Atypical Language Representation in Patients with Chronic Seizure Disorder and Achievement Deficits with Magnetoencephalography

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Summary: Purpose: To characterize the relation between hemispheric asymmetries in language-specific brain activity and reading/spelling achievement by using magnetoencephalography (MEG).

Methods: Patients (n = 83) with medically intractable complex partial seizures of either left- or right-hemisphere origin were classified as having reading and/or spelling deficits (RS) or as not impaired (NI) by using standard achievement tests. All patients had undergone noninvasive functional mapping of receptive language cortex by using MEG as part of a preoperative seizure surgery evaluation.

Results: RS patients with left-hemisphere seizure onset exhibited relatively greater activation and earlier onset of late, language-specific MEG activity in posterior temporal and inferior parietal areas of the right as compared with the left hemisphere than did NI patients. These findings also were evident on an individual basis and were independent of global intellectual abilities.

Conclusions: Reading and spelling achievement deficits in patients with complex partial seizures of left-hemisphere origin are associated with atypical language organization, possibly secondary to reorganization of language function to right-hemisphere areas that are not as efficient as homotopic areas in the left hemisphere in supporting reading and spelling functions.

Key Words: Magnetoencephalography—Epilepsy—Learning disabilities—Functional imaging.
examination of the language and memory competence of the isolated hemisphere. Results from such studies have often emphasized the negative effects of atypical language organization, as indicated by greater right-hemisphere language competence, on nonverbal functions (24–27). Loring et al. (25) found, in a relatively large group of >500 patients with left-hemisphere seizure onset, that individuals with predominantly right-hemisphere language representation exhibited a reduction in visuospatial, but not language, skills compared with those with left-hemisphere language dominance. A similar pattern of cognitive dysfunction was observed in patients with bilateral language representation who had also experienced a presumed shift in handedness. This phenomenon, which has been termed crowding, is hypothesized to occur when reorganization of language function occurs in the right hemisphere in areas that might have been originally destined to subserve nonverbal functions (24–28). Strauss et al. (26) also found significant effects of atypical language organization on nonverbal skills with limited effects on linguistic functions in patients with left hemisphere–onset seizures. Billingsley and Smith (29), however, found that when children and adolescents with early-onset temporal-lobe epilepsy of left-hemisphere origin were matched closely for age and gender, atypical speech representation was associated with lowered performance on both verbal and nonverbal intellectual abilities. Few studies have assessed the relation between atypical language organization and academic skills in groups of patients with intractable epilepsy.

In the current study, we identified patients as having achievement deficits based on patterns of performance on standard tests of reading and spelling. As in previous studies by our group (30,31) and others (32,33), we used a cutoff rather than a discrepancy definition of academic achievement deficiency. A discrepancy approach has the disadvantage of classifying individuals with lower IQ scores as being nondisabled (34,35), although they have a significant functional deficit. This is a particular problem in groups with chronic epilepsy in which the distribution of IQ scores may be skewed toward lower values (36). Both adults and children were included in the study. Whereas this resulted in a wide age range, problems with basic academic skills have been shown to persist into adulthood, with little change in the major phenotypic characteristics over time (37–39).

We hypothesized that increased abnormality in the profile of activation observed during the MEG imaging studies, characterized by greater relative activation of right as compared with left posterior superior temporal and inferior parietal areas (including Wernicke’s area) known to be involved in language function, would be associated with deficits in reading and spelling achievement within the group with left-, but not right-, hemisphere seizure onset.

METHODS

Subjects

This was a retrospective study of 83 patients aged 9 to 54 years (mean, 27.2; SD, 12.9), including 43 female and 40 male subjects, who were evaluated at the Texas Comprehensive Epilepsy Program at the University of Texas Health Science Center at Houston. This represented a consecutive series of patients who had undergone the MEG language-mapping protocol between 1997 and 2003. Evaluation included, for each patient, continuous 24-h video telemetry-EEG monitoring, magnetic resonance imaging, neuropsychological testing, and the Wada procedure. The relations between MEG and Wada findings are reported elsewhere (16). Previous studies from our center and others reported a close correspondence between estimates of hemispheric dominance for language derived from MEG testing and those determined by using the Wada procedure (16). In addition, single-photon emission computed tomography, positron emission tomography, MEG, and intracranial electrodes were used to aid identification of the epileptogenic zone in many cases.

