RESEARCH

EEG Power Spectra of Children with Dyslexia, Slow Learners, and Normally Reading Children with ADD During Verbal Processing

Peggy T. Ackerman, Roscoe A. Dykman,
D. Michael Oglesby, and Joseph E. O. Newton

EEG power spectra were studied in two poor reader groups (with dyslexia and slow learning) and a normally reading clinic control group (with attention deficit disorder) as the children viewed strings of words and letters (seven categories). The children ranged in age from 7.5 to 12 years; 33 were girls, 86 were boys. Bilateral temporal and parietal sites and four midline sites were used. The major difference between groups was in the low beta band, where the ADD group had greater power at the parietal and midline sites. Also, the slow learner group had marginally greater low beta at the left than right temporal site, with the opposite trend found for the dyslexic and ADD groups. Across groups, power was greater at the right than at the left parietal site in the delta and alpha bands and at the right than at the left temporal site in the low beta band. Stimulus category effects were modest, with some alpha suppression to word strings, relative to letter strings, found in the poor readers. In correlational analyses, the combination of greater low beta and less theta power significantly predicted better reading and spelling. Results indicate that the adequate readers more actively processed the stimuli than did the poor readers.

Along with most of our fellow investigators, we believe that one major underlying deficit in specific reading disability (or dyslexia) is impaired phonological processing (see Goswami & Bryant, 1990; and Wagner & Torgesen, 1987, for recent reviews). For convenience, we use the term *dyslexia* to refer to a failure to learn to read and spell words at a rate appropriate for both age and IQ level. Dyslexic poor readers can be theoretically distinguished, then, from "garden variety" poor readers or slow learners (Stanovich, 1988), whose reading and spelling (and usually arithmetic) standard scores are not markedly discrepant from their IQs.

In three recent studies of children with dyslexia, we have documented deficits in simple phonological sensitivity. When asked to listen to a string of three or four short words (Bradley, 1984) and choose the one word that does not sound like (rhyme with) the others, a large fraction of children with dyslexia have difficulty (see Ackerman, Anhalt, Dykman, & Holcomb, 1986; Ackerman, Dykman, & Gardner, 1990a, 1990b; Ackerman, Dykman, Holloway, Paal, & Gocio, 1991; Bradley & Bryant, 1983). At least two thirds of children with dyslexia have difficulty with more complex phonological processing, especially the decoding of pronounceable nonsense words (Ackerman et al., 1991). Moreover, this difficulty in decoding nonsense words persists into adulthood (Felton, Naylor, & Wood, 1990). Additionally, the Colorado studies of monozygotic and dizygotic twins have revealed that phonological coding accounts for most of the heritable variance in word-recognition ability (Olson, Wise, Conners, Rack, & Fulker, 1989). Thus, the problem would seem to stem from a deficit and not simply a delay.

To gain some insight into how the brains of children with dyslexia process phonologically and/or orthographically similar stimuli, we designed two EEG experiments. Elsewhere (see Ackerman, Dykman, & Oglesby, 1994) we have reported findings from a rhyme judgment task in which visual event-related potentials (ERPs) were the brain function of interest. Here we will focus on children's EEG power spectra during their visual processing of verbal stimuli (word and letter strings). Earlier, we studied power spectra in four groups of boys (with hyperactivity, learning disabilities [LD] but not hyperactivity, mixed hyperactivity/LD, and no disabilities) who participated in a visual search task (Dykman, Holcomb, Oglesby, & Ackerman, 1982). The power band providing

JOURNAL OF LEARNING DISABILITIES
VOLUME 27, NUMBER 10, DECEMBER 1994
PAGES 619-630

best separation of groups was between 16 and 20 Hz (i.e., beta). The nondisabled group had the highest power in this band and the LD group the lowest, with the two hyperactive groups intermediate. The presence of beta activity is considered by most psychophysiologists to reflect active mental processing, whereas alpha is often associated with relaxation, and delta and theta with underarousal (Andreassi, 1989).

Hughes (1985) reviewed a number of EEG studies in children with dyslexia. He particularly emphasized the ''neurometric'' studies of John and associates (John, 1977; Pricep, John, Ahn, & Kaye, 1983) and the BEAM (brain mapping) studies of Duffy and his colleagues (Duffy, Denckla, Bartels, & Sandini, 1980). Both John and Duffy et al. found greater theta activity to characterize dyslexia. Lubar et al. (1985) likewise found greater theta activity in their subjects with dyslexia. The presence of slow activity is usually hypothesized to mirror less active processing (Andreassi, 1989). Lubar (1991) considers a large theta-to-beta ratio to be a hallmark of attention deficit disorder (ADD) and concomitant learning problems.

A recent study provided EEG spectra data on subjects with dyslexia and nondisabled readers during oral and silent reading (Galin et al., 1992). These investigators recorded from bilateral sites (central, parietal, and midtemporal) and banded data into five ranges: delta, theta, alpha, low beta, and high beta. Subjects read from texts that were either easy or difficult (based on their tested reading level) in both oral and silent conditions. Each task lasted 2 to 2.5 minutes. Power in all bands increased from silent to oral reading for both easy and difficult materials. No main effect was found for group, but there was a significant group by reading type (oral, silent) interaction that involved theta, low beta, and, marginally, high beta. The nondisabled readers showed a greater increase in power going from silent to oral reading than did the dyslexic group. The group difference in low beta but not theta was also found in the change from listening to speaking. Thus, the investigators concluded that the oral–silent group difference in theta is related to some aspect of the reading tasks other than presence or absence of overt speaking, but that the low beta difference is related to some aspect of overt speaking rather than to reading per se. They then suggested that the groups differed in their reading strategies and the degree to which they changed strategies between silent and oral reading. Oral reading obviously demands greater fidelity to the exact text than silent reading.

Another recent EEG investigation also bears on the data to be reported here. Flynn, Deering, Goldstein, and Rahbar (1992) studied EEG power spectra in two dyslexic subtypes, dysphonetics (*n* = 27) and dyseidetics (*n* = 6), classified via Boder and Jarrico's (1982) method. These children were contrasted with a control group (*n* = 6) during six active processing tasks, each of which lasted 2 minutes. Two conditions (oral reading and auditory analyses of orally presented words) produced a large number of electrode and frequency differences between the dyslexic and normal reader groups. During oral reading, the dyseidetic group differed most from the control group in the left temporal region, principally in the beta band. The dysphonetic group differed most from the control group at the right parietal and right occipital leads, again mostly in the beta band.

