976) and has been used extensively in programmatic research across numerous laboratories (Brown, Marsh, & Smith, 1979; Chapman, McCrary, Bragdon, & Chapman, 1979; Donchin, Teuting, Ritter, Kutas, & Hefley, 1975; Ruchkin et al., 1981; Segalowitz & Cohen, 1989). Moreover, its findings have been replicated across laboratories (e.g., Gelfer, 1987; Segalowitz & Cohen, 1989). This analysis approach has proven successful both in identifying the ERP regions where most of the variability occurred across

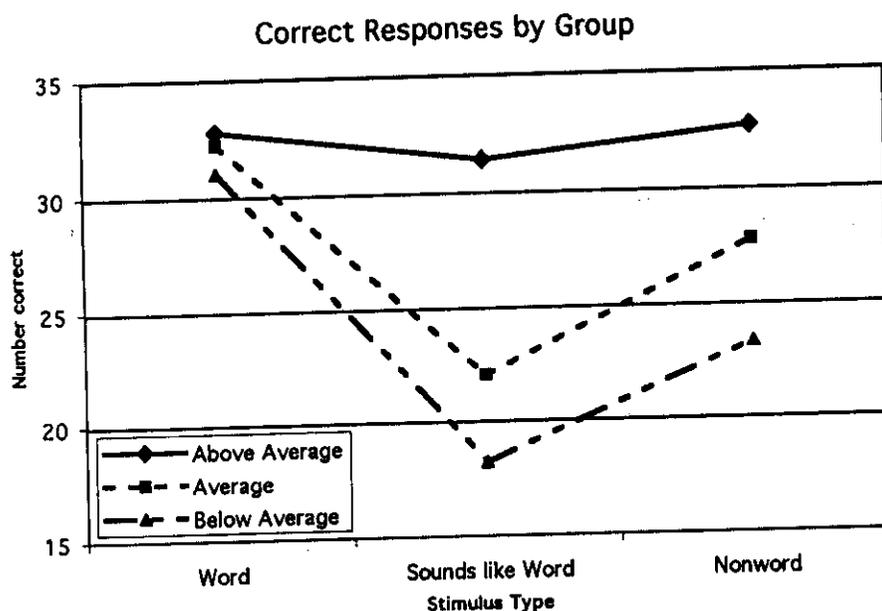


FIGURE 1. The mean correct responses for the three groups of children (above-average, average, and below-average) for the three stimulus classes of words, orthographically incorrect but phonologically correct ("sounds like") words, and non-

ERPs and children and, subsequently, in determining if the variability characterized by the different PCA extracted factors resulted from systematic changes in the independent variables under investigation (Rockstroh, Elbert, Birbaumer, & Lutzenberger, 1982, p. 63). When questions were raised regarding the misallocation of variance in a PCA analysis across immediately adjacent peaks, Wood and McCarthy (1984) noted that traditional amplitude and latency approaches were "no less subject to the problem of component overlap" (p. 258; see also Chapman & McCrary, 1995). Furthermore, when sufficient power is available, the likelihood of misallocation is marginalized. "To sum up . . . the results of Wood and McCarthy (1984) were due to an excessive and unrealistic statistical power. Moreover, baseline-to-peak measures are not superior to PCA with respect to variance misallocation and, thus, this comparison supports the use of the PCA-Varimax strategy for ERP component analysis" (Beauducel & Debener, 2003, p. 112). Given our current power estimates, we considered the PCA approach reasonable for the present investigation.

Once the PCA identified where within the ERPs most of the variability occurs, the ANOVA was used to identify the source of this variability. The repeated-measures ANOVA accomplished this task by determining whether the variability reflected in the factor scores assigned for each factor to each averaged ERP differed as a function of changes in the independent variables. This procedure directly addressed the question whether ERP wave shapes at different electrode sites and latencies (characterized by factors) changed systematically in response to different group, electrode, and stimulus conditions as a function of reading skill levels and sex.

The analysis consisted of several steps. First, the 810 averaged ERPs were subjected to a PCA in which a series of orthogonally rotated factors were identified and rotated using a

Scree criterion. Next, the factor scores (weights) from the PCA were subjected to analysis of variance, with separate repeated-measures ANOVAs for Reading Group (3; above average, average, and below average) \times Sex (2; boys and girls) \times Stimulus Category (3; words, pronounceable nonwords, and nonwords) \times Electrode Region (5; frontal, central, parietal, occipital, and temporal) \times Hemisphere (2; left and right).

