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ENERGY ERP ANALYSIS OF READING RELATED COGNITIVE FUNCTION

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ABSTRACT

Three stages of reading-related cognitive processing were analyzed in a cross-subject study of four dyslexic and four normal readers, using EEG based data. Conventional ERPs for a synonym-antonym discrimination task were mathematically converted to time integrals of scalp electrical energy density. Comparing the quantitative values of these integrals for selected cortical regions during specific periods of the ERP permitted dynamic localization of task-related cognitive processing. Comparisons with subjects' task performance scores permitted evaluation of the role of successive phases of cognitive processing in determining performance. It was found that the four dyslexics were distinguished by a very low level of activation in the left occipital cortex during the first 180 msec of the task but that some dyslexic subjects compensated through a high degree of interhemispheric interaction during the period 200-500 msec. The method of this study demonstrates the possibility of clinically classifying individuals along a quantitative continuum instead of merely in terms of dyslexic/non-dyslexic. It also demonstrates a procedure which may be used to investigate disorders of other cortical functions.

KEYWORDS: EEG, ERP.

INTRODUCTION

This research employs a new EEG methodology to pursue two objectives. The first is to produce quantitative data that show how reading performance relates to a theoretical model of cortical processing of reading-related information. The second is to show that EEG can be used to classify reading disabled as well as normal readers along a quantitative continuum, thereby complementing conventional psychological tests which provide only a binary diagnosis (dyslexic/non-dyslexic).

Many researchers have utilized EEG data to explore the nature of reading deficiencies attributed to some anomaly of cerebral function (e.g., Landwehrmeyer et al. 1990; Segalowitz et al. 1992; Taylor and Keenan 1990). Our approach is the first to take advantage of a recent improvement in EEG methodology that focuses on the energy of cortically generated scalp electrical fields rather than the voltage changes induced by those fields. This approach enhances the spatial resolution of EEG data. It also yields quantitative data that facilitate cross-subject comparisons of cortical activity during selected periods of processing at various cortical sites.

Our investigation employs such data to show how intersubject differences in reading performance relate to a conventional theoretical model of cortical processing of reading-related information. The model emphasizes three stages: The first stage is primary sensory processing of visual stimuli in the occipital cortex. The second is translation of images of visual words into auditory images for further processing in Wernicke's area. This stage is thought to involve the left angular gyrus (Craggs and Carr 1983; Posner and Raichle 1994). The third stage is interaction of association centers in the left and right parietal areas.

We postulate that genetic reading disabilities primarily affect the first and second stage of this sequence. The third stage is more malleable to volition (interest, motivation) and learning (reading practice, related knowledge). Although interhemispheric interaction may be impaired by aberrant morphology of the corpus callosum (Hynd et al. 1995), we also suspect that it is this stage that is most affected by the training and practice which allows some reading disabled persons to read well.

A point which we wish to emphasize, however, is that some so-called "normal readers" may also have genetic disadvantages that affect the early stages of cortical processing. To some extent, they too may depend upon learned compensations. In other words, instead of classifying individuals as either dyslexic or normal, our research shows that it may be more useful to classify all individuals along a common continuum. And instead of viewing "compensation" as related only to reading-disabled individuals, it seems more appropriate to view all cases of reading performance as the cumulative result of processing activity at each of the three stages. In fact, as a diagnostic tool, it may be useful to locate each individual along three separate continua, corresponding to the three stages of cognitive processing described above.

METHODS AND MATERIALS

A. Overview

On the basis of conventional theory as well as preliminary data analysis we relate each of the three stages of processing described above to a particular period during individuals' response to a reading-related task, and to a particular electrode site in the International 10-20 system (Fig 1.).

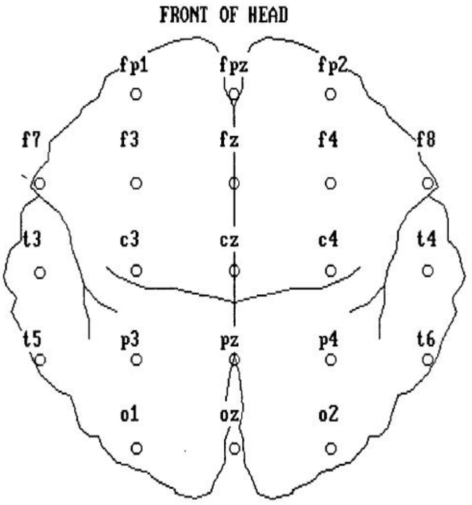

FIG 1. INTERNATIONAL 10-20 SYSTEM OF ELECTRODE PLACEMENT

Stage 1, Primary visual processing
Left-occipital electrode o1, 0-180 msec.
Stage 2, Translation from visual to auditory images:
Left-temporal electrode t5, 140-180 msec.
Stage 3, Inter-hemisphere association:
Absolute difference between parietal electrodes
p3-and-p4 at each instant, 200-500 msec.