With these methods, 60 patients were identified as having complex partial seizures emanating from the left hemisphere, and 23, from the right. Seven participants were left-handed as determined by using the Edinburgh handedness inventory (40). The preponderance of patients with left-hemisphere seizure onset is in agreement with the findings of other larger scale studies (e.g. 41–43). All patients had English as their primary language by history. None had a history of prior neurosurgical resection. All participants received a standardized test of intellectual functioning. Adults were administered either the Wechsler Adult Intelligence Scale–Revised (44) or the Wechsler Abbreviated Scale of Intelligence (45). Children ages 16 and younger were administered either the Wechsler Abbreviated Scale of Intelligence or the Wechsler Intelligence Scale for Children–III (46). Patients with Full-Scale IQ scores <70 were not included the study. All participants also were given standardized tests of reading and spelling. Adults were administered the Wide Range Achievement Test–3 (47). Children were given the Basic Reading subtests of the Woodcock–Johnson III (48) and the spelling subtest of the Wide Range Achievement Test–3. Standard scores on the subtests were averaged to form a composite for each patient, and patients were placed into the reading/spelling-disabled (RS) group on the basis of having a composite score ≤90, with at least one of the subtests being below this cutoff (13). These criteria are similar to those used in other studies (32,33,50–52). With these methods, 31 patients were placed in the RS group. The remainder were placed into a not-impaired (NI) group.

Group means on demographic and seizure variables are presented as a function of side of seizure onset in Table 1. IQ and achievement test scores are presented in
Table 1. Demographic data for achievement deficit groups by side of seizure onset

<table>
<thead>
<tr>
<th></th>
<th>Left Hemisphere Onset</th>
<th>Right Hemisphere Onset</th>
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<tbody>
<tr>
<td></td>
<td>NI</td>
<td>RS</td>
</tr>
<tr>
<td>Number of Patients</td>
<td>39</td>
<td>21</td>
</tr>
<tr>
<td>Age (years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>21.9</td>
<td>32*</td>
</tr>
<tr>
<td>SD</td>
<td>11.6</td>
<td>11.2</td>
</tr>
<tr>
<td>Females (%)</td>
<td>46%</td>
<td>52%</td>
</tr>
<tr>
<td>Left handed (%)</td>
<td>7%</td>
<td>5%</td>
</tr>
<tr>
<td>Age at Onset (years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>8.3</td>
<td>7.6</td>
</tr>
<tr>
<td>SD</td>
<td>7.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Duration of Seizure Disorder (years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>13.6</td>
<td>24.4*</td>
</tr>
<tr>
<td>SD</td>
<td>10.4</td>
<td>12.1</td>
</tr>
<tr>
<td>Etiology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symptomatic (N)</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Cryptogenic (N)</td>
<td>28</td>
<td>15</td>
</tr>
<tr>
<td>Highest School Grade (years of school)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>10.8</td>
<td>11.5</td>
</tr>
<tr>
<td>SD</td>
<td>5.8</td>
<td>2.2</td>
</tr>
</tbody>
</table>

NI, no academic deficiency; RS, Reading and/or Spelling deficient; *p < .01.

Table 2. Group differences on continuous measures were evaluated by using analysis of variance (ANOVA) with group membership (NI, RS) as the independent variable. Group differences on categorical variables were evaluated by using Fisher’s exact test. Different numbers of asterisks (*) indicate significant group differences.

