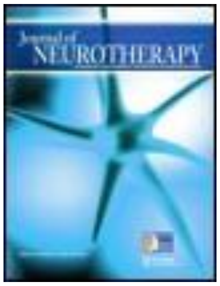

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Electrophysiological (QEEG) Correlates of Effective Reading: Towards a Generator/Activation Theory of the Mind

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Electrophysiological (QEEG) Correlates of Effective Reading: Towards a Generator/Activation Theory of the Mind

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ABSTRACT. *Introduction*. An investigation into the relationships between Quantitative EEG (QEEG) and memory scores for reading material was conducted employing 38 normal *subjects*.

Method. There were three conditions during which QEEG data was collected: (a) subject reading a story silently, (b) subject engaging in an immediate recall period, followed by subject's oral recall, and (c) delayed recall assessment, followed by the same methodology of quiet recall and subsequent oral recall. The reading and recall performances were correlated with QEEG variables.

Generator patterns were determined as a set of significant phase or coherence relationships, which all emanate from one location. The concept of emanate is an assumption based, in part, on previous literature of generator patterns and on the statistical need to reduce the number of variables. Degrees of activation values were determined as the differences in QEEG variables between two conditions (a relevant condition and the task condition). For the reading condition, a visual attention task served as the relevant condition, while for the recall tasks, the eyes closed served as the relevant control condition.

Results. During the input (reading) condition absolute levels of F7 beta generator and T5 coherence alpha generator activity were associ-

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ated with higher memory scores. Degree of activation (visual attention vs. reading) values indicated significant relationships (increased activation positively correlated with recall) between recall and eight generator patterns (coherence) in the alpha range.

Immediate recall was positively associated with absolute levels of generator activity (coherence beta2, 32 to 64 Hz) from the F4 location and with the absolute level of activations in the theta frequency predominantly at frontal locations. Degree of activation (from eyes closed) analysis indicated that increased memory scores were associated with activations in the theta frequency range in diffuse locations, activations of beta frequencies at posterior locations and generator activity predominantly in the beta2 frequency from right hemisphere locations.

Higher long-term recall was associated with higher absolute levels of generator activity (alpha set at .10) from right frontal locations and frontal theta activity. The higher the degree of activation (from eyes closed) of posterior beta activity and beta generator activity from several sites, the higher the long-term memory score.

Discussion. The results provide a new perspective on brain functioning, which cannot be accounted for by any present day theories of brain functioning.

KEYWORDS. Reading, memory, dyslexia, memory, cognition, QEEG, neurotherapy

INTRODUCTION

Theories of the relationship between mind and body have been pursued by cognitive scientists such as Hebb (1949), Schacter and Tulving (1994), Pribram (1994) and Gestalt psychologists. These theorists have employed concepts such as cell assemblies, activation areas, holography, and dynamic fields. Damasio's (1989) contribution to this problem stated memory is not stored as holistic units in narrowly circumscribed regions, for example as "grandma cells," but rather as sets of representational fragments in multiple and separate regions. Roster, Heil and Henninghausen (1995) state:

> Memory content is accessed if these representational fragments are triggered either by perceptual input or by active memory

> search. In each case, triggering means that the very same activity pattern is recreated in the distributed cortical cell assemblies that was generated originally when the entity, a face, etc. was first encountered. (p. 301)

Memory is thus a recreation of the original physical state. Damasio (1989) elaborates on this approach by emphasizing that recollections of entities and events:

> . . . are activated in time locked fashion; synchronous activations are directed from convergence zones . . . and the process of reactivation is triggered from firing in convergence with and mediated by feedback projections. This proposal rejects a single anatomical site for the integration of memory and motor processes and a single store for the meaning of entities and events. Meaning is reached by time-locked multiregional retro-activation of widespread fragment records. Only the latter records can become contents of consciousness. (p. 25)

Damasio's emphasis upon time locked regional activations places the emphasis upon activated areas. Although he speaks of projections, these projections provide the impetus for activation and are not the focus of recall. For example, he states, "consciousness emerges when retro-activations attain a level of activity that confers salience" (Damasio, p. 54).

The understanding of memory for materials read (reading memory) has been addressed from the points of view of neuropsychology (the mind side of the problem) and neuroanatomy, modern techniques of PET and electrophysiological (QEEG) measures (the body side of the problem). The value of understanding how QEEG variables relate to reading memory resides both in the theoretical value of understanding relationships between the mind and body as well as potentially providing a source of important rehabilitation information. Related to the latter, the field of neurotherapy (biofeedback of QEEG variables) has grown in interest and clinical application during the past decade due to its effectiveness in improving the cognitive and behavioral functioning of children with educational problems. EEG biofeedback has been successfully employed in the remediation of attention deficit disorder (Lubar & Lubar, 1984), and learning problems, reportedly resulting in the elevation of IQ scores by 10 to 25 points (Tansey, 1991; Othmer & Othmer, 1992; Linden, Habib & Radojevic, 1996; Thompson & Thompson, 1998). The interventions employed in these clinical situations have focused generally on the Cz scalp electrode site position and the Beta frequency range of 13 to 22 Hz. If specifics of cognitive functioning can be understood in terms of QEEG variables, then precise neurofeedback interventions can be designed which can potentially be effective in addressing a wide variety of problems in cognitive functioning.

The neuropsychology of reading historically has involved a distinction between visual and auditory word processing in terms of input, including a distinction between a phonological route to reading (involving the grapheme to phoneme conversion [visual to sound]) and a visual route (involving direct access to the lexicon). Separation and integration of these processes has attracted the attention of researchers in this area. Implicit in these distinctions are issues of input versus production, as a subject generally is asked to produce sounds for what he/she sees. Thus, reading initially involves visual attention. In a related manner, the special importance of occipital and temporal cortical regions in reading has been implicated in a number of PET studies.

Petersen and Fiez (1993) found that visual presentation of nouns activated areas bilaterally in the extrastriate area. They summarized research in the area by noting that the posterior temporal/temporal-parietal areas are not activated by simple auditory stimuli (tones, clicks, or rapidly presented synthetic syllables). However, temporoparietal activation (T5-P3 locations in the International 10-20 electrode system) was found when subjects performed rhyme-detection tasks (visually presented words). The electrode references employed the anatomical locations indicated by Homan, Herman, and Purdy (1987) and are approximate locations. Petersen, Fox, Snyder, and Raichle (1990) noted a focus of activation in the left medial occipitotemporal cortex (T5) when subjects viewed written words but not other word-like stimuli, such as strings of random consonants. Ungerleider (1995) noted that this is the same area where lesions are associated with alexia, the inability to recognize words presented visually.