Designation of the left occipital electrode (rather than both the left and right) to represent Stage 1 reflects a pragmatic choice rather than a theoretical consideration. The right electrode site was simply found to be of less quantitative value. Moreover, the left occipital electrode records electrical information from both occipital (calcarine) cortices. The choice of site t5 to represent Stage 2 was based on the fact that this electrode (which is in Broadman's area 37) is closer to the left angular gryrus than any other electrode in the 10-20 scheme. Finally, the accumulated absolute energy difference between p3 and p4 is assumed to reflect inter-hemisphere interaction (Stage 3). Our preliminary analysis of the data showed that, for all subjects, peak activation shifted repeatedly from one hemisphere to the other. By integrating the absolute (unsigned) difference in energy at p3 and p4 we measure the extent to which either hemisphere was dominant at each instant, allowing for switching. This, we postulate, is a rough index of interaction of left and right association centers.

B. Subject Selection

The electrical field energy at each of the above three sites and periods was recorded for each individual in the sample while performing a reading-related task. In order to observe a wide range of reading performance among similar-age individuals, our sample included developmental dyslexics as well as normal readers. The sample consisted of eight right-handed female college students (mean age 30.23 years, SD=2.131). Four of them were considered normal readers, without any known mental handicap. The other four were enrolled in a special college program for students with learning disabilities.

These latter four subjects all scored more that 1.5 SDs below the mean on the Peabody Picture Vocabulary Test-Revised (Dunn and Dunn 1981), the Detroit Tests of Learning Aptitude (Hammill 1985), the Clinical Evaluation of Language Fundamentals-Revised (Semel et al. 1987), and the Fullerton Language Test for Adolescents (Thorum 1986). Use of this extensive battery of tests was designed to assure as clear a diagnosis as possible. All four dyslexic subjects demonstrated specific linguistic disabilities, with the lowest scores on semantic and syntactic subtests, and their case histories indicated that their language disorders were developmental. However, all of these subjects scored within normal range on the performance scale of the Wechsler Adult Intelligence Scale-Revised (Wechsler 1981).

C. Test Protocol

After a training period to familiarize the subject with the test conditions, each subject was instrumented for EEG and seated comfortably before a computer screen. As a series of word pairs were presented on the screen, the subject decided whether each pair were synonyms or antonyms and indicated the choice by pressing the appropriate button on a hand-held key-pad. An equal number of word pairs were selected at random (without repetition) from three lists representing what the researchers believed to be easy, moderate, and difficult judgments. The subject's response automatically triggered presentation of the next word pair after a five second delay.

This particular task, antonym-synonym discrimination, may not necessarily represent all reading-related processing. But it is particularly suited to our measure of "Stage 3" activation in terms of inter-hemisphere interaction. Presumably, the task requires recognition of the connotations of words (which is often assumed to call upon right-hemisphere resources) as well as their denotations (for which the left hemisphere is assumed to be more specialized).

The subject's average performance (errors and response time) was automatically recorded and subsequently

converted into an "ErrorIndex" which combined both aspects of performance.
Error Index = Response time x (1 + percent wrong).

D. EEG Recording

Twenty-one silver-silver chloride cup electrodes were applied to each subject using "EEG-Sol" brand electrode cream (Medi-Trace Products Division of Graphic Controls, Inc. Buffalo, NY, Part #16-004). Electrode placement conformed to the International 10-20 system (Homan 1987). This pattern and the conventional electrode code is shown in Figure 1 where the small circles represent the electrodes in relationship to a schematic outline of the brain.

Voltage differences between scalp electrodes and a common (linked earlobe) reference were continuously recorded via a "Brain Atlas III" system (Biologic, Inc., Mundelin, IL.) which digitized 21 channels at a sample rate of 128 Hz. Recording impedance was kept below 2000 ohms with 20,000 gain, 30 Hz high filter and 1 Hz cosine cut-off low filter.