Stimuli and tasks

Patients were given a recognition memory task for spoken words and event-related fields (ERFs) were recorded to each word stimulus. The word list consisted of 90 abstract English nouns with scores of ≤3.0 on the Paivio Concreteness scale (53). Word frequency ranged from “very frequent” (AA) to nine occurrences per million (54). A native speaker of English with a flat intonation produced auditory stimuli (duration between 300 and 750 ms; mean, 450 ms). Stimuli were digitized with a sampling rate of 22,000 Hz and 16-bit resolution and delivered binaurally via two 5 m-long plastic tubes terminating in ear inserts. Intensity was 80 dB SPL at the patient’s outer ear. Thirty words from each list were used as targets, and the remaining 60, as distractors, forming six blocks of trials. No significant differences were found between the target and distractor lists in either word concreteness or frequency. The target stimuli were repeated in every block (in a different random order each time) mixed, with 10 new distractors. The target stimuli were presented for study immediately before the MEG scan. Stimulus presentation parameters were identical during the actual recording and study sessions. Stimuli were presented with a variable interstimulus interval (2.5–3.5 s).

Patients were asked to lift their index fingers whenever they detected a repeated word. The responding hand was varied randomly across patients. During the entire testing session, the patient was asked to keep his or her eyes open, fixating on a dark dot placed on the ceiling at eye level, to reduce eye movements or blinks and prevent ERF contamination by rhythmic activity (typically in the alpha band), which can seriously interfere with the accurate detection of task-related brain activity.

MEG data acquisition and analysis

All patients were tested with a whole-head neuromagnetometer (Magnes 2500; 4D Neuroimaging, San Diego, CA, U.S.A.) equipped with 148 magnetometer sensors and housed in a magnetically shielded room designed to reduce environmental magnetic noise that might interfere with biologic signals. The typical recording session required the patient to lie motionless on a bed with his or her

<table>
<thead>
<tr>
<th></th>
<th>NI</th>
<th>RS</th>
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<tbody>
<tr>
<td>Full Scale IQ (SS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>96.2</td>
<td>83.0**</td>
</tr>
<tr>
<td>SD</td>
<td>10.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Verbal IQ (SS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>96.6</td>
<td>82.4**</td>
</tr>
<tr>
<td>SD</td>
<td>10.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Performance IQ (SS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>96.2</td>
<td>86.3*</td>
</tr>
<tr>
<td>SD</td>
<td>12.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Reading (SS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>101.6</td>
<td>81.5**</td>
</tr>
<tr>
<td>SD</td>
<td>6.5</td>
<td>10.2</td>
</tr>
<tr>
<td>Spelling (SS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>102.4</td>
<td>81.9**</td>
</tr>
<tr>
<td>SD</td>
<td>8.2</td>
<td>13.6</td>
</tr>
</tbody>
</table>

SS, Standard Score; NI, no academic deficiency; RS, Reading and/or Spelling deficient; *p < .01; **p < .0001.
head inside the helmet-like device for ~15 min. The signal was recorded with a bandpass filter set at 0.1 and 50 Hz, and digitized for 950 ms (254-Hz sampling rate) including a 150-ms prestimulus period. The next step involved visual inspection of single-trial ERF segments to identify those contaminated by (a) eye- or head-movement-related magnetic artifacts, or (b) epileptogenic activity. Movement artifacts were defined as magnetic flux deflections >3 picoTesla (pT) peak-to-peak in the recordings from magnetometer sensors placed just above the eyes. As it is possible to mistake small blinks or lateral eye movements with magnetic deflections caused by brain activity, the surface distribution of magnetic flux associated with these deflections was frequently taken into account. ERF epochs that contained epileptiform events (spikes or sharp waves) were similarly excluded from further analyses. The recordings were then filtered offline with a bandpass between 0.1 and 20 Hz and subjected to an adaptive filtering procedure that is part of the 4-D Neuroimaging signal-analysis package. These steps are necessary to minimize the amount of low-frequency magnetic noise that is typically present in MEG recordings.