Bookheimer, Zeffiro, Blaxton, Gaillard and Theodore (1995) were able to demonstrate in their Positron Emission Tomography (PET) study that silent word reading and silent object naming activated the inferior temporal-occipital cortex of the left hemisphere (O1-T5). Larger activation increases for words (silently read) were noted in the posterior basal inferior temporal gyrus (closest to T3) or Mills' naming area. Homologous right hemisphere activations (though smaller) were also noted. A more posterior location (fusiform gyrus) produced somewhat larger effects for the object naming condition. A more lateral position was observed for words (versus objects, which activated more medial positions). In addition there were activations in the posterior medial occipital cortex (Brodmann's area 18 [BA]–approximately O1/O2 in the 10-20 system) for both tasks, as well as in the anterior cingulate (BA 10). Frontal activations were evident (for both tasks) at BA 47, 11, 8 and 9 (insula). These locations are approximately equivalent to the F7, F3 and Fp1 electrode positions (and their homologous locations).

There were some differences in frontal activations dependent upon whether words or objects were targets of silent reading or identification. Silent reading of words activated a frontal location (BA 11) and left hemisphere locations (BA 6/8) that were not activated by object naming. Object naming activated bilateral inferior temporal/fusiform gyrus locations while words activated only these locations in the left hemisphere.

Pugh et al. (1996) examined cerebral activation differences (PET study) during processing of line judgment, orthographic, phonological (non-word rhyme) and semantic information. They found that processing orthographic stimuli produced maximum demands on an extrastriate site, phonological on a number of frontal and temporal sites and lexical-semantic on middle and superior temporal sites. Thus the act of reading heavily involves occipital, temporal (left hemisphere) and frontal regions at least in terms of blood flow studies.

Recall of reading material presents a different set of cerebral activations. Many studies involving short-term episodic memory employ a visual presentation with an immediate visual recognition type task. Cabeza, Kapur, Craik and McIntosh (1997) examined regional blood flow in episodic-memory recall and recognition with subjects visually studying word pairs. Compared to a reading-only condition, both recall and recognition were associated with greater activation at identical right prefrontal sites (BA 47, 45, 10–approximately equivalent to electrodes sites F8 and Fp2) and at the anterior cingulate. Recall, as compared to recognition, was associated with higher activation in the anterior cingulate, globus pallidus, thalamus, and cerebellum as compared to recognition. Recognition also activated areas in the right inferior parietal cortex (BA 39, 40 and 19). They noted that PET studies of recall and recognition have consistently found increases in: (a) prefrontal cortex, especially the right hemisphere; (b) hippocampal and parahippocampal regions of the medial temporal lobe; (c) anterior cingulate cortex; (d) posterior midline area that includes posterior cingulate, retrosplenial, precuneus and cuneus regions; (e) inferior parietal cortex, especially on the right hemisphere; and (f) cerebellum, particularly on the left.

Hendersen (1986) reviewed Dejerine's 1892 hypothesis of pure alexia (acquired reading disorder in which written and oral language are spared) in terms of a visual-verbal disconnection. Dejerine postulated a disconnection between the visual cortex and the left angular gyrus. Hendersen concludes that Dejerine's hypothesis remains generally supported, but modification is required. He asserts that clinical data suggest that the left angular gyrus does more than translate visual language into sound, which then allows lexical access via Wernicke's area. Crosson (1985) focused on the subcortical components of spoken language and proposed a theory emphasizing the dynamic interaction between cortex, thalamus, and basal ganglia. In summary, PET studies of reading have regularly implicated bilateral extrastriate areas, left medial occipital/temporal areas, inferior temporal/occipital areas (especially left hemisphere) and frontal areas. Recall appears to involve a right frontal/right hemisphere focus. Exploring possible overlap between findings from the blood flow studies and QEEG is part of the focus of the present research.

Also relevant to memory functioning have been studies of the phenomena known as long-term potentiation (LTP), which has been considered a critical component in the memory process. LTP is a "form of synaptic enhancement . . . believed to be a contributing component to the neural mechanisms for explicit forms of learning" (Gazzaniga, 1995, pp. 24-25).

LTP is the "long-lasting enhancement in synaptic transmission, measured as increased amplitudes of excitatory postsynaptic potentials or the currents generated by these potentials in specific circuits after high-frequency, high-intensity activation of other discrete paths" (Gazzaniga, 1995, p. 1065). Biochemical investigations of LTP have focused on the NMDA-dependent LTP.

Location and frequency issues are important considerations in LTP research. Research by Larouche, Jay, and Thierry (1990) and a literature review by Doyere, Burette, Negro, and Larouche (1993) have supported the LTP connection between hippocampal activation and output to the prefrontal cortex. However, other forms of LTP have been discovered in other areas of the cortex including sensory and motor areas. Additionally, Doyere et al. were able to demonstrate (in rats) the hippocampal theta rhythm's (7.7 Hz) ability to induce reliable LTP changes in the prefrontal cortex. The prefrontal response, however, lasted for only one day. The present research (by examination of the relationship between EEG frequency and memory) may expand, indirectly, our knowledge of the LTP response.

High reliability of QEEG measures in cognitive activation studies have been demonstrated by Fernandez et al. (1993) and McEvoy, Smith and Gevins (2000). Fernandez et al. demonstrated the reliability (30-day interval) of absolute and relative power during a series of cognitive tasks (verbal and mental arithmetic). McEvoy et al. obtained .80 to .90 reliability figures for QEEG measures during working memory and a psychomotor vigilance task (7-day interval). These studies provide further background for the present study which delineates QEEG parameters related to memory.

METHOD

Subjects

Thirty-eight subjects were involved in this study. These normal subjects (no history of left-handedness, learning problems, brain injuries or other neurological problems) were part of a larger group of 175 subjects (which included brain injured, learning disabled, psychiatric patients, left-handed persons and children under the age of 14) who underwent procedures lasting about one to one and one-half hours during which 18 cognitive tasks were administered and QEEG measures obtained. Table 1 shows demographics of the 38 subjects. Subjects were paid $25 for participation and their parents (when subjects were under the age of 18) signed an informed consent form as required in human research situations. Four subjects were taking blood pressure medication at the time of the procedure. One was taking heart medication and another an anti-depressant. The Shipley Institute of Living Scale was administered to obtain a rough measure of intelligence. The purpose of obtaining this measure was to evaluate its relationship to the QEEG measures during the tasks and overall performance.

Apparatus

The subject's performances were videotaped and otherwise recorded. The recording device used combines a computer and video and audio recording equipment, and allows an experimental recording session to be saved to a hi-8 mm tape. The videotape is split screen videotape, with the left side reflecting the EEG recording with the appropriate epoch numbers and the right side of the screen showing the subject during the experiment. The epoch number refers to a one-second period. Thus, ep-

TABLE 1. Descriptive Data on Subject Population

	Male	*Female*	*P level*
Number	16	22	
Age (Yrs.)	39.5 (19)	37.9 (15.3)	.77
Education	13.8 (3.7)	13.7 (2.5)	.90
Shipley Scale			
Raw Verbal	32.6 (3.7)	33 (4.1)	.78
Raw Abstraction	31.6 (5.2)	30.4 (5.7)	.49
Verbal IQ*	114.7 (6.5)	114 (6)	.75
Abstraction IQ*	108 (9.9)	103.5 (12.4)	.21
Speed	4.2 (1.5)	3.9 (1.9)	.64
Lines	26.4 (11.3)	27.9 (10)	.67
MPL	1.87 (4.3)	.69 (.34)	.69
Short-Term Memory	17.9 (8.4)	18.7 (10.7)	.79
Long-Term Memory	19.3 (9.6)	19.1(12.8)	.97
Savings	1.06 (.2)	1.02(.31)	
Total Memory	38.9 (17.7)	38(23.2)	

No significant differences between the sexes on any variable. Standard Deviations in parenthesis. **VIQ** = Verbal IQ; **AIQ** = Abstraction IQ; **Speed** = number of seconds spent reading divided by number of lines read, smaller number reflects faster speed; **Lines** = number of lines read; M**PL** = memory per line, calculated as number of lines read divided by memory score.