Flynn et al. (1992) considered the dyseidetic dyslexic readers to be similar to Lovett's (1984) rate-disabled readers. These children over-rely on phonics and do not easily automatize recognition of words. It is interesting to note that the dysphonetic and dyseidetic subtypes differed most from the control group in brain regions of presumed processing strength, but amplitudes were reduced, casting doubt on a compensation-from-strength hypothesis. In two other samples, Flynn and Deering (1989) also found increased left theta power during reading in dyseidetic poor readers. They suggested that children classified as dyseidetic expend more effort. Nondisabled children read without great effort, while the dysphonetic subtype gives up and skips or miscalls words, thus expending less effort than the dyseidetic subtype.

The design for the present study did not call for separation of the poor readers into dysphonetic and dyseidetic subtypes. Rather, we were interested in the question of whether ''garden-variety'' poor readers differ from dyslexic poor readers. As noted, garden-variety poor readers read and spell at approximately the level predicted for their age and IQ, whereas dyslexic poor readers read and spell at a significantly lower level than predicted from age and IQ (see Dykman & Ackerman, 1992, for a justification of this grouping). Fortuitously, for the purpose of comparing our data with that of Flynn et al. (1992), the garden-variety poor readers in our study were phonologically more advanced than the dyslexic poor readers (see Ackerman & Dykman, 1993); and both poor reader groups were phonologically impaired relative to the normally reading children with ADD, who were the clinical control group.

As elaborated in other reports (see Ackerman & Dykman, 1993; Ackerman et al., 1994), children with ADD provide a better control group for the two groups of poor readers than would the usual control group because it is virtually impossible to recruit poor readers who do not exhibit some attention problems (Dykman & Ackerman, 1991; Dykman, Ackerman, & Holcomb, 1985). Our aim was to have the three groups evenly matched on indices of attentional problems and hyperactivity. If a nondisabled control group had been used to contrast with the two poor reader groups, this normally reading group would differ from them on attention measures as well as reading ability. Therefore, EEG differences, if found between nondisabled and poor reader groups, could not be ascribed solely to the reading ability dimension.

It is disappointing that some 20 years after Chapman and Chapman's (1973) seminal book on the importance of using clinical control groups, so few investigators use them.

Given the literature reviewed above, we hypothesized that relative to the ADD control group, both groups of poor readers would exhibit greater theta power and less beta power while viewing lists of letters and first-grade-level words. The word and letter lists were constructed to contrast rhyming and nonrhyming conditions because, as noted above, impaired sensitivity to rhyme characterizes a majority of children with dyslexia. We hypothesized that nondisabled readers would be "primed" by rhyming lists and hence not exhibit as much beta activity as when viewing nonrelated stimuli. We further predicted that the poor readers would exhibit more alpha suppression, and/or greater beta power, to words than letters, as recognition of words is not apt to be as fully automatized as recognition of letters.

Method

Subjects

Subjects were 119 children, ages 7.5 to 12 years, who were referred to our Child Study Center or Developmental Center for psychoeducational evaluation. Those admitted to the study met clinical criteria for diagnoses of developmental reading disorder, attention-deficit/hyperactivity disorder (ADHD), or both (American Psychiatric Association, 1980, 1987). The sample included 33 girls and 86 boys; 11 were African American, 108 were White. Inclusion criteria included normal intelligence (Full Scale IQ $\geq$ 80 on the Wechsler Intelligence Scale for Children–Revised [WISC-R]; Wechsler, 1974); normal hearing and vision; normal physical health; a history of regular attendance at accredited schools; and English as the only language. Children with known neurological conditions or who were in need of psychiatric intervention were excluded. Children taking psychostimulants were admitted, provided they could go on drug holiday for the study.

Subjects were assigned to three groups: dyslexia, slow learning/borderline, or ADD only. These groups were formed using cut-scores on the WISC-R and Jastak and Jastak's (1984) Wide Range Achievement Test–Revised (WRAT-R). The children with ADD only (n = 56) were average or better readers and spellers (mean standard scores on the WRAT-R Reading and Spelling subtests > 90). The other two groups were below-average readers (mean Reading/Spelling standard scores $\leq$ 90). Poor readers designated as having developmental dyslexia (n = 42) had Full Scale IQs at least 17 points higher than their Reading/Spelling averages. The term *dyslexia* is used to designate an unexpected failure in literacy acquisition (single-word decoding and spelling) but does not imply a specific etiology. Poor readers classified as slow learners/borderline (n = 21) had less than a 17-point difference between IQ and Reading/Spelling. These children are intended to represent the garden-variety poor reader. The mean discrepancy between the Reading and Spelling index and IQ was 28.4 points for the dyslexic group, 8.1 points for the slow group, and 5.0 points for the ADD-only group, $F(2,116) = 77.87$, $p < .001$. Two of the slow learners and 14 of the ADD group actually had Reading/Spelling means greater than their IQs. Also, 8 subjects with ADD only had IQs > 17 points above their Reading/Spelling scores, but they were not disabled-for-age readers. The assignment to groups is obviously somewhat arbitrary but is defensible from the standpoint of educational policy as well as the regression of achievement scores on IQ (see Dykman & Ackerman, 1992, for an elaboration of the latter point). The research plan called for equal numbers of subjects in the two poor reader groups, but this goal could not be reached from our referral base. A school referral base would probably yield as many slow as dyslexic readers, especially if the IQ criterion was lowered to 70 or 75.

Note that children in the two poor reader groups could also have a clinical diagnosis of ADD or ADHD, including ADD without hyperactivity (ADD/WO). As expected, the three groups had highly similar mean scores on indices of attention and hyperactivity (see below). This finding replicates previous studies (i.e., Dykman & Ackerman, 1991; Dykman et al., 1985); that is, ADD and specific or developmental learning disorders are separate but often overlapping diagnoses.

Preliminary Workup

Subjects came to our Child Study Center for administration of a battery of reading tests. If their WISC-R and/or WRAT-R scores were not current (done within the year), these were also given. The reading battery included the word list from the Woodcock Reading Mastery Tests–Revised (Woodcock, 1987); the revised Gray Oral Reading Tests (GORT-R) (Wiederholt & Bryant, 1986), which entails reading graded paragraphs and answering comprehension questions; and Part II of the Decoding Skills Test (Richardson & DiBenedetto, 1985), which requires reading lists of real and nonsense words, each nonsense word being a pronounceable rhyme match for a paired real word. The real words (30 monosyllabic and 30 polysyllabic) are presented first, followed by the nonsense list.