At least 140 ERF artifact-free epochs were used to calculate two averaged waveforms (one for trial blocks 1–3 and a second reflecting magnetic activity obtained during trial blocks 4–6). The intracranial generators, or activity sources, of the averaged ERFs were modeled as single equivalent current dipoles (ECDs) and fitted at successive 4-ms intervals (55). For a given time, the source-fitting algorithm was applied to the magnetic flux measurements obtained from a group of 34–38 sensors, always including both magnetic flux extremes. Source computation was restricted to latency periods during which a single pair of magnetic flux extremes dominated the left and/or the right half of the head surface. The algorithm used in this study searched for the source that was most likely to have produced the observed magnetic field distribution at a given time. Source solutions were considered satisfactory if they were associated with a correlation coefficient of ≥0.9 between the observed and the “best” predicted magnetic field distribution. After dipole modeling was performed, the estimated activity sources associated with the late components of the ERFs (>200 ms after stimulus onset) were examined in detail. Contiguous activity sources from each of the two (split-half) ERFs were compared according to their (a) degree of latency overlap and (b) spatial proximity. With this procedure, we identified reproducible clusters of activity sources, which in previous studies have been verified to overlap anatomically with Wernicke’s area (17,18). The number of consecutive late activity sources reflects the amount of time neuromagnetic activity took place in each area during processing of the word stimuli. This measure has been shown to be an excellent index of the degree of engagement of language-specific cortices in each hemisphere in language tasks (16). Hemispheric asymmetries of language-specific magnetic activity were determined by using a laterality index (LI), which was calculated according to the formula: \( R - L \)/(R + L), where R represents the number of acceptable late activity sources in the right hemisphere, and L, the corresponding number in the left hemisphere. In addition, the earliest latency when late activity sources were first noted in language-specific cortices was examined. In previous studies, this measure was found to be a significant predictor of behavioral performance in language tasks (57). To determine the anatomic regions corresponding to each activity source, source locations, which were initially computed in reference to the MEG cartesian coordinate system mentioned earlier, were coregistered on T1-weighted, magnetic resonance images (MRIs) (TR, 13.6 ms; TE, 4.8 ms; recording matrix, 256 × 256 pixels, 1 excitation, 240-mm field of view, and 1.4-mm slice thickness) obtained from each participant. Transformation of the MEG coordinate system into MRI-defined space was achieved with the aid of three lipid capsules inserted into the ear canals and attached to the nasion, which were easily visualized on the MRIs, by using the MRI Overlay tool, which is part of the 4-D Neuroimaging software. A standard MRI atlas of the human brain (58) served as a reference for the identification of the cerebral structures where sources were localized.

RESULTS

All patients exhibited late activity sources (after the resolution of the N1m, ~200 ms after stimulus onset) in the posterior portions of the left and/or right temporal lobes, including superior temporal gyrus (often extending into the superior temporal sulcus and the middle temporal gyrus, and occasionally into the supramarginal and angular gyri).

To examine the temporal course of late, language-specific MEG activation during the language task within these areas, the number of sources, averaged across the two split-halves of the data, were determined for successive 100-ms bins beginning after the resolution of the N1m for each patient. Means for the achievement-deficit groups with left-hemisphere seizure onset are presented in Fig. 1a for the left hemisphere and in Fig. 1b for the right hemisphere. Group means for patients with right-hemisphere seizure onset are presented in Fig. 1c and d.

These trends were analyzed by using a multivariate approach to a repeated measures design with Epoch (200–299 ms, 300–399 ms, . . . , 600–700 ms) and Hemisphere (left, right) as within-subjects variables and Group membership (RS, NI) as the between-subjects variable. This analysis was performed separately for the left- and right-hemisphere seizure-onset groups. Performance IQ was included as a covariate to control for group differences in intellectual function. Within the left seizure-onset group,
a significant Group × Hemisphere interaction was found: \( F(1, 57) = 4.13; p < 0.05 \). Follow-up analyses, performed separately for each achievement group, indicated a significant effect of Hemisphere for the NI group, \( F(1, 38) = 34.75; p < 0.0001 \). In contrast, the effect of Hemisphere was not significant for the RS group (\( p > 0.1 \)). Analyses for patients with right-hemisphere seizure onset indicated a significant effect of Hemisphere \( [F(1, 20) = 5.46, p < 0.03] \) but no effects of achievement-deficit Group (\( p > 0.35 \)).