* Employed Paulson, M. J. and Lin, T. (1970) formulas in estimation of verbal and abstraction IQ

och number 1 is the first one-second period of the recording and epoch number 60 is the sixtieth second of the recording. This device enables the experimenter to review the tape to check and confirm scoring of a subject's responses.

Lexicor Medical Technology, Inc. (NRS-24) EEG recording equipment was used. The sampling rate was set to 256 (to allow for examination of up to the 64 Hz range), with a 60 Hz notch filter. Filtering is accomplished in the software. The signals passed were between .5 and 64 Hz (3dB points). The passed signals were subjected to a Fast Fourier Transform (FT) using Cosine-tapered windows, which output spectral magnitude in microvolts as a function of frequency. The frequency bandwidths were divided as follows: delta: 0 to 3.5 Hz, theta 4 to 7.5 Hz, alpha 8 to 12.5 Hz, beta1 13 to 31.5 Hz, beta2 32 to 63.5 Hz. This equipment provides for the collection of data in the standard international 10-20 electrode system (linked ear references) format of EEG data collection. Impedances below 5 Ω (and within 1.5 K of each other) were obtained at all electrode locations. Gain was set to 32000 and the high pass filter was set to off. Earlobes and forehead were prepped with rubbing alcohol and Nu-Prep. An electrode cap from Electrocap International was employed and spaces filled with electrode gel. The data were visually analyzed for eye movement and muscle activity and marked for deletion when artifact was evident.

All measurements available through the software provided by Lexicor Medical Technology, Inc. were used. These employed the peak-to-peak method and included the following.

Activation Measures

Absolute Magnitude. The average EEG magnitude (as defined in microvolts) within a frequency band over a specific time-period (epoch).

Relative Magnitude. The relative EEG magnitude within a frequency band (absolute magnitude in a particular band divided by the total microvolts generated at a particular location in all bands).

Peak Amplitude. The peak amplitude of a frequency band during an epoch of time (defined in microvolts).

Peak Frequency. The peak frequency within a band during an epoch of time (defined in frequency).

Symmetry. The peak amplitude symmetry between two locations in a particular bandwidth (i.e., defined as [A-B]/[A + B], where A and B are electrode locations).

Connectivity Measures

Coherence. The average similarity between the waveform morphology in a particular frequency band from two locations over an epoch (one-second period in this research). Conceptualized as the strength/number of connections between the two locations. Lexicor software provides an amplitude-matching algorithm.

Phase. The time lag between waves from two locations in a particular band as defined by how soon after the beginning of an epoch a particular waveform at location #1 is matched in location #2 (amplitude).

Roland (1993) discusses issues of connectivity of the brain in terms of the anatomical organization of the neocortex, which contains six layers (with layer I being closest to the scalp and approximately 3 mm thick). The pyramidal cells (excitatory) in layer II and the upper part of layer III send their axons to the cortex in the same hemisphere while the pyramidal neurons in the lower part of layer III send their axons to the other hemisphere or over longer distances intercortically. Apart from other subcortical considerations, these are the physiological foundations of coherence and phase figures.

Statistical Considerations

The Bonferroni correction was not considered appropriate for analysis as it fails to take into account different categories of information. Setting the Alpha level to .05 would result in 147 significant findings (of the 2945 variables under consideration) by chance alone. To reduce this statistical problem to manageable levels the following were considered.

Epochs with only minor delta activity (under 100 microvolts) were included in the data analysis for two reasons: (a) eye movement (the predominant delta activity artifactual concern) may relate to cognitive functioning as rightward eye movements have been shown in some studies to activate left posterior cortical areas and vice-versa, and (b) the need to obtain as many acceptable epochs in the short 30-second data-gathering period of time as possible to increase statistical power. However, actual delta band activity from these epochs was not included in the reporting of the results for two reasons: (a) the inclusion of delta activity could be misleading as to the nature of the underlying brain activity, and (b) reading-related effective QEEG parameters were focused in the higher bandwidths, thus minimizing the probability that delta activity would be found to be of importance in this study. The effect of this decision will be discussed in the results section.

Statistical significance was considered in view of the particular parameter under consideration. For example, with one of the activation measures (relative power) there are 19 locations and 4 bands (excluding delta), resulting in 76 possible significant findings. An Alpha level of .05 would produce 3.8 significant findings by chance alone. Significant activations are reported only if there were: (a) two or more in adjacent positions, (b) different bands in the same location, or (c) measures were relevant to both the phase and coherence activity. The total number of activation variables resulting from 19 locations, 4 bandwidths, and 4 parameters (excluding symmetry) is 304. The symmetry measures include 674 variables. The total number of connection measures resulting from 19 locations, 4 bandwidths, and 2 parameters is 1368. For the purposes of this research, the number of symmetry measures was reduced by summation of each location's symmetry relationship to the 18 other locations (for the beta1 and beta2 bands only). Thus, each location had two symmetry measures for the beta bands activity. The resulting total number of variables (after removal of delta related variables) under consideration was 2346.

The connection measures (phase and coherence) were reduced by examination of the four frequencies emanating from each location to all other locations. Conceptually this is equivalent to considering that a location is capable of "generator capacity" in the different frequencies. The concept of generators has been employed previously in EEG research (Moran, Tepley, Jacobson, & Barkley, 1993). This pattern of analysis assumes a cortical generator for the separate bands. For example, the phase alpha value from F7 to all 18 other locations was summed. This method of data reduction was conducted for all four frequencies (theta to beta2), both connection variables (phase, coherence) and all locations. Thus, each location would have eight possible significant relationships (phase alpha, coherence alpha, etc.). Any significant relationship from a location (Alpha set at .05) would be above chance levels.

Method

Subjects were asked to read silently a story from the New York Times Sunday magazine section for 100 seconds. When the examiner said "End" the subjects were instructed to start recalling the story to themselves in as much detail as possible and with eyes closed. At the end of a 30-second period, the examiner paused the EEG recording and asked subjects to open their eyes and repeat orally what they recalled of the reading material. The subject then read the same material orally for 60 seconds. This repetition accounted for an increase in memory performance for the delayed recall aspect of the test, with a resulting savings score above 100%. After about 45 minutes of other demanding cognitive tasks during which the EEG was being recorded (e.g., solving Ravens Matrices, multiplication problems, spatial addition problems, spelling tasks, delayed memory recall for word lists, paragraphs, names of faces), the subjects were asked to close their eyes and silently recall the story for 30 seconds while the EEG was being recorded. At the end of the 30 seconds, the EEG recording was paused and subjects were asked to recall aloud the story they had read 45 minutes earlier. The stories were scored following a point and one-half point approach. For example, if the original phrase "worth of rare and protected snakes" was recalled as "worth of rare snakes" a score of one-half point was given.