A timing spike was recorded along with the EEG montage to mark presentation of each problem. From approximately 150 trial epochs (each 1-second in length), 96 were visually selected by a trained EEG analyst to be free of eye-blink or other artifacts. These were smoothed with a five point moving average filter as recommended by Ruchkin (1987) and were then averaged to produce a single 21 channel voltage ERP (event-related potential) for each subject.

E. Conversion to Energy Density ERPs

A novel feature of our research was the conversion of the voltage ERPs into "energy density ERPs" so that scalp recorded surges in electrical energy rather than the resulting voltage fluctuations could be used as a measure of localized cortical activity. EEG recordings show variation in voltage drop between recording sites and a reference electrode. But the fundamental property of an electrostatic field is, of course, its energy; and a method has now been developed to statistically estimate the levels of scalp energy density (joules/cu.cm.) underlying the voltage fluctuations recorded at different points in a multielectrode grid. (Guisado et al. 1992).

In many clinical applications of EEG based upon general waveform appearance and frequency the distinction between voltage and energy may not be important. Large cortically-generated energy surges are likely to coincide with large excursions in the EEG voltage time traces. But for ERP investigations of the spatial localization of cortical activity, voltage may be an inadequate proxy for energy of the underlying electrical fields. Voltage fluctuations at scalp electrodes are only one effect of changes in the energy of these fields. Another effect is the redistribution of scalp charge density, and this latter effect may cause the voltage traces to misrepresent the spatio-temporal pattern of energy variation. Since electrostatic potential energy is the product of voltage and charge, one may picture energy as the area of a rectangle, the height and width of which are, respectively, voltage and charge. Only if one of these dimensions can be assumed to remain constant can the other be assumed to be perfectly correlated with the area of the rectangle (representing energy).

Fortunately, this problem can now be overcome by exploiting modern EEG instruments that allow data from twenty or more scalp electrodes to be digitized for subsequent computer analysis. It is then possible, by taking advantage of information latent in the spatial juxtaposition of the voltage readings, to statistically reconstruct the underlying electrostatic energy distribution. A description of this post-hoc mathematical transformation of the data is found in Montgomery, et.al. (1993).

In addition to improving the spatial resolution of scalp EEG data, the estimate of electrical energy has another important advantage: It permits time-integration. No meaning can be attached to the time-integral of voltage (and if DC variation has been filtered out during recording, the time integral will be zero). However, electrical energy is an inherently positive quantity and its time-integral is meaningful (it is electrical power.) Time integration of cortical energy over specified periods following stimulus presentation is useful because it facilitates quantitative cross-subject comparisons and statistical analyses. The more conventional approach to ERP analysis, which emphasizes the amplitude of selected ERP peaks, may obscure cross-subject comparisons because of slight differences in ERP latency and waveform among subjects.

RESULTS

Table I presents the quantitative data relevant to this report. The first column shows the Subject Number. The second column shows each subject's performance score, in terms of the error index mentioned above. (Note that low values of this index imply good performance). The next three columns report the energy density time-integrals for each subject at one of the three selected electrode sites and time periods described above. The units are milliwatts, multiplied by an unknown (but constant) scale coefficient. The last column, labeled "Pct Lag", shows each subject's electrode site o1 energy recorded from 300-600 msec as a percentage of the total energy recorded there from 0-600 msec. The significance of this column will be discussed later.

Table I shows that, as a group, the dyslexic subjects did not perform consistently worse than the normal readers. Two of the dyslexics performed better than two of the normal readers. This is not surprising, given the age of the subjects and the possibility of learned compensation. Furthermore, the nature of the dyslexics' impairment may not necessarily be evident in the particular reading-related task in this experiment (synonym/ antonym discrimination). Finally, of course, not all normal readers necessarily read well. The third column of Table 1 shows, however, that the two groups of subjects do differ significantly with respect to energy expenditure at electrode site o1 during the first 180 milliseconds after stimulus presentation (Stage 1). Based on a one-tail t-test, the null-hypothesis of no group mean difference can be rejected at the .005 level. There is less than one-half of one percent chance of the observed group mean difference having occurred by chance alone. (The one-tail test reflects the prior expectation that it would be the dyslexics that would have the lower level of cortical activation.)