The mean number of activity sources in each hemisphere across epochs and the onset latency for this activation for each achievement-deficit group with left and right seizure onset are presented in Table 3. Both measures are significant predictors of behavioral performance in language tasks (56). As these analyses indicate, whereas all four groups exhibit greater left- as compared with right-hemisphere activation, this asymmetry is attenuated in RS patients with left-hemisphere seizure onset. As mentioned earlier, group effects on the onset latency of late language-specific activation were evaluated by using a repeated measures approach to a within-subjects design with Hemisphere (left, right) as the within-subjects variable and Group (NI, RS) as the between-subjects variable.

### TABLE 3. Group Means on MEG measures

<table>
<thead>
<tr>
<th></th>
<th>NI Left Hemisphere</th>
<th>NI Right Hemisphere</th>
<th>RS Left Hemisphere</th>
<th>RS Right Hemisphere</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Hemisphere Seizure Onset</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of Activity Sources</td>
<td>M 30.5</td>
<td>16.6</td>
<td>21.9</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>SD 27.9</td>
<td>21.5</td>
<td>13.6</td>
<td>10.3</td>
</tr>
<tr>
<td>Onset Latency (ms post stimulus onset)</td>
<td>M 340.4</td>
<td>365.2</td>
<td>331.2</td>
<td>302.0</td>
</tr>
<tr>
<td></td>
<td>SD 93.6</td>
<td>126.0</td>
<td>105.3</td>
<td>59.2</td>
</tr>
<tr>
<td><strong>Right Hemisphere Seizure Onset</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of Activity Sources</td>
<td>M 33.5</td>
<td>19.5</td>
<td>33.4</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>SD 20.5</td>
<td>18.9</td>
<td>25.1</td>
<td>25.7</td>
</tr>
<tr>
<td>Onset Latency (ms post stimulus onset)</td>
<td>M 270.1</td>
<td>310.4</td>
<td>237.4</td>
<td>301.8</td>
</tr>
<tr>
<td></td>
<td>SD 47.5</td>
<td>80.5</td>
<td>48.6</td>
<td>148.1</td>
</tr>
</tbody>
</table>
Although analyses did not reach significance for either the right- (p > 0.6) or left-hemisphere onset groups (p > 0.12), the typical asymmetry in onset latency, with earlier onset in the left as compared with right hemisphere for late, language-specific MEG activation, is reversed in the RS group with left-hemisphere seizure onset.

The averaged waveforms and examples of isofield contour maps obtained at specific times for a single patient are presented in Fig. 2. The coregistered MEG-MRI scans for patients with typical profiles of language-specific MEG activity from the NI and RS groups are presented in Fig. 3a and 3b, respectively. The RS patient exhibits a more bilateral profile of activation in posterior language areas than the NI patient.

The relation between language representation and academic achievement as a continuous variable

To evaluate the relation between academic achievement and language organization on an individual basis, the reading/spelling achievement composite score was regressed on the MEG LI. Again, Performance IQ was used as a covariate to control for effects of general intellectual function on results. A significant relation was found between the two measures within the left-hemisphere group \[F(1, 57) = 5.18, \ p < 0.03\] but not within the right-hemisphere group (p > 0.45). The mean of the spelling and reading scores is plotted as a function of the MEG LI in Fig. 3. Academic skills tend to decrease as the MEG LI becomes more positive, indicating a greater degree of atypical (more relative activity in the right hemisphere) hemispheric asymmetry in language-specific brain activity.
The relation between global intellectual abilities and patterns of language-specific MEG activity

Within the left hemisphere–onset group, no significant correlations were noted between Full-Scale (p > 0.09), Verbal (p > 0.11), or Performance (p > 0.2) IQ scores and the MEG LI.

DISCUSSION

The MEG task used in the present study has been shown to provide a reliable and valid index of the relative engagement of areas of the brain specialized for receptive language function (16). Therefore current findings suggest that deficits in reading and spelling achievement are associated with atypical language organization in patients with chronic seizure disorder of left-hemisphere onset. This abnormality appears to be characterized by greater relative engagement of the right hemisphere during language processing. Consistent with group findings, examination of the relation between academic achievement and language laterality on an individual basis indicated that the probability of poor academic achievement increased significantly with increasing lateralization of receptive language representation to the right hemisphere across patients with left-hemisphere seizure onset.