Parents (usually mothers) or guardians were asked to fill out the Child Behavior Checklist (Achenbach & Edelbrock, 1983), which yields two broadband factors (Internalizing and Externalizing) as well as several narrowband scores. They were also asked the attention deficit disorder questions from the Diagnostic Interview for Children–Parent Version (DICA) (Herjanic & Reich, 1982) to validate the clinical diagnosis of ADD.

Teachers were asked to complete our expanded Conners' (1973) questionnaire, which includes 10 attention items listed in the DSM-III (American Psychiatric Association, 1980) as well as the 10-item abbreviated hyperkinesis index. The questionnaire also includes the items constituting the Iowa overactive/inattention and aggression factors (five items each) (see Loney & Milich, 1982). Each item is rated on a scale of 0 to 3 (0 = *absent;* 3 = *very much a problem*).

Laboratory Procedures

Children arrived at our laboratory at 8:45 a.m. A research assistant toured the area with them and then administered, in her office, a battery of brief tests hypothesized to tap dysfunctional processes underlying or associated with poor reading. The results from these tests have been reported elsewhere (Ackerman & Dykman, 1993). Three of the tasks that discriminated groups were (a) Bradley's (1984) oddity test, which assesses auditory phonological sensitivity to rhyme and alliteration; (b) Denckla and Rudel's (1976) Rapid Automatized Naming (RAN) task, which assesses rapid, continuous naming of letters and numbers; and (c) Cohen and Netley's (1981) running memory task, which taps the recency process in that rehearsal is precluded by list length and speed of presentation.

At approximately 10:30 a.m., the children were escorted to our physiological recording area, where electrodes were attached for three EEG procedures. The first was an arithmetic verification task (Ackerman, Newton, Oglesby, & Dykman, 1993); the second entailed viewing pairs of words and judging whether the second rhymed with the first (Ackerman et al., 1994).

In the third procedure, which is reported here, the children viewed five types of word strings and two types of letter strings. They were asked to focus on the Zenith color monitor screen and read silently all the words and letters they saw between the start and stop signals (green and red squares, respectively). They were told that they could not be sure how many words or letters would come between the signals, but that they should try to remember the last one seen in each series and report that word or letter to the experimenter. Only first-grade monosyllabic words were used.

The seven series (conditions), each of which lasted 40 seconds, were characterized as follows:

1. Orthographically similar rhyming words (e.g., *cat, hat, fat, bat, rat, mat, sat, pat*)
2. Orthographically dissimilar rhyming words (*blue, coo, do, few, who, you*)
3. Orthographically similar nonrhyming words (*car, can, cat, cab, cap*)
4. Dissimilar words (*boy, dog, tree, cake, bus*)
5. Semantically (categorically) similar words (*dog, cat, pig, bear, lamb, cow, horse*)
6. Phonemically confusable (rhyming) letters (*B, C, D, G, P, T, V*)
7. Phonemically nonconfusing letters (*F, H, J, L, M, N, R, S*)

The stimuli in each type of list were flashed at the rate of one every 2 seconds. Following the start signal, the first stimulus appeared 2 seconds later and remained on the screen until the next stimulus appeared. The letters within words and those singly presented were upper case, red in color, and 1 inch high. The stimuli within each list were arranged in pseudorandom order (no repeating sequences), and lists were randomized across subjects.

An experimenter stayed in the test cell throughout. The children were told they had won 10 cents after each correct answer.

Recording Procedures

The children were seated in a comfortable lounge chair in a sound-shielded and electrically shielded room. The chair was situated such that the child's head was 5 ft. from an eye-level color monitor. EEG electrodes were quickly attached with an expandable elastic cap fitted with tin electrodes. We have used this type of cap in previous studies with excellent results (see Holcomb, Ackerman, & Dykman, 1985, 1986). Lubar et al. (1985) also used the cap, as have numerous other investigators. Once the cap was in place, the electrodes were filled with electrolyte gel, which was gently rubbed into the scalp with the wooden end of a cotton swab. Electrode resistances were kept below 5000 ohms. EEG was recorded from frontal, central, parietal, and occipital midline sites (FZ, CZ, PZ, OZ) and from bilateral temporal (T3, T4) and parietal (P3, P4) sites. One additional electrode, attached half an inch below and half an inch to the left of the left eye, was used to reject trials during which eye movements or blinks occurred. All EEG electrodes were referenced to linked ear leads, and the subject was grounded with the ground lead of the skin conductance amplifier. EEG was recorded with a polygraph with filter constants set at 0.1 and 100 Hz. In addition, a 5-pole digital band pass filter was employed, the high pass set at 0.3 Hz (3 db down at 0.3 Hz) and the low pass at 24 Hz (3 db down at 24 Hz). This prevents the aliasing of brain and muscle artifact at frequencies beyond the cutoff.

A data-acquisition system recorded and digitized each physiological record at 256 data points/sec. This data set was then transferred to our workstation (8 megabytes), where we performed a Hanning window tapering and the fast Fourier transformation (FFT) analyses reported here. The FFT yielded plots of power for each subject in each condition and for each electrode site. For each subject, we did a separate Fourier transform of each artifact-free second of each condition (computer algorithm method with rejection set at ±105 microvolts). We then averaged the successive 1-sec epochs to obtain an average waveform for each subject in each condition. Only frequencies between 1 and 28 were considered because they encompassed most of the observed activity.

Prior to statistical analyses, frequencies were grouped into the five bands traditionally reported (e.g., see Galin et al., 1992): delta (1 to 3 Hz), theta (4 to 7 Hz), alpha (8 to 13 Hz), low beta (14 to 22 Hz), and high beta (23 to 28 Hz). Values were logged, in order to achieve more normalized distributions; significant differences were generally reflected in the third and fourth decimal places. All biomedical data processing (BMDP) programs were run on the workstation.

Results

The recordings of 20 subjects were not technically adequate for the FFT analysis (excessive artifacts, equipment failure). Table 1 presents the demographic characteristics of the three FFT study groups, which were composed of 47 children with ADD, 33 children with dyslexia (DYS), and 19 slow learners (SLO). Significant differences were obviously found on the variables used in classification (IQ and achievement scores), but the groups did not differ on behavioral ratings. Sixty-one percent of the subjects with dyslexia had abbreviated hyperkinesis index scores (teacher ratings) ≥ 15, a common research criterion cut-score for ADHD (Dykman & Ackerman, 1991); this figure is comparable to 50% of the SLO group and 63% of the ADD group. Parents (guardians) were administered only the ADD/ADHD questions from the DICA. However, using a standard score of ≥ 70 on the parent-rated Child Behavior Checklist as evidence of comorbid internalizing disorders, 30% of the ADD group, 31% of the dyslexic group, and 16% of the slow learner group were affected. By the same standard, 57% of the ADD group, 38% of the dyslexic group, and 16% of the SLO group had externalizing disorders. On the teacher-rated Iowa aggression index, 19% of the ADD and of the dyslexic groups, as compared with 11% of the SLO group, had suspect scores (≥ 6; see Dykman & Ackerman, 1991, for an ADD/ADHD subtyping study).