Data Analysis

The raw EEG data were visually analyzed for artifact (eye movement, EMG, etc.) and epochs with artifact were marked for deletion. A reading task can generate considerable eye movement artifacts, which may mimic delta activity, especially at some frontal sites. Delta activity (under 100 microvolts) was not marked as artifact in order to increase the number of epochs available for analysis, but delta activity was not analyzed in the results. An additional criterion was employed for subject inclusion: the relative power value of delta at the Fp1 location had to be less than 45 or 50 (depending upon the task). The Exporter program, available from Lexicor Medical Technologies, was employed to generate the QEEG variable values. The Exporter software program was commissioned by the experimenter to solve the cumbersome time problem of obtaining required figures from the Lexicor raw data file. The program generates values for the variables under consideration from the raw data file and generates ASCII, comma delimited files, which can be imported into Excel or CSS Statistica. One CSS spreadsheet was generated for each subject. Every epoch of the spreadsheet was labeled according to what study-related QEEG activity was occurring at the time. Once labeling was completed, the file was subjected to a series of t-test comparisons (e.g., visual attention versus reading). The visual attention condition required the subject to visually attend to an upside down Spanish text and respond to a laser light illuminated on the page (randomly flashed approximately once a second) by raising the right index finger. Subjects were instructed not to attempt to read the material. A t-value was generated for each of 2945 variables (across all epochs under consideration) for each of the reading-related comparisons conducted. These comparisons (means, t-values, difference values) were placed into Excel spreadsheets. Each subject had an Excel spreadsheet containing all of the comparison results. Once all the comparisons were completed, results from the Excel spreadsheet were transferred to a CSS statistical file containing similar comparisons for the other subjects. Two CSS files were used for each comparison. Thus, for example, one CSS file would contain QEEG parameters for all subjects for the absolute level of variables while listening to paragraphs, while another would contain the degree of activation from visual attention values for all subjects (reading condition).

An additional analysis was undertaken to understand the normal response of the brain to the different tasks. Measures of degree of QEEG activation were employed which involved computing the average standard deviation difference between the conditions across all subjects. Comparisons were conducted which analyzed: (a) eyes closed vs. visual attention, (b) visual attention vs. reading, (c) reading vs. recalling short term, and (d) recalling short term vs. delayed recall.

Description of Figures

There are two sets of figures for each of the three conditions (study, immediate recall, and delayed recall). The first figure for each of the comparisons presents the absolute level of activation for the variables, which were found to be positively related to the memory score for the condition under study. The second figure for each of the comparisons presents the degree of activation from the subject's relevant comparison condition (e.g., visual attention or eyes closed) which was positively correlated with recall.

The black-filled circles represent the locations activated (magnitude, relative power, peak frequency, and amplitude asymmetry) to a significant level according to the previous discussion of significance (statistical significance section). The lines represent the significant phase and coherence values between locations. A black-filled circle represents the "origin" of these lines. For ease of visual inspection, some of the circles are not drawn where the line terminates. The effective (positive relationships) and ineffective (negative relationships) parameters are noted on each set of figures. The label on top of each "head" figure indicates the variable that the "head" figure is referring to, according to the following nomenclature. Each figure is accompanied by text that presents the relevant variables (*T*–theta; *A*–alpha; *B1*–beta1; *B2*–beta2; *M*–Absolute Magnitude; *R*–Relative Magnitude; *PKA*–Peak Amplitude; *PKF*–Peak Frequency; *Sym*–Symmetry; *P*–Phase; *C*–Coherence).

The following examples are provided for clarification: *PA*–reflects phase alpha; *CT*–reflects coherence theta; *RPB2*–reflects relative power of beta2; *MB1*–reflects magnitude of beta1; *PKAA*– reflects peak amplitude of alpha; *PKFB2*–reflects peak frequency of beta2; *SymB1*–reflects symmetry of beta1 band. (Symmetry measures employ a combination method, where a particular location's symmetry measure is calculated in reference to all other positions and is calculated only for the beta bands.) This method of calculating the symmetry method was to aid in reducing the number of variables under consideration. Only beta activity was considered in these calculations, as it is generally considered most relevant to task conditions.

RESULTS

This study focused on ability to recall verbally information from a short story presented visually during both immediate and delayed recall conditions. Integration of results of this research with previous PET and QEEG studies requires consideration of degree of EEG activation of the subject group as a whole during relevant comparison conditions (visual attention or eyes closed) as well as consideration of the QEEG relationships to successful recall. The first presentation is of findings involving comparisons of broad changes in QEEG response, irrespective of success at the task. Sample sizes vary due to the availability of the subjects. All of the comparison groups (eyes closed, visual attention) involved right-handed subjects over the age of 13 who had a relative power of delta value from the Fp1 location under 45.

The subtraction of the absolute level of QEEG variables during the eyes closed (no task) condition (n = 43) from activation during the control visual attention (laser flashing) condition (n = 46) resulted in many significant differences. A greater than one standard deviation (SD) difference criterion was employed to decrease the number of numerous reportable changes. The change from eyes closed to visual attention resulted in predominantly decreased alpha activity and alpha connectivity patterns and increased activation of the beta2 frequency.

There were significant decreases in the alpha coherence generators from all locations with a few of the posterior locations just below the one SD criterion (T5, P3, P4 Fz, Cz, Pz). Decreases were evident in (a) the relative power of alpha value at all locations, (b) in the peak amplitudes (alpha) at almost all locations (except P4, O2, Fz, Cz and Pz), and (c) magnitudes of alpha at T6, O1 and O2. Increases in beta2 were evident in (a) relative power at almost all locations except Fp1, Fp2, F3, Fz, C3 and Cz (where difference values were still above .50 SD), (b) magnitude of beta2 at T4 and T5, and (c) amplitude at F7. Peak frequencies of theta decreased in almost all locations (except F8, T3 and T6). Peak frequencies of beta1 increased at T3 and T5. Symmetry of beta1 increased at T3 and T4 and decreased at P3 and P4. Peak amplitude of beta1 decreased at O1.

The change from visual attention (N = 46) to reading silently (N = 38) resulted in decreased connectivity values in the lower frequency bands (alpha, theta), increased connectivity values in the beta frequency (from posterior locations), decreased beta activity (relative power) in frontal locations with the exception of an increased right frontal (Fp2, F8) beta symmetry values and magnitude of beta1 (Fp2) and increased posterior beta2 magnitudes and relative power values. Based on the findings, reading is predominantly a posterior beta2 activity, with right frontal locations also activated in the beta (1 and 2) frequency. A comparison of these results (normal activation pattern) with Figure 2 indicates that the normal activation pattern does not include any of the parameters found to be related to successful recall. This finding raises a serious question to the implicit assumption behind PET studies that if an area is part of an activation pattern it is somehow related to success at that task. A required qualifying statement, however, is that the critical locations may be activated but not to a significant degree in a group comparison situation.