Previous studies in patients with chronic seizure disorder regarding the relation between atypical language organization, as indexed by the Wada test, and cognition have often emphasized the negative effects of reorganization of language cortex to the right hemisphere on nonverbal functions, with relative preservation of verbal functions (24–28). Few studies, however, have assessed academic skills in this group. In the current study, we found evidence for a reduction in reading and spelling skills to be related to abnormal patterns of activation of posterior temporal and inferior parietal language areas known to be involved in these skills.

Although evidence was found for an association between a reduction in academic skills and atypical language organization, unlike Loring et al. (25), we did not find a strong relation between atypical language organization and Performance IQ. As indicated earlier, Loring et al. (25) found that the “crowding” effect was specific to patients who had sustained a lesion severe enough to cause either a complete shift of language function to the right hemisphere or bilateral representation with a presumed shift of hand dominance from right to left. Current findings suggest no effect of atypical language representation on Performance IQ when the language shift is not complete, but only one patient exhibited what was interpreted as a complete shift of language function to the right hemisphere, and only seven patients with left-hemisphere seizure onset were left-handed. As this was a small number of patients, they were included with the larger group, and no effort was made to address the effect of handedness on the relation between academic achievement and language representation. In a larger group, this factor could be included in analyses, and the negative effects of atypical language organization on global nonverbal abilities might emerge.

It is not surprising that relations between reading and spelling skills and the degree of atypical language representation were limited to patients with left-hemisphere seizure onset. Language function is represented within the left hemisphere in the vast majority of neurologically intact right-handed controls (58,59), and a number of studies have found a significant increase in bilateral and/or right-hemisphere representation of language function in patients with epilepsy of left-hemisphere origin (16,29,60–63), presumably secondary either to the seizures themselves or to the seizure substrate. Seizure onset in the right hemisphere would, therefore, not be expected to affect language organization except in the most unusual cases in which the right hemisphere was genetically predetermined to be dominant for language function. The consistent relation between atypical language representation and achievement deficits does support the hypothesis that either the seizure substrate and/or seizures themselves result in a neurophysiologic abnormality that affects the acquisition of academic skills in individuals with chronic seizure disorder of left-hemisphere origin. The relatively earlier onset of activity in the right hemisphere in this group suggests that this abnormality may be secondary to reorganization of language function to right-hemisphere areas that are not as efficient as homotopic areas in the left hemisphere in supporting reading and spelling functions.

We used a cutoff definition of reading disability that is similar to that used in studies by our group (30,31) and others (32,33). This type of approach is consistent with suggestions that reading ability may be normally distributed in populations without neurologic involvement (64). In addition, a discrepancy approach has the disadvantage of classifying individuals with lower IQ scores as being nondisabled (34,35), although they may have a
significant functional deficit. The utility of the cutoff approach in populations with chronic epilepsy is highlighted by the finding that only four participants in the current study would have been classified as having reading disability by using a standard discrepancy approach of one standard deviation between IQ and reading achievement scores, although a much larger number clearly have a significant reading deficit. Furthermore, findings were independent of intellectual function, again providing support for the current approach.

Individuals with seizure disorder experience achievement deficits because of reduction in the quality and quantity of academic experience and alterations in parental and teacher expectations (5,65,66). All of the patients in the current study, however, had chronic seizures, no significant differences were seen among groups in highest school grade achieved, group differences in MEG data were independent of Performance IQ, and the relations between measures of verbal, nonverbal, and global IQ and atypical language organization were not significant. However, significant differences appeared among achievement-deficit groups in IQ scores. In addition, although the areas activated during MEG imaging are known to be involved in reading and spelling function, the MEG method used in this study was developed to image receptive language cortex. Therefore further research is necessary to determine to what extent the current findings generalize to specific cognitive functions and more homogeneous groups of patients.

Acknowledgment: This study was supported in part by NINDS grant NS37941 to Andrew C. Papanicolaou, Ph.D., and by the Vivian L. Smith Center for Neurologic Research, Houston, Texas.

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