In pairwise contrasts, the ADD group was significantly older than the DYS group, $t(96) = 2.87$, $p < .01$, but age was not significantly correlated with any of the EEG variables. Hence, age was not used as a covariate. Likewise, gender was not significantly associated with any of the EEG variables. Verbal IQ was significantly correlated with theta and beta values but was not a significant covariate in these analyses. Hence, only ANOVAs are reported. In a final section, we will present correlations among cognitive/achievement values, behavioral ratings, and EEG values.

Given the complexity of the data set and the differing findings reviewed above, we chose to analyze each of the five frequency bands separately, looking at T3 and T4 in one set of ANOVAs, P3 and P4 in another, and all midline leads in a third. This procedure allowed an evaluation of hemispheric effects, if any, and anterior to

TABLE 1
Mean Descriptive Values for Groups

	ADD (n = 47)	Dyslexia (n = 33)	Slow (n = 19)	$F_{2,96}$
Gender	34:13	26:7	11:8	
Race	43:4	30:3	17:2	
Age (mos.)	121.3 (14.1)	112.5 (12.0)	118.7 (14.9)	4.16*
WISC-R				
Verbal IQ	105.5 (10.1)	97.5 (11.3)	89.9 (9.2)	16.45**
Performance IQ	105.3 (12.6)	111.0 (11.4)	95.5 (10.6)	10.38**
Full Scale IQ	105.9 (10.1)	103.9 (9.6)	91.6 (6.6)	16.16**
WRAT-R				
Reading SS	102.9 (9.6)	74.0 (10.0)	84.3 (6.1)	100.16**
Spelling SS	99.8 (8.3)	75.9 (8.3)	83.7 (6.6)	90.71**
Math SS	99.3 (11.9)	91.3 (13.9)	85.6 (8.1)	10.03**
Woodcock SS	101.2 (8.3)	82.8 (10.9)	88.6 (11.0)	35.03**
Teacher Ratings				
ADD Index	20.0 (6.5)	16.9 (8.2)	16.2 (5.9)	2.84
Hyperkinesis Index	16.3 (6.8)	15.2 (8.4)	15.7 (7.1)	0.24
Iowa Inattention/Overactivity	9.5 (3.7)	7.8 (4.7)	7.7 (3.8)	2.25
Iowa Aggression	3.9 (4.6)	2.6 (4.0)	2.4 (3.2)	1.43
Parent Ratings				
Internalizing T Score	64.1 (8.6)	61.1 (12.7)	61.3 (7.8)	1.03
Externalizing T Score	67.3 (8.3)	61.8 (13.3)	64.7 (8.6)	2.74

Note. SS = standard score; ADD = Attention Deficit Disorder; WRAT-R = Wide Range Achievement Test–Revised; WISC-R = Wechsler Intelligence Scale for Children–Revised. Standard deviations are given in parentheses.
*$p < .05$. **$p < .01$.

posterior effects, if any. Table 2 lists all effects significant at the .05 level or less, but readers may choose to focus on effects at the .01 level, given the number of ANOVAs computed. However, where directional hypotheses were made (for groups and with regard to band), the .05 level should suffice. Group effects were teased out via pairwise contrasts (ADD vs. DYS, ADD vs. SLO, DYS vs. SLO). Site and condition effects were likewise examined. Graphs were used to guide comparisons necessary to explain interactions. Degrees of freedom for repeated measures were corrected by the BMDP 4V program, and reported significance levels were adjusted by the Huynh-Feldt procedure, where appropriate.

Within Effects

Effects not involving group will be reported first. Grand mean values for each lead are graphed in Figure 1.

Delta. Delta power was significantly higher at the right than left parietal site, $F(1,96) = 6.11$, $p < .02$, but the effect size was very small (.09 *SD*). The temporal contrast was not significant (i.e., T3 = T4). Delta power in the midline sites was ordered from highest to lowest, FZ, PZ, CZ, and OZ, $F(3, 288) = 35.19$, $p < .001$. Pairwise contrasts showed FZ, CZ, and PZ to be greater than OZ. It is obvious from Figure 1 that delta power was lowest overall in the temporal areas. The condition effect was nonsignificant in all delta analyses.

Theta. The only significant effect for theta involved the midline sites, $F(3, 288) = 54.92$, $p < .001$. Pairwise contrasts showed CZ > PZ = FZ > OZ. As with delta, theta power was lowest overall in the temporal areas.

Alpha. Alpha power was significantly higher at the right than left parietal site, $F(1, 96) = 3.83$, $p < .05$, but the effect size was small (.10 *SD*). The temporal sites contrast did not reach significance. The condition effect was significant at P3 and P4, $F(6, 576) = 2.32$, $p < .05$, but the effect size was small (< .10 *SD*). The two letter conditions had greater alpha values than the two rhyming word conditions.

Alpha within effects were quite strong at the midline sites. For site, $F(3, 288) = 46.31$, $p < .001$, and for condition, $F(6, 576) = 2.92$, $p < .01$. There was also a condition × site interaction, $F(18, 1728) = 1.97$, $p < .02$. Alpha power in midline sites was ordered PZ = OZ > CZ > FZ. Over all midline sites, the two letter viewing conditions elicited greater alpha power than the other conditions. The condition × site interaction stems from small magnitude differences and not crossovers. That is, the ordering of sites was invariant in all conditions; overall, alpha power was greater at the posterior sites.

Low beta. Low beta power at P3, P4 yielded a condition effect, $F(6, 576) = 3.00$, $p < .01$, and a condition × site interaction $F(6, 576) = 2.07$, $p = .05$. These effects were quite small, with P4 > P3 in three conditions (similar words that rhyme, similar words that do not rhyme, and nonrelated words), P3 > P4 in two conditions (semantically similar words and letters that rhyme), and P3 = P4 in two conditions (dissimilar words that rhyme, letters that do not rhyme).

Low beta at T3, T4 also yielded a condition × site interaction, $F(6, 576) = 2.64$, $p < .02$. T4 power was greater than T3 in all conditions but most marked for the dissimilar rhyming words (effect size = .27 *SD*) and least to the nonrelated words.