Table I: Subject Energy Time Integrals and Error Indices During Task Performance.

Subject Number	Error Index	Energy at Stage 1	Time at Stage 2	Integrals at Stage 3	Pct o1 energy after 300 mec during 600 msec
Normal Readers:					
1	5.000	762.9	249.8	570.3	31.1
2	1.183	548.5	317.1	797.4	38.2
3	1.363	567.4	383.8	1025.6	33.2
4	16.315	509.0	127.0	258.5	28.7
Means:	5.965	597.0	269.5	663.0	33.3
Dyslexics:					
5	29.441	188.9	34.9	229.2	52.8
6	7.560	424.1	218.0	868.6	57.3
7	18.218	287.9	83.2	430.6	60.5
8	2.837	355.6	241.8	1021.6	66.9
Means:	14.514	314.1	144.5	637.5	59.4

What is important about this observation is that, if a lower level of occipital activation is indeed one of the distinguishing features of dyslexia, then data such as that presented here permit quantitative classification of the severity of the problem. Thus, for example, it is evident that Subject #5 was far more disadvantaged than Subject 6. Similarly, one could extend the quantitative ranking of individuals to include the normal subjects as well. Subject #4 was, in this sense, more handicapped than Subject 1. This approach, in which both dyslexic and normal subjects are located among each other along a continuum is consistent with the hypothesis (Shaywitz et al. 1992) that dyslexia is at the lower tail of a normal distribution of reading ability rather than constituting a lower mode of a bimodal distribution.

Figure 2 plots each subject's position along three axes corresponding to the three processing stages. (The energy integrals representing these three stages may not necessarily be orthogonal, of course.) The plot immediately shows, for example, that dyslexic Subjects 6 and 8 benefit from a much higher level of Stage 3 learned compensation than do dyslexic Subjects 5 and 7. On this basis, one would predict better reading performance for Subjects 6 and 8, which happens to be the case. It is also interesting to note that Subject 4, although classified as a normal reader (and rightly so, based on early occipital processing) is distinguished from the other normal readers by a low level of activation at both Stage 2 and Stage 3. And, predictably, that subject's performance is worst among the normal readers (and also worse than dyslexic subjects 6 and 8). This type of analysis may be of practical benefit in diagnosis of poor reading performance in schools.

For example, if Subject 4 is indeed a poor reader, the explanation might be a lack of supporting knowledge affecting the association stages of higher cortical processing.

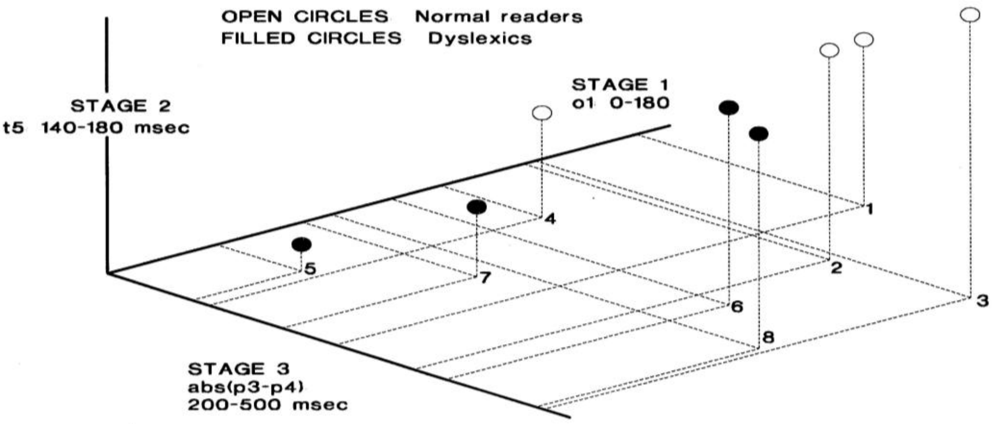

Figure 2. Cortical Energy at Three Successive Processing Stages

The three stages of processing depicted as separate dimensions in Figure 2 influence task performance successively and cumulatively. One would therefore predict that task performance should become progressively more related to the energy integral as each successive stage is added. This progression is illustrated in Figures 3, 4, and 5. In each figure the same set of the eight subjects' performance scores ("error indices") is plotted as a function of the energy integral at the particular location and period selected to reflect one of the three stages of processing.