PCA. Figure 2 displays the waveforms for the centroid, or grand averaged ERP waveform, and plots the six factor loadings derived from this data set by PCA. Three major peaks were

clearly observed in the centroid (at the top of the figure): an initial positive peak that reached its maximum positive value at 112 ms (P112), a subsequent large negative peak at 220 ms (N220), and a later positive peak at 320 ms (P320), which was then followed by a slow, negative trend in polarity that continued to the end of the data window. Factor 1, accounting for 30.81% of the total variance, was characterized by a late slow wave that began approximately 400 ms after stimulus onset, peaked at 616 ms, and slowly declined through 700 ms, the end of the analysis window. Factor 2, accounting for 24.42% of the variance,

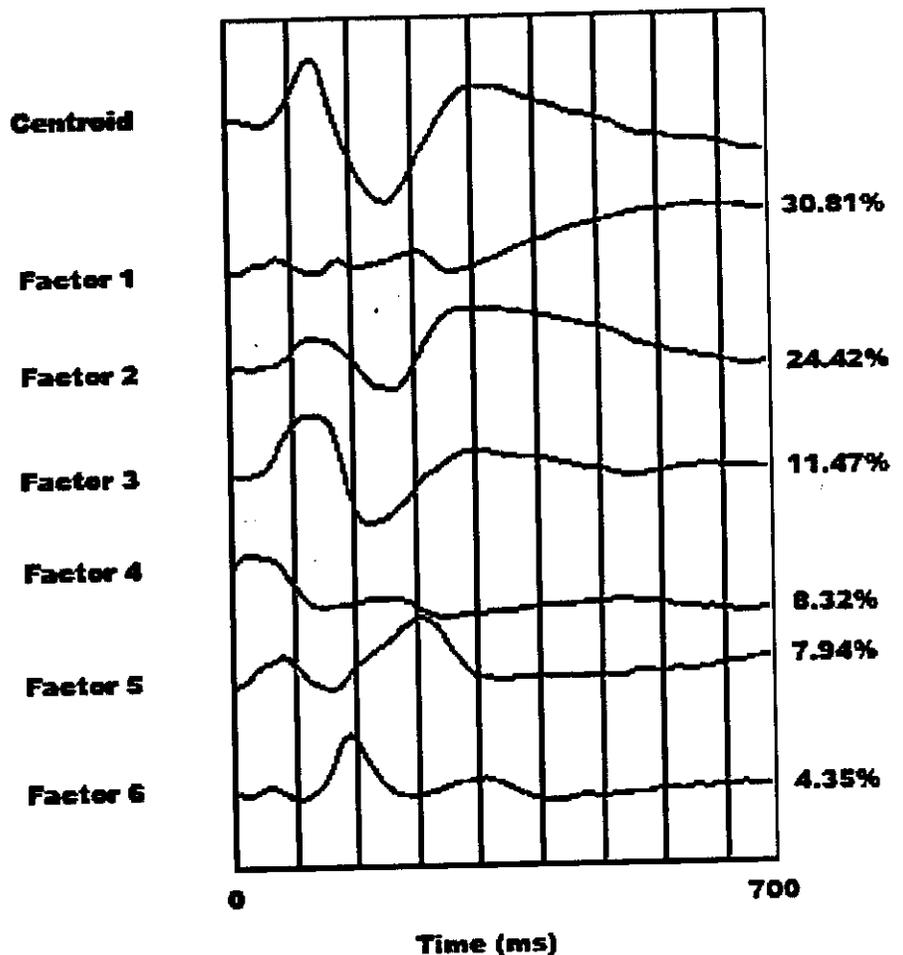


FIGURE 2. The centroid (grand average ERP) and the 6 factors derived from the principal components analysis for the 704-ms period of the data analysis. Total percentage variances accounted for by each factor are displayed to the right of that factor.

reflected increasing variance between 268 ms and 524 ms, with peak variance reached at 308 ms. Factor 2, then, appears to capture the variability in the ERP waveform surrounding the first negative (N220) and the second positive (P320) peak. Factor 3 (11.47% variance) also captured two regions of variability—the first from 76 to 140 ms (peaking at 112 ms), and a second between 164 and 228 ms (peaking at 188 ms). The former region appears to capture the variability surrounding P112, whereas the second captures the variability associated with N220. Factor 4 captured variability that occurred at the start of the waveform and continued up to 84 ms (peaking at 28 ms) and may have contributed at some level to the initial rising slope of P112, whereas Factor 5 (7.94% variance) reflected variations in the ERP between 196 ms and 284 ms (peaking at 252 ms), thereby appearing to reflect more specifically variations in P320. Finally, Factor 6 (4.25% variance) characterized changes in the ERP waveform surrounding N220 between 140 and 180 ms (peaking at 156 ms).