Specific changes (visual attention vs. silent reading) included generator decreases in coherence theta (F3, F4), and coherence alpha (Fz), and increases in coherence beta1 (C3, P3, O2) and coherence beta2 (T5, P3, P4, O2). Phase decreases in theta included all but a few posterior locations (T5, P, O1, Pz). Additional phase generator decreases were evident in alpha (F7 and F8) and Fp2 (phase beta1 and beta2). Frontal decreases of relative power were evident in the alpha values (Fp1, Fp2, F7, F8), beta1 values (Fp2, F7, F8, F4, T3, T4) and beta2 values (F7, F8, T4).

Frontal locations showed elevations in peak amplitudes of alpha (Fp1, Fp2, F7, F8, F3, F4, T4, T5), peak amplitudes of beta1 (Fp1, F7, F8, F4, T4), magnitudes of theta (Fp1, Fp2, F7, F8 F4, T4), magnitudes of alpha (Fp2, F7, F8), magnitude of beta1 (Fp2), magnitudes of beta2 (Fp1, Fp2, P3, Cz, Pz) and symmetry of beta1 (Fp2, F8) and beta2 (Fp2). Relative power of beta2 increased in posterior locations (P3, Cz, Pz). Peak amplitudes of theta increased in almost all locations (except T5, P3, Cz). Peak amplitudes of beta2 increased at T3 and Cz and magnitudes of beta2 increased at Fp1, Fp2, P3, Cz, and Pz.

The subtraction of silent reading condition values from immediate silent recall condition values (N = 32; employing a one SD criterion) indicated increased connectivity patterns in the lower frequencies (alpha, theta) and diffuse increases in relative power, magnitudes, and peak amplitudes of alpha, decreased frontal beta and posterior beta2. Specific changes included increased coherence alpha generators values (1.2 to 3.8 SD), almost all phase theta generator values (except T5, P3, P4, O2) and frontal phase alpha generator values (Fp1, Fp2, F7, F8, T3), and a decrease in phase alpha from O2. Increases in relative power of alpha were evident from all locations as well as decreases in frontal beta activity (Fp1 and Fp2-relative power of beta1; Fp1-relative power of beta2) and posterior relative power of beta2 activity (P3, Pz, O1, O2).

Increases were evident in the peak amplitudes of alpha (P4, Pz, O1, O2) and global increases in magnitude of alpha (except F8).

A comparison of the eyes-closed condition to the immediate recall condition demonstrated decreased (more than .50 SD) frontal activity in the theta, alpha and beta frequencies and increased beta2 activity in posterior and temporal locations. Some of the frontal theta activations were related to successful recall. The magnitudes of beta2 at Cz and Pz were related to successful recall. Although the general response change shows few significant changes, which overlap with successful recall, it should be kept in mind that some of the differences did not reach significance but were in the same pattern of change as the success related parameters.

Specifically, in this comparison there was decreased frontal coherence theta generator activity (Fp1, Fp2), and relative power changes included decreased posterior theta values (T3, T4, C3, C4, P4, Cz, Pz), decreased frontal alpha (Fp1, Fp2, F8, T3), decreased frontal beta1 (Fp1, Fp2, F7, F8, F3, F4, Fz) and increased posterior beta2 (T3, T4, C4, T5, P3, P4, Cz, Pz). Peak amplitude results indicated decreased frontal theta amplitudes (Fp1, Fp2, F7, F8, F3, F4), and diffuse increases in peak amplitudes of beta2 in almost all locations (except F7, F3, C3, T6). Decreased peak frequencies of theta (and magnitudes) were evident at frontal locations (Fp1, Fp2, F7, F8, F3, F4, Fz), while peak frequencies of beta1 increased at T3, T5 and T4. Peak frequencies of beta2 increased in almost all locations (except F3, F4, T3, T4, O1, O2, Fz and Pz) as well as magnitudes of beta2 (except at F7, F3, C3, T6). Symmetry of beta1 at T3 increased and symmetry of beta2 at Cz decreased.

The subtraction of immediate recall ($N = 34$) condition from delayed recall condition ($N = 36$) indicated only significant increases in coherence beta2 generator activity from F8 and F4 (.50 SD).

The subtraction of eyes closed condition from delayed recall condition indicated significant ($SD > .50$) decreased theta activity and increased beta (predominantly beta2) activity with a focus on the left posterior locations. Thirteen of the twenty-nine beta activation patterns (from eyes closed) that were found to be related to successful recall (Figure 6) were located in left posterior locations (T5, P3, O1).

Specifically, there were increased F7 coherence theta values as well as Cz coherence beta2 and F3 phase beta2 values. In addition there were decreased values of central and posterior relative power of theta (T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2), frontal peak amplitudes of theta (Fp1, Fp2, F7, F8), frontal peak frequencies of theta (Fp1, Fp2, F7, F3, Fz, F4 and F8) and frontal magnitudes of theta (Fp1, Fp2, F7, F8). Beta changes included decreased frontal beta1 relative power (Fp1, Fp2, F7, F3, Fz, F4, F8), increased peak frequency of beta1 (T3, T5), peak frequencies of beta2 (Fp2, F8, F3), increased magnitude of beta1 (T5), increased temporal and parietal beta2 relative power (T3, T4, P3, T5), increased peak amplitudes and magnitudes of beta2 (except F3, C3, T6), increased symmetry beta1 (T3) and increased symmetry beta2 (T5). There was also a significant decrease in symmetry beta2 at Cz.

The beta activations, which were also related to successful recall, included symmetry beta2 at T5, relative power beta2 at T5 and P3 and the peak amplitudes and magnitudes of beta2 at T5, P3, Pz and Cz.

The following figures address the obtained relationships between memory performance and QEEG variables (absolute level values and degree of activation from a relevant comparison condition) during the studying, immediate, and delayed recall conditions.

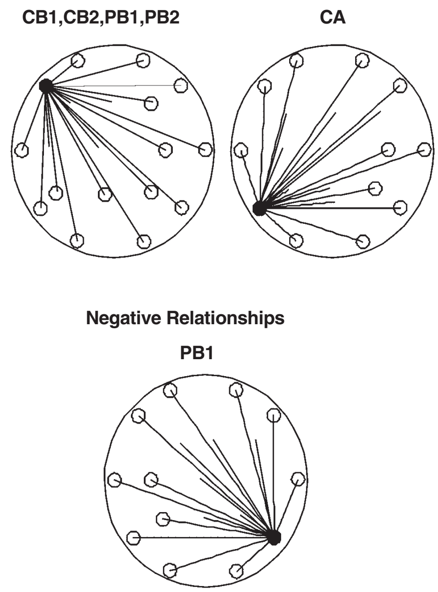
Input Stage

Figures 1 and 2 present the results for the reading condition. Figure 1 presents results of the analysis for the period when subjects were reading in terms of absolute values of the variables. For example in Figure 1, as the Fp1 to F7 coherence alpha value increases (e.g., from 50 to 70), the memory score increases. The figures present both the significantly positively related parameters and the significantly negatively related parameters following the previous discussion of significance. Results were calculated in terms of total memory score, which combines both short-term recall and long-term recall. Figure 2 presents results in terms of degree of activation of QEEG from the visual attention condition. The purpose of this subtraction from this comparison condition was to help separate the visual attention aspects of reading from the memory processes.