Low beta at the midline sites showed a significant site effect, $F(3, 288) = 10.11$, $p < .001$, with OZ = FZ > PZ = CZ (effect size = .33 *SD*).

High beta. The midline sites yielded a significant site effect, $F(3, 288) = 24.03$, $p < .001$, and a condition × site interaction, $F(18, 1728) = 1.73$, $p < .05$. In all conditions the sites were ordered OZ > FZ > CZ > PZ. The interaction stemmed from magnitude of differences within conditions and not crossovers (e.g., the OZ–FZ difference was greatest for nonrelated words; effect size = .50 *SD*).

Summary. Reliable but small hemispheric differences were found for delta (P4 > P3), alpha (P4 > P3), and low beta (T4 > T3). The temporal sites had relatively less power in the delta, theta, and alpha bands than in the parietal and midline sites. At the midline, delta and theta were most suppressed at the OZ site, whereas alpha was most suppressed at FZ. Low and high beta were

TABLE 2
Summary of Significant Effects for FFT Power Spectra

	Group (G)	Site (S)	Condition (C)	C × G	C × S
Delta					
P3, P4		.02			
Midline		.01			
Theta					
Midline		.01			
Alpha					
P3, P4		.05	.03		
Midline		.01	.01	.01	.02
Low beta					
P3, P4	.01		.01		.05
T3, T4					.02
Midline	.01	.01			
High beta					
P3, P4	.06				
Midline		.01			.05

Note. F values are reported in the text.

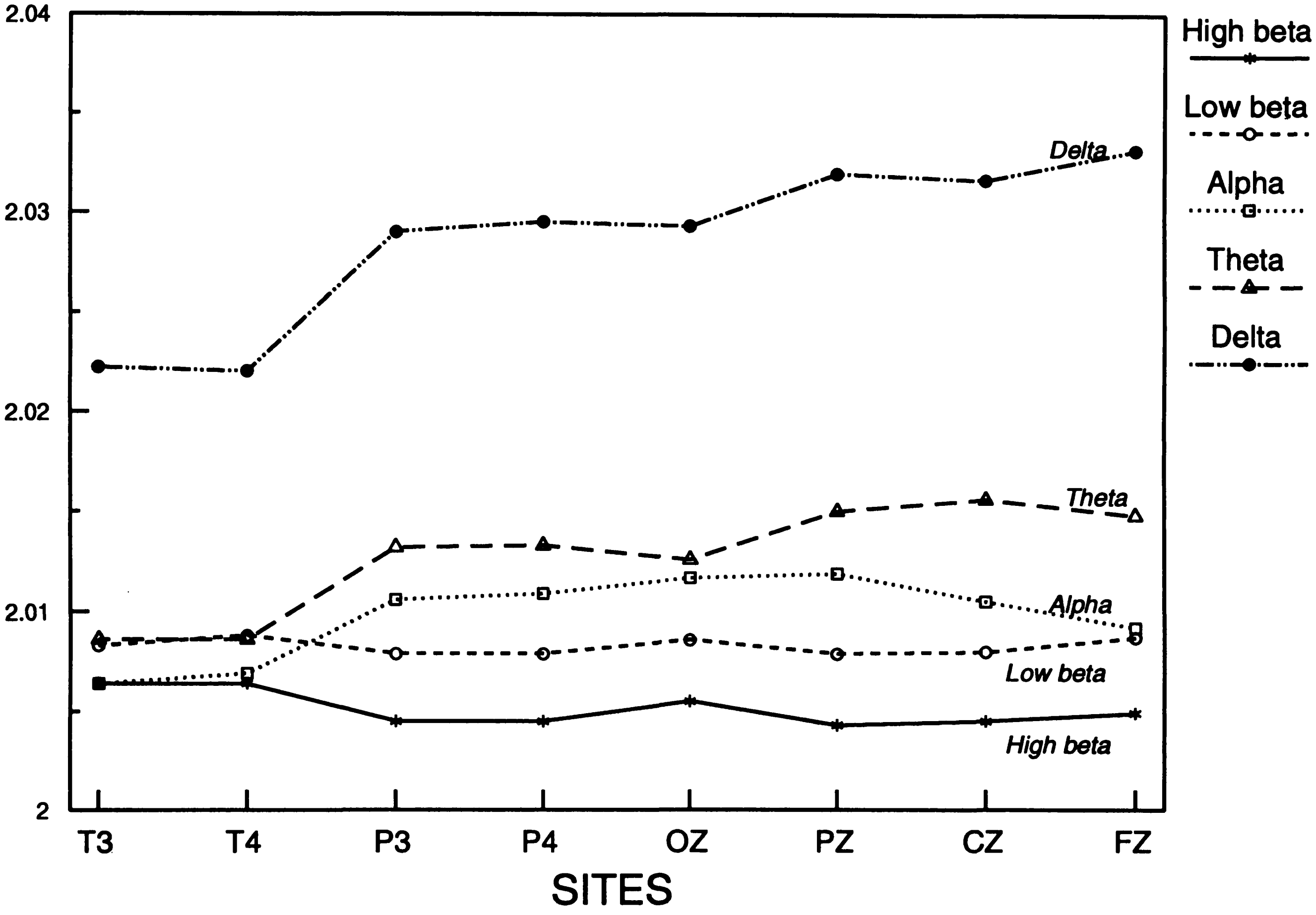

FIGURE 1. Grand means for logged FFT values in each power band. Sites are abbreviated as follows: T3 = left temporal, T4 = right temporal, P3 = left parietal, P4 = right parietal, OZ = midline occipital, PZ = midline parietal, CZ = midline central, and FZ = midline frontal.

most pronounced in OZ and FZ midline, but the temporal sites had highest beta overall.

Group Effects

Group main effects and interactions involving group are reported below. No significant group effects were found in delta and theta power.

Alpha. The alpha midline sites yielded a significant condition × group interaction, $F(6, 576) = 2.26$, $p < .01$, which is graphed in Figure 2. Pairwise constrasts revealed the group × condition interaction to hold for ADD versus DYS, $F(6, 468) = 3.02$, $p < .01$, and for ADD versus SLO, $F(6, 384) = 2.19$, $p = .04$. When conditions were examined one by one, there were no group effects. Hence, we next compared Condition 7 (letters, nonrhyming), in which the groups had equivalent values, with Conditions 1, 2, and 4, in which the groups were maximally separated. In these contrasts the ADD group showed less difference between 7 and 2 (dissimilar words that rhyme) and 7 and 4 (semantically similar words) than the DYS group, $F(1, 78) = 7.47$, $p < .01$, and 5.12, $p < .03$, respectively. Also, the ADD group showed less difference between 7 and 1 (similar words that rhyme), 7 and 2, and 7 and 4 than did the SLO group, $F(1, 64) = 6.45$, $p < .01$; 5.46, $p < .02$; and 6.82, $p < .01$, respectively. These findings indicate relative alpha suppression to dissimilar words that rhyme and semantically similar words in both poor reader groups, and to similar words that rhyme in the SLO group.