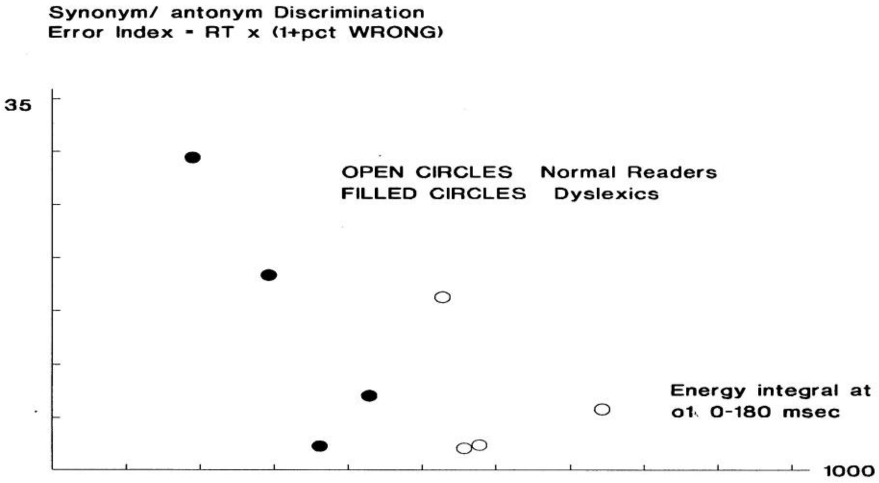

Figure 3. Performance as a Fuction of Stage 1 Activation

In Figure 3 (for "Stage 1": early occipital visual processing) the scatterplot of the eight data points shows only a hint of a correlation between performance and energy - although, as would be expected from the previous analysis of the group separation, the filled circles representing the dyslexic subjects are separated horizontally from the open circles representing the normal readers. In Figure 4, however, ("Stage 2": translation of visual into auditory information) the data points have begun to line up along a curve suggesting a definite relationship between the performance error index and the energy integral. Finally, in Figure 5, ("Stage 3": inter-hemispheric interaction) an almost precise relationship between performance and the energy integral appears. Moreover, the relationship is distinctly "shifted" between the two groups: The curve fitted to the dyslexics' data points suggests that a higher degree of hemispheric interaction was required, for them, in order to achieve any given performance level.