Reading Group Differences. A Group \times Electrode Region \times Hemisphere interaction was identified through analyses conducted on Factor 6, a factor that appeared to detect differences in the region of the N220 component, $F(8, 84) = 3.337, p < .002$, power = .964. Group differences were noted for the right temporal electrode region only, $F(2, 24) = 3.81, p = .037$. Follow-up analyses indicated that the ERPs of above-average readers had larger amplitude than those of the average readers, $F(1, 15) = 10.977, p = .005$, but there were no significant differences between the average and below-average readers.

Furthermore, ERPs from the above-average group over the left-hemisphere sites were consistently larger than those recorded over right-hemisphere sites for frontal, $t(7) = 4.05, p < .005$; temporal, $t(7) = 2.54, p < .038$; and central sites, $t(7) = 2.41, p < .005$. However, larger ERPs did occur over the right hemisphere at the occipital sites, $t(7) = -2.69, p < .031$. Within-hemisphere differences were also noted between left-hemisphere pari-

etal and occipital sites, $t(7) = 2.82, p < .026$, and between left-hemisphere temporal and occipital electrode regions, $t(7) = 2.83, p < .025$. No between-hemisphere ERP differences were obtained from the average readers, although within-hemisphere variations did occur at two right-hemisphere regions. Specifically, ERPs from frontal right-hemisphere electrodes were smaller than those recorded from central right-hemisphere sites, $t(8) = -2.437, p < .041$, whereas larger amplitudes were detected at parietal right-hemisphere electrode sites than at occipital electrode sites, $t(8) = 3.015, p < .017$. No between- or within-hemisphere differences were found for any electrode sites for the below-average readers. Figure 3 illustrates the Group \times Hemisphere aspect of this interaction. Left-hemisphere ERPs for the average reader group exhibited a relatively small P112 component that occurred at approximately 120 ms, whereas the ERP amplitude for the above-average readers was larger and occurred later, at approximately 150 ms. The below-average reading group exhibited the largest P112 amplitude, which also occurred markedly later in time than that for the above-average and average readers. No such relationships characterized the right-hemisphere responses.

A Group \times Electrode \times Hemisphere interaction was also found for Factor 1, in the region of the ERP waveform that characterized the slow negative shift toward baseline activity after 400 ms following stimulus onset, $F(8, 84) = 3.335, p < .002$, power = .877. Contrasts for this interaction indicated that toward the end of the ERP, between-group differences occurred over the right central electrode region, $F(2, 24) = 5.03, p = .015$. Follow-up analyses indicated that the ERPs of above-average readers returned more quickly to baseline compared to the average readers, $F(1, 15) = 5.208, p = .037$, whose ERPs were more positive. ERPs of average readers were also more positive relative to below-average readers, $F(1, 15) = 11.782, p = .003$. Moreover, the av-

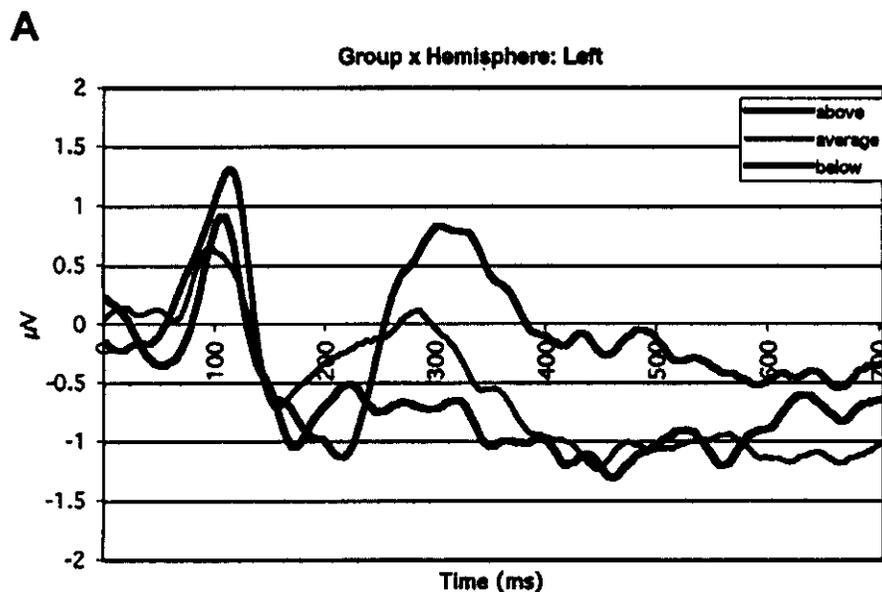


FIGURE 3. A. Group-averaged ERPs collapsed across all left-hemisphere electrodes for children in the above-average, average, and below-average groups. B. Group-averaged ERPs collapsed across all right-hemisphere electrodes for children in the above-average, average, and below-average groups.

average readers generated smaller amplitude ERPs than the below-average readers generated over the left frontal electrode region, $F(1, 17) = 4.802, p = .043$.