Low beta. The parietal sites yielded a group difference, $F(2, 96) = 7.58$, $p < .001$, as did the midline sites, $F(2, 96) = 4.93$, $p < .01$. Figure 3 shows low beta values for the three groups at all sites. Pairwise contrasts of the groups on P3, P4 revealed that the ADD group had greater power than the DYS group, $F(1, 78) = 6.02$, $p < .02$, and the SLO group, $F(1, 64) = 13.54$, $p < .001$. The effect size was moderate to large, .50 *SD* for the ADD–DYS contrast and .85 *SD* for the ADD–SLO contrast. Pairwise contrasts of the groups on midline sites also showed ADD > DYS, $F(1, 78) = 4.21$, $p < .05$, effect size = .35 *SD*, and ADD > SLO, $F(1, 64) = 8.84$, $p < .01$, effect size =

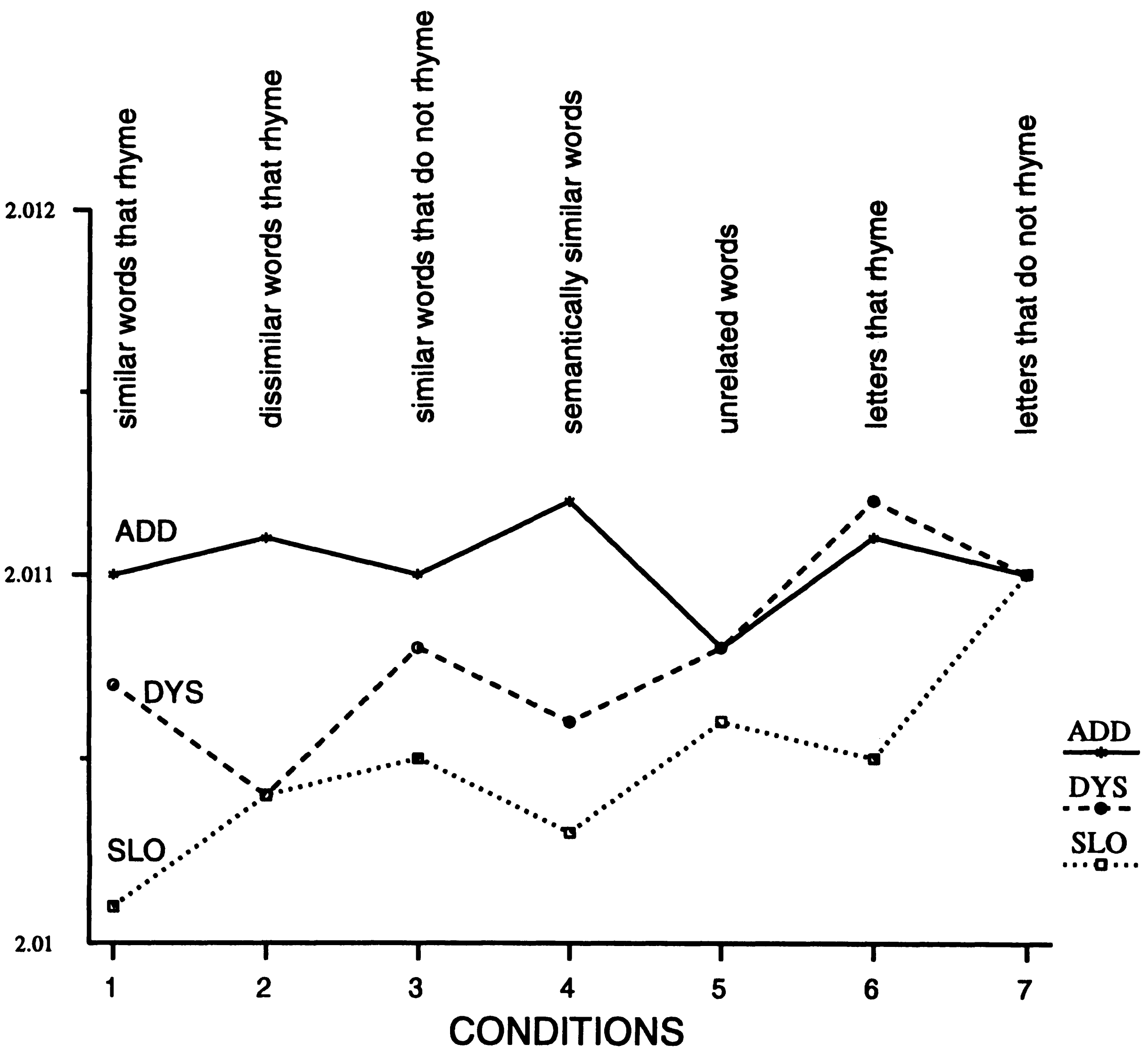

FIGURE 2. Group mean alpha power at the four midline sites (OZ, PZ, CZ, FZ) during the seven conditions. ADD = children with attention deficit disorder; DYS = children with dyslexia; SLO = slow learners.

.60 *SD*. The SLO and DYS groups did not differ significantly.

Figure 3 suggests a significant site × group interaction for T3, T4, but the effect was only marginal, $F(2, 96) = 2.32$, $p = .10$. Pairwise contrasts did not reach the .05 level, either, possibly because the *SD* for T3, T4 low beta was .0043—twice as great as at the other sites.

High beta. The parietal sites yielded a marginal group effect, $F(2, 96) = 2.83$, $p = .06$. Pairwise contrasts showed ADD > SLO, $F(1, 64) = 5.28$, $p = .02$. Means were as follows: ADD = 2.0047, DYS = 2.0045, and SLO = 2.0040. The sample *SD* was .0013; hence, the ADD–SLO difference is a moderately sizable effect.

Correlational Analyses

Because condition and condition × group effects did not stem from crossovers, we summed values across conditions to derive a more manageable data set of 40 spectral values (5 bands × 8 sites). For this analysis, the site × band × group interaction was significant, $F(56, 2688) = 1.72$, adjusted $p < .03$. Univariate analyses showed group differences ($p < .05$) in low beta at five sites (FZ, CZ, PZ, P3, and P4), as would be expected from the previous analyses.