The electrode sites that were related to higher total memory scores (the variable's absolute level) involved generator activity from the left frontal region (F7-coherence beta1 and beta2, phase beta1 and beta2) in addition to T5-coherence alpha. The T6 phase beta1 generator was negatively related to memory ability.

Figure 2 presents the analysis of degree of activation (visual attention to reading) indicating the powerful role of the generator activity of coherence alpha (F8, Fz, C3, T5, P3, P4, T6, O1 and O2) and symmetry of beta1 (O2). Negative relationships to recall included theta activity (relative power of theta at Cz and Pz; magnitude of theta at Cz, Pz and P4)

FIGURE 1. Reading Silently–significant correlations between total recall scores and QEEG variables (absolute level) (N = 38).



CA–Coherence Alpha, **CB1**–Coherence Beta1, **CB2**–Coherence Beta2, **PB1**–Phase Beta1, **PB2**–Phase Beta2

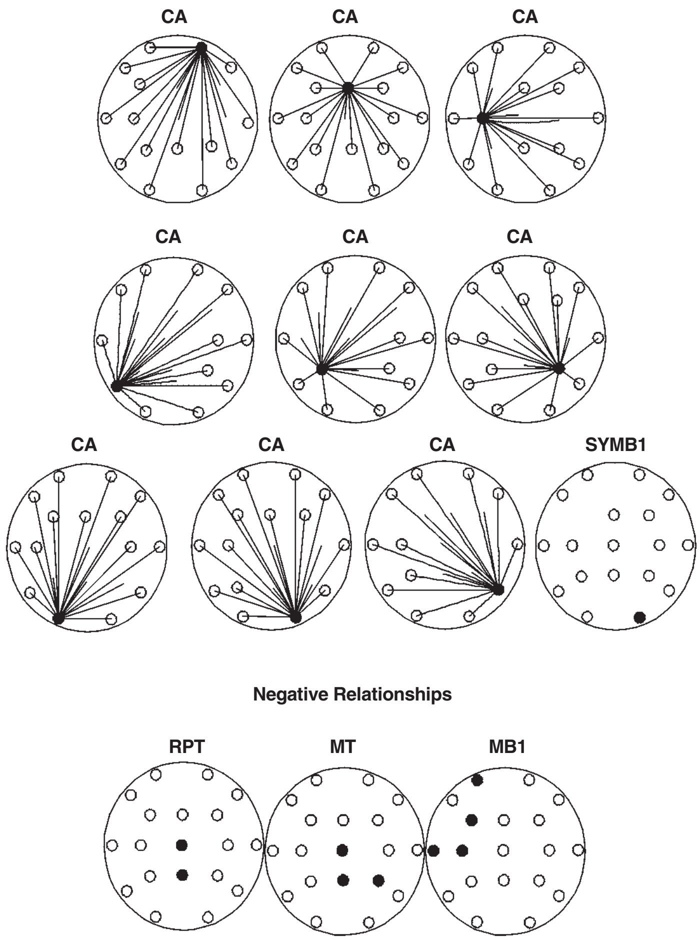
and magnitudes of beta1 (Fp1, F3, T3 and C3). Positively related variables included O2 (symmetry of beta1). The only variable, which was the same for both absolute level and degree of activation analysis, was coherence alpha from T5.

Output Stage

Immediate Silent Recall. Figures 3 and 4 present the results of the immediate silent recall condition. Figure 3 presents the level of activation analysis, while Figure 4 presents the degree of activation from eyes closed. The relative power of delta at the Fp1 location (Fp1RPD) was set at 50 to allow the 32 subjects into the analysis, otherwise only 23 subjects would have been available.

Generators relevant to success included (absolute level) the F4 coherence beta2 generator. There were numerous findings for the activation variables with theta activity dominating (relative power of theta–F7, F3,

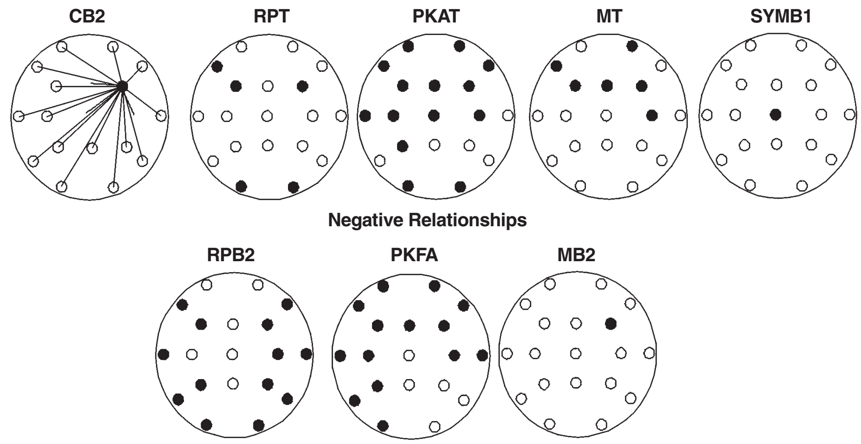
FIGURE 2. Reading Silently–significant correlations between total recall scores and QEEG Variables (degree of activation from visual attention) (N = 38).



CA–Coherence Alpha, **RPT**–Relative Power Theta, **MT**–Magnitude Theta, **MB1**–Magnitude Beta1, **SymB1**–Symmetry Beta1

F4, O1 and O2; peak amplitude of theta–Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, P3, O1 and O2; magnitude of theta–Fp2, F7, F3, Fz and F4) and symmetry of beta1 at Cz. Negatively related variables included relative power of beta2 (F7, F8, F3, F4, T3, C4, T4, P3, P4, O1 and O2), peak frequency of alpha (Fp1, Fp2, F7, F8, F3, Fz, F4, T3, C3, C4, T4, T5, P3 and O1), and magnitude of beta2 at F4. Thus successful

FIGURE 3. Immediate Recall–significant correlations between total recall scores and QEEG variables (absolute level) (N = 34).