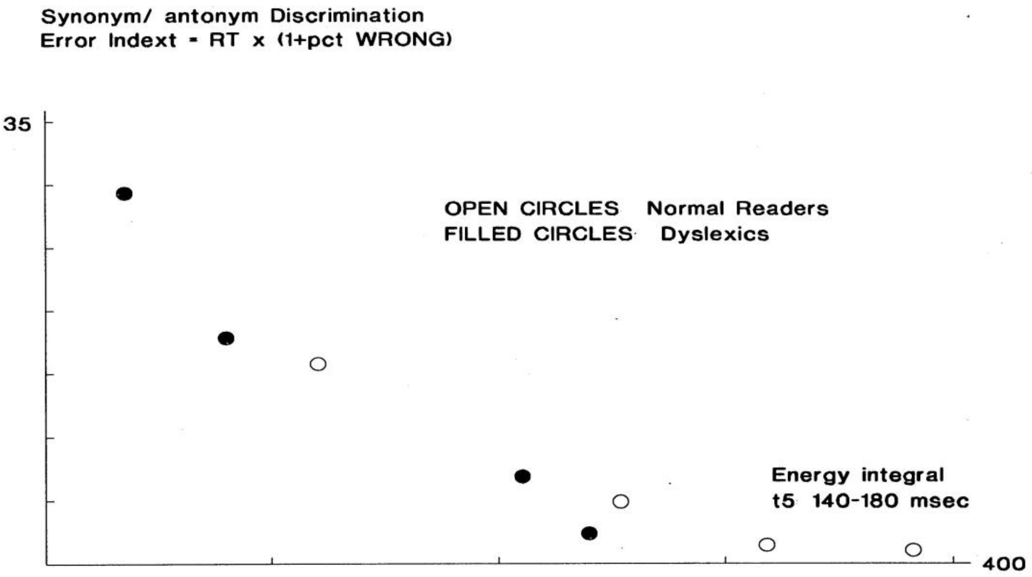

Figure 4. Peformance as a Function of Stage 2 Activation

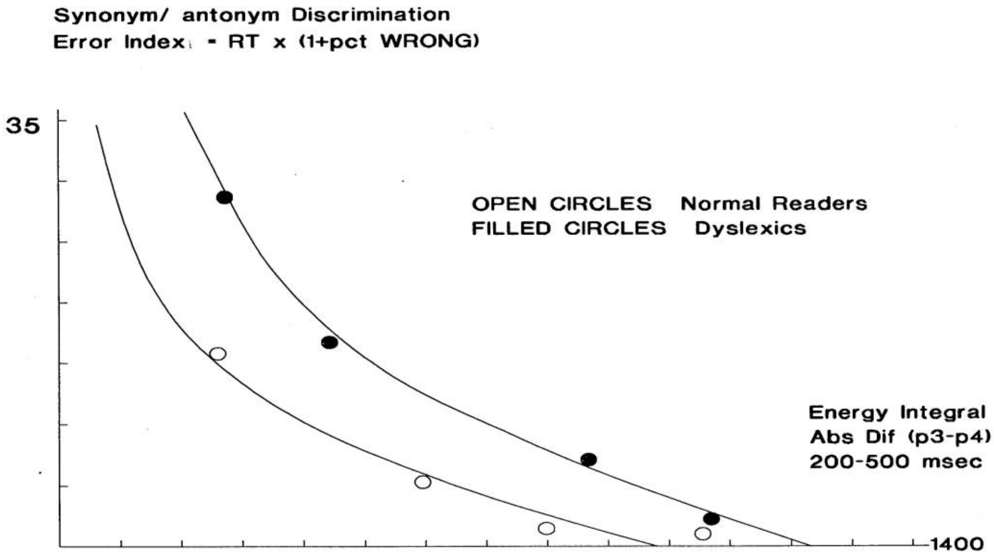

Figure 5. Performance as a Function of Stage 3 Activation

Thus, Figure 5 shows that the low level early occipital activation which characterized all four of the dyslexics in our study could be overcome by sufficient inter-hemispheric interaction at a later stage of processing. This suggests that it is hemispheric interaction rather than hemispheric dominance or lateralization that is important for reading success. And, indeed, we found no correlation between hemispheric dominance and either reading performance or group membership (dyslexic or normal). The transmission of information to Wernicke's area through the left angular gyrus does, of course, imply a special role for the left hemisphere. But after this early phase of processing it appears that it is inter-hemisphere interaction that contributes most to the outcome of the reading task (at least for the task in our study). The time resolution of EEG is well suited to distinguishing between the various stages of processing, and this is one finding which should be explored in future research employing other task stimuli.

Although we are anxious to emphasize the possibility of viewing all subjects along a continuum, rather than simply labeling some dyslexic and others normal, there remains nonetheless the challenge of explaining why some subjects manifested such a low level of early occipital activation. We have no hypothesis to offer, yet it may be of interest that the dyslexic group tended to lag the control group in activation of the occipital cortex. The lag was especially evident when the energy integrals recorded after 300 milliseconds at each electrode site were expressed as a percentage of total energy recorded there over the whole period of the ERP (600 msec). This is shown in the last column of Table I for the left occipital electrode, o1. Student's t-distribution is not strictly applicable for comparing the two groups where the variable is a percentage. Yet the size of the difference suggests that it may be of substantive significance.

Finally, although it is quite understandable that young adults' actual reading performance may not correlate well with their classification as either normal or dyslexic (because of learned compensation), it may be desirable, nonetheless, to be able to predict individual's reading performance. The energy ERP data used here facilitates a rather precise prediction (at least within the sample). For this purpose we have used multiple regression analysis, regressing the subjects' performance index on various combinations of the energy integrals shown in Table I. The best fitting combination was the integrals representing Stages 2 and 3. (The idea of using all three was rejected on the basis of likely multicollinearity).

A scatterplot of the relevant data is shown in Figure 6. The relationship between the error index and the two energy integrals is clearly non-linear. This is logical, considering that a zero value of cortical energy (!) would be associated with an infinitely large response time and error index. On the other hand, for some high value of the regressor it is conceivable that the error index could approach zero. Geometrically, this suggests that the relationship might be approximately linear in the logarithms of the energy integrals. The result is the following equation:

ERROR INDEX = Ln (84.96) - 3.53 Ln (|p3-p4|) - 10.23 Ln (o1)
RSQ=.985 t = -3.79 t = -4.99
ADJ RSQ=.980 (6 df) p <.005 p <.0025

The eight subjects' actual and predicted Error Indices are as follows.