A factor analysis of the 40 spectral values (principal components, varimax rotation) revealed eight factors: (a) high and low beta at FZ, CZ, PZ, P3, and P4; (b) delta at all sites; (c) alpha at all sites; (d) theta at all sites; (e) all bands at T4; (f) high and low beta at T3; (g) high and low beta at OZ; and (h) delta, theta, and alpha at T3.

An exploratory correlational matrix revealed that a subset of the 40 variables was significantly related to cognitive/achievement variables: that is, low beta at FZ, PZ, and CZ and theta at OZ and the parietal sites. A series of multiple-regression analyses with WRAT-R and WISC-R scores showed low beta at FZ and theta at PZ to be the best combined predictors of reading and spelling scores and Verbal IQ (Rs ranging from 0.40 to 0.47, $p < .01$ for all). That is, the better readers and spellers and children with higher Verbal IQs exhibited higher power in the low beta range coupled with lower power in the theta range. Teacher ratings of ADD, hyperactivity, and aggression were not significantly correlated with any of the 40 FFT values.

Next, we used a stepwise multiple-regression analysis to explore whether the spectral data added any unique variance in the prediction of reading and spelling if age, Verbal IQ, phonological sensitivity (Bradley, 1984), rapid continuous naming (Denckla & Rudel, 1976; Wolf, 1991), and running memory (Cohen & Netley, 1981) were also taken into account. From prior analyses on the full sample (see Ackerman et al., 1993), we learned that the latter five variables accounted for 73% of the variance in Woodcock word list raw scores. In the prediction of Woodcock scores, the spectral values did not explain additional variance once Verbal IQ entered the equation. The five variables named above yielded a multiple R of 0.84 ($p < .01$). In the prediction of WRAT-R spelling scores, the FZ low beta scores did contribute unique variance and, when combined with Bradley phonological sensitivity scores and Verbal IQ, produced an R of 0.68 ($R^2 = 0.46$), $F(3, 95) = 26.90$, $p < .01$. In the final equation, the standardized regression coefficient for FZ low beta was .294, as compared with .231 for Verbal IQ and .406 for Bradley scores.

The FZ low beta values also entered significantly in the multiple-regression equation for the prediction of nonsense word reading, explaining another 2% of the variance after the entrance of age, Bradley phonological sensitivity scores, and running-memory scores. The final R was 0.71

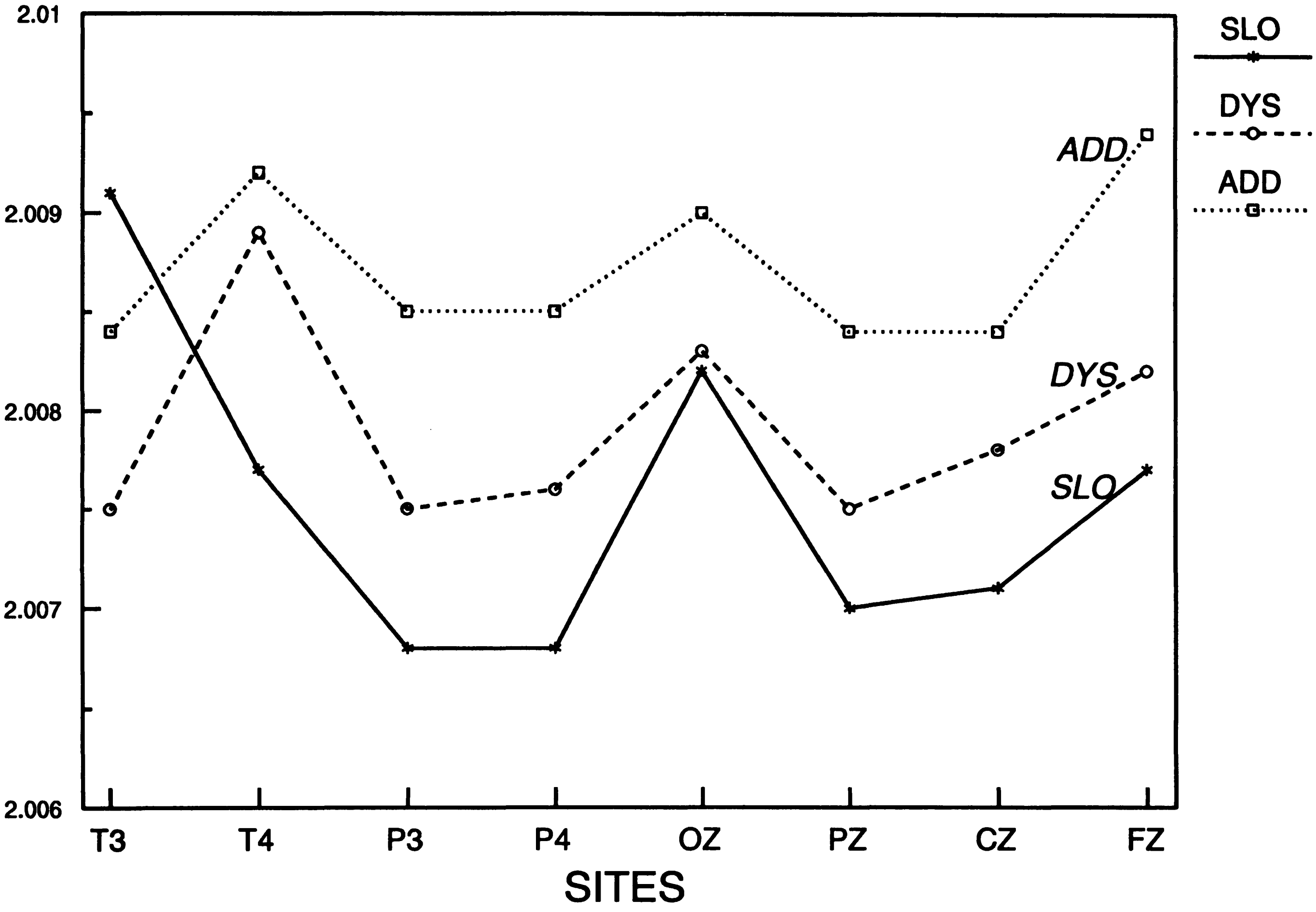

FIGURE 3. Group mean low beta power at all sites. ADD = children with attention deficit disorder; DYS = children with dyslexia; SLO = slow learners. Sites are abbreviated as follows: T3 = left temporal, T4 = right temporal, P3 = left parietal, P4 = right parietal, OZ = midline occipital, PZ = midline parietal, CZ = midline central, and FZ = midline frontal.