Furthermore, no effects were detected for the above-average readers over right-hemisphere sites, whereas right-hemisphere ERPs were larger for the average readers at frontal, $t(8) = -2.458, p < .039$; parietal, $t(8) = -2.565, p < .033$; central, $t(8) = -2.569, p < .033$; and occipital, $t(8) = -2.473, p < .039$, sites. ERPs recorded from the below-average readers also were larger over right-hemisphere electrode sites at parietal, $t(9) = -2.673, p < .025$, and occipital sites, $t(9) = -2.332, p < .045$. A within-hemisphere difference was noted in which ERP amplitudes were larger at frontal than at central electrode sites, $t(9) = 2.695, p < .025$.

Condition Differences. ERPs did vary in response to the different stimulus categories, and these effects appeared to be consistent across individuals with different reading skill levels. A main effect for condition, $F(2, 42) = 5.827, p < .0006$, power = .847; a Condition \times Electrode interaction, $F(8, 168) = 3.782, p < .001$, power = .986; and a Condition \times Hemisphere interaction, $F(2, 42) = 3.89, p < .028$, power = .671, characterized Factor 6—the factor that in part characterized the initial large negative component, N220. The Condition \times Electrode interaction reflected ERP differences between responses to words and nonwords as well as responses to words versus the orthographically misspelled words. In general, larger amplitudes were recorded from more posterior sites to all visual stimuli. Frontal electrode sites generated smaller ERPs to words than to the orthographically incorrect but pronounceable words, $t(26) = -2.449, p < .021$, whereas parietal, $t(26) = 2.617, p < .015$, and occipital electrode sites, $t(26) = 3.392, p < .002$, generated larger amplitude responses to words. Likewise, occipital sites generated larger amplitude ERPs to words than to orthographically incorrect but pro-

nounceable words. Moreover, frontal electrode sites generated smaller amplitude responses to words than central sites, $t(26) = -2.326, p < .028$, whereas occipital sites generated larger responses than temporal sites, $t(26) = 2.424, p < .023$; parietal sites generated larger amplitudes to both orthographically incorrect but pronounceable words and nonwords than did occipital sites, $t(26) = 3.22, p < .003$, and $t(26) = 2.694, p < .012$, respectively.

A Condition \times Hemisphere interaction for Factor 3, $F(2, 42) = 4.56, p < .016$, power = .744, indicated that ERPs recorded to words from left-hemisphere sites were overall larger than those from right-hemisphere sites, $t(26) = 3.165, p < .004$, and that left-hemisphere sites responded with larger amplitudes to words than to orthographically incorrect but pronounceable words, $t(26) = 3.143, p < .004$, and nonwords, $t(26) = 3.422, p < .002$. Finally, nonwords elicited larger amplitudes than words over right-hemisphere electrode sites, $t(26) = -2.397, p < .024$.

Sex Differences. Several interactions involving sex-related effects were noted. These included a Condition \times Sex interaction for Factor 2 (latencies related to peaks at N220 and P320), $F(2, 42) = 3.453, p < .041$, power = .616, as well as an Electrode \times Sex interaction, $F(4, 84) = 7.183, p < .001$, power = .994. The first interaction reflected variations in *only* the girls' ERPs that were larger in response to words than to pronounceable nonwords, $t(13) = 2.645, p < .02$. The Electrode \times Sex interaction also reflected a marked difference in responding between boys and girls. Female children's ERPs differed between four scalp regions: frontal versus central, $t(13) = -3.792, p < .001$; central versus parietal, $t(13) = -8.395, p < .001$; parietal versus occipital, $t(13) = -4.937, p < .001$; and occipital versus temporal, $t(13) = 7.337, p < .001$. In other words, amplitude differences increased as the electrode sites became more posterior on the head for girls. A more limited pattern of larger poste-

rior amplitudes was noted in the boys, but for only parietal and occipital regions, with ERPs larger at parietal than occipital sites, $t(12) = -3.662, p < .003$, and occipital ERPs larger than temporal sites, $t(12) = 2.232, p < .05$.