Subject	Actual	Predicted
---------	--------	------------
1	5.000	6.067
2	1.183	2.439
3	1.363	-0.404
4	16.315	15.778
5	29.441	29.431
6	7.560	5.968
7	18.218	18.300
8	2.837	4.337

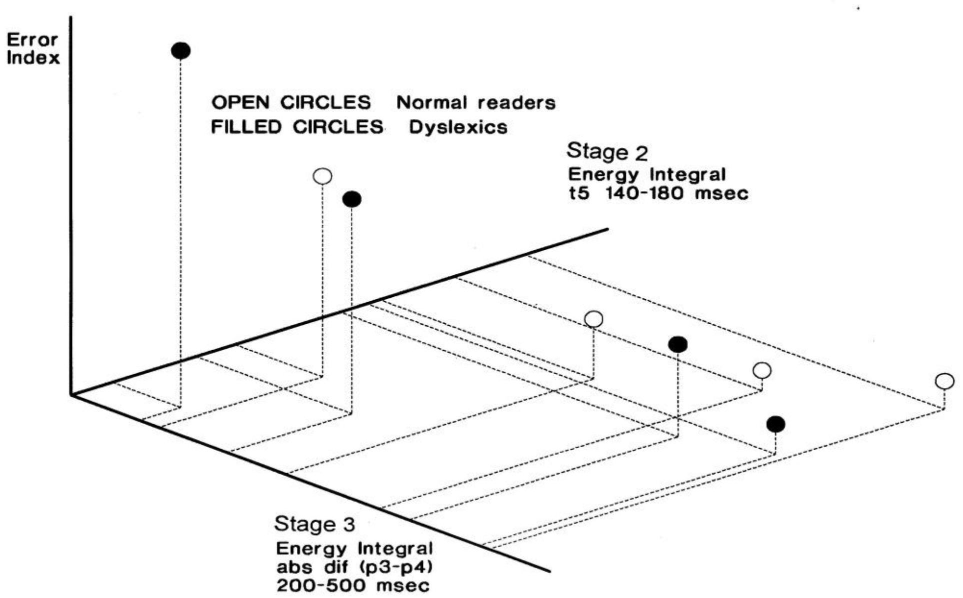

Figure 6. Performance as a Function of Stages 2 and 3

Figure 6 also helps explain Figures 4 and 5. Figure 4 is the projection of the data points onto the two-dimensional plane of the axes for the error-index and the t5 energy integral. Similarly, Figure 5 is the projection on the axes of the error-index and the p3-p4 energy integral.

DISCUSSION

If this study is confirmed in future research, it would have three practical implications. First, it would reinforce the view that dyslexia is primarily an impairment of visual sensory processing. Second, it would suggest the efficacy of therapeutic strategies that strengthen individuals' capacity for higher-level integrative processing (e.g. practice in relating words to their connotations and metaphorical values). Third, it would imply that a simple easily-automated EEG procedure can be used, not only to identify dyslexic individuals, but also to provide a quantitative evaluation of the severity of the underlying neurophysiological deficit.

With respect to methodology, this study demonstrates that the ‘energy density ERP’ approach to EEG research can be useful in quantitative validation of theories of brain function as well as clinical assessment of dysfunction. It must be emphasized that none of the results shown here could be obtained without the conversion from voltage to energy.

We recognize that the research reported here is based upon a rather small sample, and upon only one type of stimulus task (synonym-antonym discrimination). Yet the results seem to show sufficient internal consistency to warrant further research along similar lines. That is, it demonstrates the possibility of ‘dynamic localization’ of brain function by means of cross-subject statistical comparison of cognitive performance with energy ERP integrals for selected cortical sites and periods during task response. This procedure may be useful in the analysis of a variety of cognitive dysfunctions, perhaps including, for example, autism and memory loss.

ACKNOWLEDGMENTS

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DEDICATION

This article is dedicated to Alvirda Farmer, Ph.D, now deceased. She was an important part of this work. She arranged for subject participation and testing and initial prepareation of this manuscript.

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