($R^2 = 0.50$), $F(4, 91) = 22.58$, $p < .01$. Note that Verbal IQ did not enter as a significant predictor in this equation.

Discussion

The results of this study, when added to findings reviewed in the introduction, strongly suggest that the brains of poor readers do not process visually presented easy words in the same manner as the brains of adequate readers, whether normally behaved or attention disordered. The clearest group difference found here was in low beta power at parietal, central, and frontal sites, which corroborates an earlier finding from our laboratory (Dykman et al., 1982) and the recent work of Flynn et al. (1992). Studies from other laboratories (see Duffy et al., 1980; Galin et al., 1992; John, 1977) point more to theta power than to low beta power. Recall, however, that even though the above ANOVAs on theta values did not yield significant group effects, theta power was significantly correlated with reading and spelling, as well as Verbal IQ. Moreover, when low beta and theta were combined in multiple regression, the prediction of cognitive/achievement variables was stronger than for either band alone.

Psychophysiologists generally agree that beta activity is common when a person is involved in mental processing (Andreassi, 1989). Hence, we surmise that the normally reading group with ADD more actively processed the letter and word lists than the two groups of poor readers. We further assume that the more actively a child processes a word, the more likely he or she is to detect common patterns in words, which is basic to learning to read (via either phonological decoding or orthographic analogy).

Although the two poor reader groups did not differ significantly on any of the spectral values, the slow group (garden-variety poor readers) had the lowest values in the low beta band, and the ADD–SLO contrasts yielded higher significance levels than ADD–DYS contrasts. The SLO group had lower Verbal IQs but read and spelled at a higher level than the dyslexic group. FZ low beta was correlated only .21 ($p < .05$) with Verbal IQ but .41 with WRAT-R reading and spelling (both $p < .01$). These figures suggest that the poorer reading/spelling dyslexic group should have lower FZ low beta values than the slow group, rather than the opposite ordering, as shown in Figure 3.

In the ERP data collected on these same groups (Ackerman et al., 1994), the slow group more closely resembled the ADD control group than did the dyslexic group. The ERP paradigm required the children to compare two short words (or nonsense words) and decide whether they rhymed. As the children with dyslexia had greater difficulty with Bradley's rhyme detection task than the slow learners, the ERP findings were consistent with degree of phonological impairment.

Condition effects were modest in the present study, but there did appear to be alpha suppression in the two poor reader groups during word viewing as compared with letter viewing. This finding indicates that word processing was more difficult for them than letter processing, as would be expected.

We did not obtain resting level EEGs because we did not believe the groups would differ except under active verbal processing conditions. This was the finding of Ortiz, Exposito, Miguel, Martin-Loeches, and Rubia (1992) as well as Fein et al. (1986). On the other hand, Morris, Obrzut, and Coulthard-Morris (1989) did find resting EEG differences between LD and control groups. The LD group exhibited a relative *depression* of temporal delta and theta and a relative increase in alpha in the eyes-closed condition. However, *increased* theta in children with reading disability has been the more common finding (see Duffy et al., 1980; John, 1977; Lubar et al., 1985).

When we contrasted the ADD, DYS, and SLO groups on EEG spectral data acquired during an arithmetic task, we found that the groups did not differ (Ackerman et al., 1993). In this task, those children who had low WRAT-R arithmetic scores had *lower* theta and delta values than those with higher arithmetic scores, yet the arithmetic groups did not differ on the verbal task reported here. Clearly, the type of task employed is critical, and comparison of EEG in different types of tasks is more informative than rest-to-task comparisons.

Hemispheric effects were modest in the present study. Unexpectedly, low beta power was greater at T4 than at T3, being most marked to orthographically dissimilar rhyming words. Both alpha and delta power were greater at P4 than at P3. Taken together, these findings suggest that P3 and T4 centers were more activated than P4 and T3 centers. A planned coherence analysis will shed more light on this issue.

Although the ANOVAs yielded no significant hemisphere × group interactions, the T3, T4 contrast of low beta did yield a marginally significant interaction. Inspection of the means suggested that the effect stemmed from a different pattern of values for the SLO group. For the ADD and DYS groups, T4 had higher values than T3, whereas the opposite held for the SLO group.

Although we could not divide our dyslexic group into dysphonetic and dyseidetic subtypes, as Flynn et al. (1992) did, we found the DYS group to be more phonetically impaired than the SLO group. But the confounding factor is that phonetically impaired readers are much poorer readers than those with some phonetic skills. Thus, the multiple-regression analyses showed that the same two spectral values (FZ low beta and PZ theta) best predicted real-word reading, nonsense word reading, and spelling.

The most parsimonious interpretation of the ANOVA and correlational results is that adequate readers, when viewing words and letters, exhibit greater power in the low beta band and less power in the theta band than poor readers. That is, the adequate readers appear to process these verbal stimuli more actively. Lubar (1991) suggested that an elevated ratio of theta to beta may be the EEG hallmark of attention and learning disabilities in children, and he uses biofeedback training to teach these children to increase beta and decrease theta. He reports that children who successfully do so then show significant improvement in the classroom (see also Tansey, 1990). We found that contingent reward increased beta production on our arithmetic task (Ackerman et al., 1993), and we speculate that psychostimulants also increase beta production in children with ADD and those with LD.

ABOUT THE AUTHORS

Peggy T. Ackerman, *MA, is a research associate in the Departments of Pediatrics and Psychiatry, University of Arkansas for Medical Sciences (UAMS).* ***Roscoe A. Dykman,*** *PhD, is emeritus professor of psychiatry, UAMS, and director of the Psychophysiology Laboratory, Center for Applied Research and Evaluation, Arkansas Children's Hospital.* ***D. Michael Oglesby,*** *BS, and* ***Joseph E. O. Newton,*** *MD, are research associates in the Psychophysiology Laboratory. Address: Peggy T. Ackerman, Department of Pediatrics, Center for Applied Research and Evaluation, Arkansas Children's Hospital, 800 Marshall St., Little Rock, AR 72202.*

AUTHORS' NOTE

This research was supported by Grant No. HD24634 from the National Institute of Child Health and Human Development and by the Marie Wilson Howells Fund. The authors are indebted to co-workers Michelle Gocio, Nancy Weir, Dwayne Tucker, and Nancy Stewart for their help in data collection, statistical analyses, and manuscript preparation. They are also indebted to colleagues at the Child Study Center and the Center for Ambulatory Research and Education who assisted in recruiting subjects.

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