Both a Condition \times Sex interaction, $F(2, 42) = 5.41, p < .008$, power = .818, and an Electrode \times Sex interaction, $F(4, 84) = 6.678, p < .001$, power = .99, were found also for Factor 3. As noted earlier, this factor reflected variations in the region of the N220. The Condition \times Sex interaction was due in part to larger ERPs produced by boys in response to nonwords than to the pronounceable nonwords, $t(12) = 2.541, p < .026$. No effects were noted for the girls. Unlike that for Factor 2, the Electrode \times Sex interaction for Factor 3 indicated similar patterns of responses for boys and girls, with female children generating larger ERPs at posterior sites, so that occipital responses were larger than ERPs recorded at parietal, $t(13) = -2.703, p < .018$, and temporal sites, $t(13) = 2.713, p < .018$, and parietal responses were larger than central ERP amplitudes, $t(13) = -2.447, p < .029$. Boys exhibited comparable amplitude differences, with larger responses at occipital than at parietal, $t(12) = -4.793, p < .001$, and temporal sites, $t(12) = 6.453, p < .001$, as well as larger parietal than central ERPs, $t(12) = -5.099, p < .001$.

Electrode Differences. The electrode differences noted in main effects generally exhibited the same patterns of responding reflected in the interactions described earlier for a number of factors. For Factor 2, the main effect for electrode, $F(4, 84) = 35.31, p < .001$, power = 1.00, reflected the pattern of increasing ERP amplitudes as electrode sites shifted to more posterior electrode sites. Parietal ERP amplitudes were larger than central, $t(26) = -7.615, p < .001$, which, in turn, were larger than frontally recorded ERPs, $t(26) = -2.551, p < .001$. Likewise, occipital ERP amplitudes were larger than those recorded from temporal sites, $t(26) = 5.735, p < .017$. Similar pat-

terms were noted for Factor 3, $F(4, 84) = 32.56, p < .001, \text{power} = 1.0$; Factor 4, $F(4, 84) = 6.77, p < .001, \text{power} = .991$; and Factor 5, $F(4, 84) = 6.57, p < .001, \text{power} = .989$.

Hemisphere Differences. Two regions or factors in the analyses identified main effects for hemisphere that did not interact with other variables in the design. These included a main effect for hemisphere for Factor 2, $F(1, 21) = 16.616, p < .001, \text{power} = .973$, in which the right-hemisphere response across electrode sites was larger than the left-hemisphere response between 100 and 132 ms and again between 268 and 524 ms, $t(26) = -3.62, p < .001$; and a main effect for hemisphere for Factor 5, $F(1, 21) = 18.386, p < .001, \text{power} = .983$, in which left-hemisphere responses were markedly larger than those recorded over the right hemisphere between 196 and 284 ms.

Discussion

This study investigated electrophysiological indicators of word processing in children who varied in their reading skills. The ERPs reflected both differences and similarities in ERP responses between groups of children who exhibited different reading skill levels.

ERP Effects Related to Reading Levels

In support of Hypotheses 1 and 2, there were clear differences in both processing regions (i.e., electrode sites) and processing speed (i.e., latency) between children with different reading levels. This was reflected specifically in the Group \times Electrode \times Hemisphere interactions for Factors 1 and 6. Factor 6 reflected variations in ERP effects in the earlier region of the N220, and larger ERP amplitudes over four of the five left-hemisphere electrode regions, whereas a reversed laterality pattern occurred at the occipital sites. Intriguingly, these hemisphere differences

were noted at this latency only for the above-average readers; no hemisphere differences were found for either average or below-average readers. This effect was manifested in amplitude and latency variations in the large negative peak and the immediately following positive peak (P320), with shorter latencies and smaller amplitudes occurring for the above-average readers over the average readers, who, in turn, generated smaller and faster latencies than the below-average readers. Breznitz and Meyler (2003) reported similar findings of a latency advantage for ERP latencies for typical readers, with latencies delayed among participants with dyslexia for their second and third positive ERP components.

In contrast, the interaction identified through Factor 1, which characterized the last third of the ERP waveform, failed to identify any effects for the above-average readers but did find larger amplitude ERPs over right-hemisphere sites for four electrode regions in the average readers and for two regions in the below-average readers. One could conclude from this that (a) processing of reading information by above-average readers occurs markedly faster than in average and below-average readers, and (b) above-average reading skills draw more heavily and more consistently on left-hemisphere mechanisms, as reflected by the higher left-hemisphere amplitudes. Average and below-average readers, in contrast, draw more heavily on right-hemisphere skills (as characterized by their larger right-hemisphere amplitude ERPs in this temporal region). Finally, the hemisphere differences decrease as reading skills decrease. Above-average readers exhibit more hemisphere differences than average readers, who, in turn, generate more hemisphere differences than below-average readers. This latter finding suggests that different brain regions of individuals with lower reading skills are more likely to respond to processing demands in a similar fashion, thereby suggesting less brain dif-

ferentiation in people with lower reading skill levels.