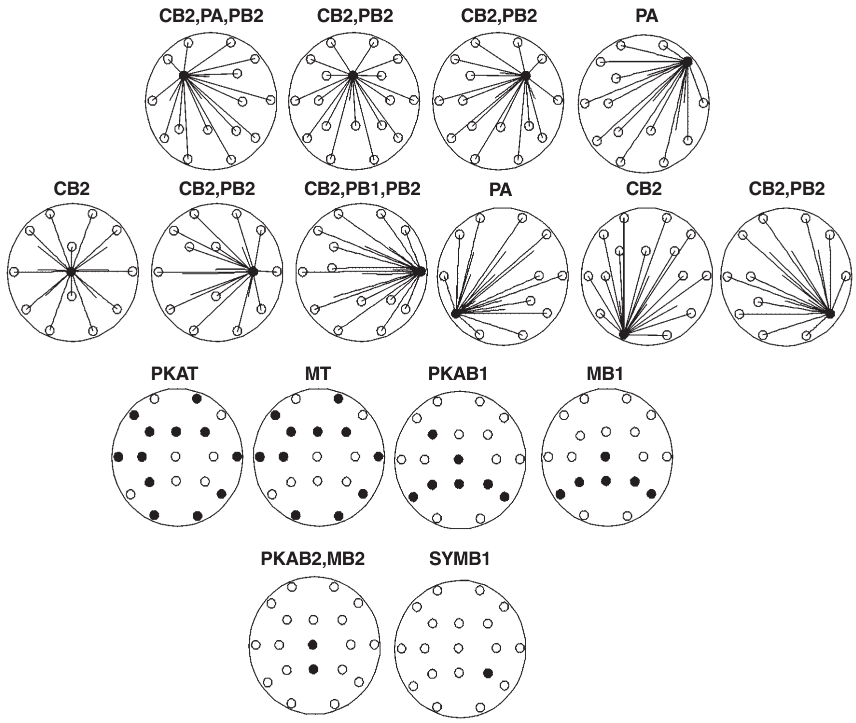
CB2–Coherence Beta2, **RPT**–Relative Power Theta, **RPB2**–Relative Power Beta2, **PKAT**–Peak Amplitude Theta, **MB2**–Magnitude Beta2, **PKFA**–Peak Frequency Alpha, **SymB1**–Symmetry Beta1

immediate recall is dominated by a "relaxing" of the system with low values in the upper frequencies and increased values in the lower frequencies and right frontal coherence beta2 generator activity.

Figure 4 presents the QEEG variables whose degree of activation from eyes closed were positively related to recall ability. Thus the greater the variable activated, the greater the recall score. The critical variables involved generator activity from F3 (coherence beta2, phase alpha, phase beta2), Fz (coherence and phase beta2), F4 (coherence and phase beta2), F8 (phase alpha), Cz (coherence beta2), C4 (coherence and phase beta2), T4 (coherence and phase beta2, phase beta1), T5 (phase alpha), O1 (coherence beta2) and T6 (coherence and phase beta2). Activations of theta (peak amplitudes–Fp2, F7, F3, Fz, F4, T3, C3, T4, P3, T6, O1 and O2; magnitudes–Fp2, F7, F3, Fz, F4, T3, C3, T4, T6, O1 and O2) and beta1 (peak amplitudes–F3, Cz, T5, P3, Pz, P4 and T6; magnitudes–Cz, T5, P3, Pz, P4 and T6; symmetry beta1-P4) and beta2 (peak amplitudes–Cz and Pz; magnitudes–Cz and Pz) were all positively related to successful recall.

Although a lower level of the beta2 frequency (relative power) is related to success, the degree of activation results impressively demonstrate the role of the beta2 coherence and phase generators with 12 of the 16 patterns involving these generators. The right hemisphere is

FIGURE 4. Immediate Recall–significant correlations between total recall scores and QEEG variables (degree of activation from eyes closed) (N = 34).



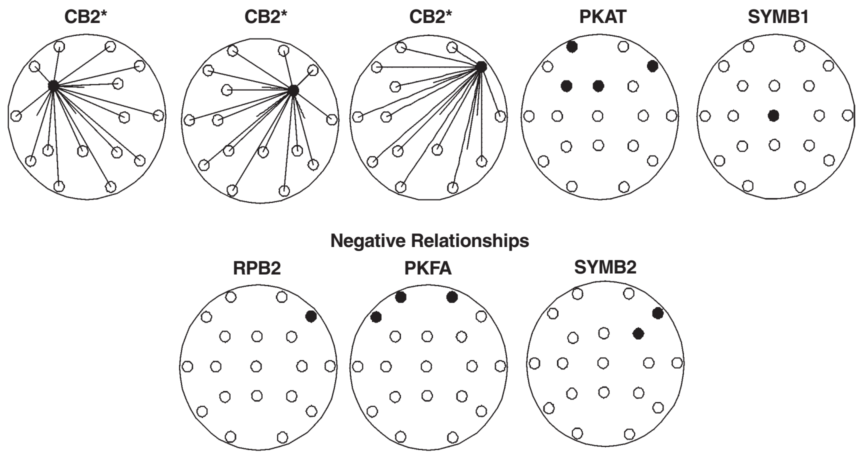
CB2–Coherence Beta2, **PA**–Phase Alpha, **PB2**–Phase Beta2, **RPT**–Relative Power Theta, **PKAT**–Peak Amplitude Theta, **PKAB1**–Peak Amplitude Beta1, **PKAB2**–Peak Amplitude Beta2, **MT**–Magnitude Theta, **MB1**–Magnitude Beta1, **SymB1**–Symmetry Beta1

strongly involved in successful recall. This involvement is evident in the positive relationship between the absolute level of the F4 coherence beta2 value and the degree of activation results (10 right hemisphere versus 5 left hemisphere generator variables).

The variables, which were the same for the absolute level and degree of activation analysis, were the generator activity from F4 (coherence beta2) and the theta values (peak amplitude and magnitude). Of particular interest is the relationship between the negatively related activation at F4 of the magnitude of beta2 and the strong positive relationship the generator activity has at this location in the same frequency.

Long Term Delayed Recall. Figures 5 and 6 present results of the delayed recall condition, with Figure 5 presenting absolute level of the

FIGURE 5. Delayed Recall–significant correlations between delayed recall scores and QEEG variables (absolute level)–CB2*–indicates significant at .10 alpha level (N = 36).