ERP Effects Independent of Reading Levels

Hypothesis 3 held that the brain responses of the different reading skill groups would differ between the different stimulus types. In fact, however, ERP effects only noted stimulus differences shared across all reading groups. The ERP responses of all children were characterized by some marked similarities in responding to their environments. First, the ERPs collected from all children consistently discriminated between the different stimulus sets, as indicated by Factor 3. Left-hemisphere sites clearly generated larger amplitude ERPs to words than to orthographically incorrect but pronounceable words and nonwords, whereas right-hemisphere electrode sites generated larger amplitude ERPs to nonwords. Thus, the left-hemisphere brain responses of *all* children appeared to process words differently from the other two stimulus sets, whereas ERPs collected from the right hemisphere in turn discriminated the nonwords from the other two sets, including words and pronounceable nonwords.

Second, regardless of reading skill levels, the brain responses at certain latencies clearly reflected hemisphere differences (Factors 2 and 5). For Factor 2, a larger left-hemisphere amplitude occurred between 196 ms and 284 ms, followed in time by a larger right-hemisphere amplitude between 268 ms and 524 ms. Certainly, other investigators have reported hemisphere differences in ERP responses between good and poor readers (Segalowitz, Wagner, & Menna, 1992). However, although some good readers exhibited certain hemispheric ERP asymmetries and some poor readers did not, such group difference failed to account for variations in overall reading skills. Although changes in hemisphere responding have been noted for decades, the basis for such differences remains

unclear, especially given moment-by-moment changes across the ERP waveform. Factors such as volume conduction—where currents can move across the scalp and create larger amplitudes through the convergence and addition of voltages on the scalp—can produce scalp ERP differences that may be unrelated to the tissue directly under that scalp region. Answers to questions about the basis of hemisphere differences are beyond the scope of the present article, but they may be resolved through other data analysis techniques, such as source and dipole localization (Giard, Perrin, Echallier, Thevenet, Fromenet, & Pernier, 1994; Scherg, Vajsar, & Picton, 1989), and through other investigative methodologies, such as Positron Emission Tomograph (PET; Shaywitz, Pugh, et al., 1995) and functional magnetic resonance imaging (fMRI; Hugdahl, Heiervang, et al., 1998). The latter investigators have argued for both structural and functional bases for differences in reading abilities.

Third, marked and consistent sex differences occurred across reading levels at different points of time during the brain response to the three stimulus sets (Factors 2, 3, and 5). Notably, none of these differences interacted with reading skill levels. That is, ERPs recorded from these children failed to show any sex differences related to reading ability. Where differences in the brain waves did occur, however, related to how male and female children processed words from other material they read. Boys responded to nonwords with larger ERPs than to orthographically incorrect but pronounceable words. The female responses appeared to be delayed to the area of the P320 (Factor 2), when they generated larger ERPs to words than to the orthographically incorrect but pronounceable nonwords. Sex differences were also noted in the distribution of ERP amplitudes across the scalp. For example, early in the waveform (112 ms), similar patterns of ERP responses were found for both boys and girls,

with both sexes generating larger ERPs at posterior sites, so that occipital responses were larger than ERPs recorded at parietal, temporal, and central electrode sites. Subsequently, at 320 ms (Factor 2), ERP amplitude differences in female children increased as the electrode sites became more posterior on the head, whereas only a much more limited pattern of larger ERP amplitudes occurred for boys at the most posterior sites (parietal and occipital regions). However, even there, the pattern was somewhat different in boys, with larger ERPs noted at parietal than at occipital sites.

Clearly, the brain responses of children with different reading skills respond in complex ways to simple reading tasks. The task used in the present study involved reading words in isolation, which is a less complex task than isolating individual words in a text passage. However, it is clear that the processing of reading information changes rapidly over even a very short period of time (i.e., 700 ms). The latency differences that characterize the different ERP components show that reading activities for different types of materials evoke rapid, temporal similarities and differences, with some activity simultaneously displayed over different scalp regions, whereas other activity occurs subsequently in time over yet other brain regions. Moreover, although there are clear processing differences between children who read at different skill levels, there are also a number of marked commonalities in the way that the brains of all children respond during a reading scenario. These commonalities exist both across reading skill levels and across sex differences. Although the number of children in the present study was relatively small, clearly enough power existed (typically between .8 and 1.0) to detect small differences in brain processing. Even so, both male and female children at different reading skill levels responded alike. The presence in this study of so many similarities in brain responding across the sexes and read-

ing abilities strongly suggests that at least as far as a reading deficit is concerned, the impact on boys and girls will be the same. At the same time, sex differences are noted in the ways in which both sexes respond to different types of reading materials.

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REFERENCES

- Beauducel, A., & Debener, S. (2003). Misallocation of variance in event-related po-

- tentials: simulation studies on the effects of test power, topography, and baseline-to-peak versus principal component quantifications. *Journal of Neuroscience Methods*, 124, 103-112.
- Brady, S. (1991). The role of working memory in reading disability. In S. Brady & D. Shankweiler (Eds.), *Phonological processes in literacy: A tribute to Isabelle Y. Liberman* (pp. 129-161). Hillsdale, NY: Erlbaum.
- Breznitz, Z., & Leikin, M. (2001). Effects of accelerated reading rate on processing words' syntactic functions by normal and dyslexic readers: Event related potentials evidence. *The Journal of Genetic Psychology*, 162, 276-296.
- Breznitz, Z., & Meyler, A. (2003). Speed of lower-level auditory and visual processing as a basic factor in dyslexia: Electrophysiological evidence. *Brain and Language*, 85, 166-184.
- Brown, W., March, J. & Smith, J. (1979). Principal component analysis of ERP differences related to the meaning of an ambiguous word. *Electroencephalography and Clinical Neurophysiology*, 46, 709-714.
- Chapman, R., & McCrary, J. (1995). EP component identification and measurement by principal components analysis. *Brain and Cognition*, 27, 288-310.
- Chapman, R., McCrary, J., Bragdon, H., & Chyapman, J. (1979). Latent components of event-related potentials functionally related to information processing. In J. E. Desmedt (Ed.), *Cerebral evoked potentials in man*. London: Oxford University Press.
- Curran, T. (1999). The electrophysiology of incidental and intentional retrieval: ERP old/new effect in lexical decision and recognition memory. *Neuropsychologia*, 37, 771-785.
- Donchin, E., Teuting, P., Ritter, W., Kutas, M. & Heffley, E. (1975). On the independence of the CNV and the p300 components of the human averaged evoked potential. *Journal of Electroencephalography and Clinical Neurophysiology*, 38, 449-461.
- Eilers, R. (1977). Context-sensitive perception of naturally produced stop and fricative consonants by infants. *The Journal of the Acoustical Society of America*, 61, 1321-1336.
- Eilers, R., Wilson, W., & Moore, J. (1977). Developmental changes in speech discrimination in infants. *Journal of Speech and Hearing Research*, 20, 766-780.
- Eimas, P., Siqueland, E., Jusczyk, P., & Vigorito, J. (1971). Speech perception in infants. *Science*, 171, 303-306.
- Elliott, C., Smith, P., McCulloch, K. (1996). *The British Ability Scales: Second Edition*. Windsor, Berkshire, UK: Nelson Publishing.
- Fletcher, J., Foorman, B., Shaywitz, S., & Shaywitz, B. (1999). Conceptual and methodological issues in dyslexia research: A lesson for developmental disorders. In H. Tager-Flusberg (Ed.), *Neurodevelopmental disorders* (pp. 271-305). Cambridge, MA: MIT Press.
- Gelfer, M. (1987). An AER study of stop-consonant discrimination. *Perception & Psychophysics*, 42, 318-327.
- Giard, M. H., Perrin, F., Echallier, J. F., Thevenet, M., Fromenet, J. C., & Pernier, J. (1994). Dissociation of temporal and frontal components in the human auditory N1 wave: A scalp current density and dipole model analysis. *Electroencephalography and Clinical Neurophysiology*, 92, 238-252.
- Hugdahl, K., Heiervang, E., Nordby, H., Smievoll, A., Steinmetz, H., Stevenson, J., et al. (1998). Central auditory processing, MRI morphometry and brain laterality: Applications to dyslexia. *Scandinavian Audiology. Supplementum*, 49, 26-34.
- Korkman, Kirk, & Kemp. (1998). *NEPSY: A Developmental Neuropsychological Assessment-Manual*. New York: Psychological Corp.
- Leikin, M. (2002). Processing syntactic functions of words in normal and dyslexic readers. *Journal of Psycholinguistic Research*, 31, 145-163.
- Liberman, A., Cooper, F., Shankweiler, D., & Studdert-Kennedy, M. (1967). Perception of the speech code. *Psychological Review*, 74, 431-461.
- Lovrich, D., Cheng, J. C., Velting, D., & Kazmerski, V., et al. (1997). Auditory ERPs during rhyme and semantic processing: effects of reading ability in college students. *Journal of Clinical and Experimental Neuropsychology*, 19, 313-330.
- Lovrich, D., Cheng, J., & Velting, D., et al. (2003). ERP correlates of form and rhyme letter tasks in impaired reading children: A critical evaluation. *Neuropsychology, Development, and Cognition. Section C, Child Neuropsychology*, 9, 159-174.
- Molfese, D. (1978a). Left and right hemisphere involvement in speech perception: Electrophysiological correlates. *Perceptual Psychophysiology*, 23, 237-243.
- Molfese, D. L. (1978b). Electrophysiological correlates of categorical speech perception in adults. *Brain and Language*, 5, 25-35.
- Molfese, D. (1983). Event-related potentials and language processes. In A. W. K. Gaillard & W. Ritter (Eds.), *Tutorials in ERP research: Endogenous components* (pp. 345-368). Amsterdam: The Netherlands: North Holland.
- Molfese, D. L. (1989). Electrophysiological correlates of word meanings in 14-month-old human infants. *Developmental Neuropsychology*, 5, 79-103.
- Molfese, D. L. (2000). Predicting dyslexia at 8 years using neonatal brain responses. *Brain and Language*, 72, 238-245.
- Molfese, D. L., & Molfese, V. J. (1979). Hemisphere and stimulus differences as reflected in the cortical responses of newborn infants to speech stimuli. *Developmental Psychology*, 15, 505-511.
- Molfese, D. L., & Molfese, V. J. (1980). Cortical responses of preterm infants to phonetic and nonphonetic speech stimuli. *Developmental Psychology*, 16, 574-581.
- Molfese, D. L., & Molfese, V. J. (1985). Electrophysiological indices of auditory discrimination in newborn infants: The bases for predicting later language development. *Infant Behavior and Development*, 8, 197-211.
- Molfese, D.L., Molfese, V.J., & Kelly, S. (2001). The use of brain electrophysiology techniques to study language: A basic guide for the beginning consumer of electrophysiology information. *Learning Disability Quarterly*, 24, 177-188.
- Molfese, D. L., Morse, P. A., & Peters, C. J. (1990). Auditory evoked responses from infants to names for different objects: Cross modal processing as a basis for early language acquisition. *Developmental Psychology*, 26, 780-795.
- Molfese, D. L., Nunez, G., Seibert, S., & Ramaiah, N. (1976). Changes in factors affecting differential hemispheric activity in infants. *Annals of the New York Academy of Sciences*, 280, 821-833.
- Muter, V., Hulme, C., & Snowling, M. (1997). *The phonological abilities test*. London: Psychological Corp.
- Nelson, C., & Salapatek, P. (1986). Electrophysiological correlates of infant recognition memory. *Child Development*, 57, 1483-1497.
- Oldfield, R. (1971). The assessment of handedness: The Edinburgh Inventory. *Neuropsychologia*, 9, 97-113.
- Proverbio, A. M., Vecchi, L., & Zani, A., et al. (2004). From orthography to phonetics: ERP measures of grapheme-to-phoneme conversion mechanisms in

- reading. *Journal of Cognitive Neuroscience*, 16, 301-317.
- Rockstroh, B., Elbert, T., Birbaumer, N., & Lutzenberger, W. (1982). *Slow brain potentials and behavior*. Baltimore: Urban-Schwarzenberg.
- Ruchkin, D., Sutton, S., Munson, R., & Macar, F. (1981). P300 and feedback provided by the absence of the stimuli. *Psychophysiology*, 18, 271-282.
- Scherg, M., Vajsar, J., & Picton, T. (1989). A source analysis of the late human auditory evoked potentials. *Journal of Cognitive Neuroscience*, 1, 336-355.
- Schulte-Korne, G., Deimel, W., Bartling, J., & Remschmidt, H., et al. (2004). Neurophysiological correlates of word recognition in dyslexia. *Journal of Neural Transmission*, 111, 971-984.
- Segalowitz, S., & Cohen, H. (1989). Right hemisphere EEG sensitivity to speech. *Brain and Language*, 37, 220-231.
- Segalowitz, S. J., & Wagner, W. J., Menna, R., et al. (1992). Lateral versus frontal ERP predictors of reading skill. *Brain and Cognition*, 20, 85-103.
- Shaywitz, B. A., Pugh, K. R., Constable, R., Shaywitz, S., Bronen, R., & Fulbright, R., et al. (1995). Localization of semantic processing using functional magnetic resonance imaging. *Human Brain Mapping*, 2, 149-158.
- Slosson, R., & Nicholson, C. (1994). *Slosson oral reading test-Revised*. New York: Slosson.
- Vellutino, F., & Scanlon, D. (1987). Phonological coding, phonological awareness, and reading ability: Evidence from a longitudinal and experimental study. *Merrill-Palmer Quarterly*, 33, 321-363.
- Wagner, R., Torgesen, J., & Rashotte, C. (1994). Development of reading-related phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology*, 30, 73-87.
- Wood, C., & McCarthy, G. (1984). Principal component analysis of event-related potentials: simulation studies demonstrate misallocation of variance across components. *Electroencephalography and Clinical Neurophysiology*, 59, 249-256.