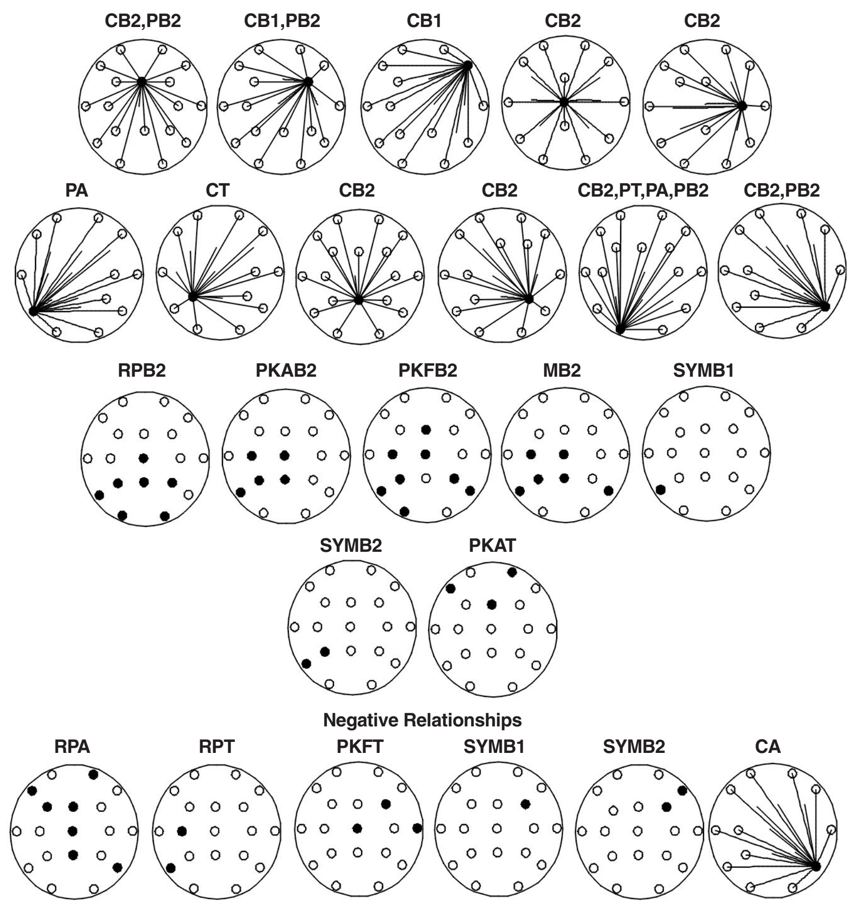


CB2–Coherence Beta2, **RPB2**–Relative Power Beta2, **PKAT**–Peak Amplitude Theta, **PKFA**–Peak Frequency Alpha, **SymB1**–Symmetry Beta1, **SymB2**–Symmetry Beta2

variable which correlated with delayed recall, while Figure 6 presents degree of activation from the eyes closed condition. The analysis involved the correlations with the delayed recall score only and not the total recall score. Long-term recall is positively related to (absolute level) coherence beta2 generator activity at F3, F4 and F8. This is similar to the immediate recall condition with a right frontal dominant generator pattern. The coherence beta2 generator activity was significant at the .10 alpha levels. It was included due to the similarity of the results with the immediate recall condition. Additional variables related to successful recall included frontal peak amplitude of theta (Fp1, F8, F3 and Fz) and symmetry of beta1 (Cz). Negatively related activations included F8 (relative power of beta2), peak frequency of alpha (Fp1, Fp2 and F7) and symmetry of beta2 (F8 and F4). The negative influence on memory of the right frontal (F8 and F4) activation of the relative power of beta2 was similar to the immediate recall condition (F4-relative power of beta2).

Degree of activation variables indicated significant generation from frontal regions (Fz–coherence and phase beta2; F4–coherence beta1 and phase beta2; F8–coherence beta1), central locations (Cz–coherence

FIGURE 6. Delayed Recall–significant correlations between delayed recall scores and QEEG variables (degree of activation from eyes closed) (N = 36).



CT–Coherence Theta, **CA**–Coherence Alpha, **CB1**–Coherence Beta1, **CB2**–Coherence Beta2, **PT**–Phase Theta, **PA**–Phase Alpha, **PB2**–Phase Beta2, **RPT**–Relative Power Theta, **RPA**–Relative Power Alpha, **RPB2**–Relative Power Beta2, **PKAT**–Peak Amplitude Theta, **PKAB2**–Peak Amplitude Beta2, **MB2**–Magnitude Beta2, **PKFT**–Peak Frequency Theta, **SymB1**–Symmetry Beta1, **SymB2**–Symmetry Beta2

beta2; C4–coherence beta2) and posterior locations (T5–phase alpha; P3–coherence theta; Pz–coherence beta2; P4–coherence beta2); O1 (coherence beta2, phase theta, phase alpha and phase beta2); T6 (coherence and phase beta2). Location activation variables indicated posterior activations in the beta2 frequency (relative power of beta2–Cz, T5, P3, Pz, P4, O1 and O2; peak amplitudes of beta2–C3, Cz, T5, P3 and Pz);

peak frequency of beta2 (Fz, C3, Cz, T5, P3, P4, T6 and O1); magnitudes of beta2 (C3, Cz, T5, P3, Pz and T6); symmetry beta2 (T5 and P3) in addition to symmetry beta1 (T5) and peak amplitude of theta (Fp2, F7 and Fz). Beta activations at T5 (six significant variables) and P3 (five significant variables) dominated the location parameters for beta activations. Negatively related variables included relative power of alpha (Fp2, F7, F3, Fz, Cz, Pz and T6), relative power of theta (C3, T5), peak frequency of theta (F4, Cz, T4), symmetry of beta1 (F4), symmetry of beta2 (F8 and F4), and T6 coherence alpha.

The only variables which were the same for the absolute level and degree of activation, involved the negative relationships between recall and the activation of right frontal locations (symmetry beta2 at F8 and F4).

Summary of Results. The similarity of the delayed recall to the immediate recall results was evident in five patterns. First, as in the immediate recall condition the importance of the beta2 generator activity was evident in nine of the 15 significant generators. Second, there was a strong right hemisphere involvement (5 of 11 generators–excluding Fz, Cz and Pz). This pattern was not, however, as strong as it was in the immediate recall condition. Third, there was a pattern of decreased performance with activation of the beta2 activity in the right frontal region in both immediate and delayed recall. Fourth, the absolute level analysis indicated in both the immediate and delayed condition the importance of a few right frontal coherence beta2 generator activity, while the degree of activation analysis indicated for both conditions (immediate and delayed) posterior beta activations and diffuse generator activity. Fifth, there was also a pattern of the absolute level analysis indicating that the generator activity emanated from frontal locations (8 of 9), while the degree of activation results indicated a more balanced pattern (15 from frontal locations, 9 from central (T3-C3-Cz-C4-T4) and 15 from posterior locations. The most important locations for the generator activity across all conditions (absolute level and degree of activation) were O1 (6), Fz (5), F7 (4), T5 (4) and F3 (4), indicating the important role of the frontal region in memory processes (13 of 23).

Relationship Between Demographic Variables and QEEG Success Related Variables. Table 2 presents the correlations between the demographic variables and the significant generator systems involved in the reading condition (absolute values of the variables). The variables are indicated in Figure 1. The table indicates that females obtain higher levels of the T5 coherence alpha generator and total memory is related significantly to education, raw verbal score and verbal IQ score of the

TABLE 2. Relationship Between QEEG Variables, Recall and Demographic Information Between Critical Generators at Time of Reading Task

	T5CA	F7CB1	F7CB2	F7PB1	F7PB2	TMEM
SEX	**−.38**	.16	.13	.08	.11	−.07
ED	.16	.20	.13	.14	.05	**.39**
RAWV	.11	.07	.03	.03	−.06	**.45**
RAWA	.03	.20	.04	.17	.05	.10
VIQ*	.09	.17	.05	.13	−.01	**.37**
AIQ*	−.10	−.10	−.21	−.10	−.12	**−.43**
SPEED	−.17	−.08	−.18	−.18	−.14	**−.44**
LINES	.11	.20	.29	.23	.24	**.40**
STM	**.40**	**.35**	**.31**	.30	.27	**.97**
LTM	**.35**	**.37**	**.38**	**.29**	**.30**	**.98**
MPL	−.07	**.30**	**.30**	**.33**	**.25**	**.67**
SAV	.03	.04	.18	−.02	.10	.17
TMEM	**.38**	**.43**	**.42**	**.37**	**.35**	**1.00**
AGE	.02	−.24	−.29	−.27	**−.33**	−.04

All correlations in bold are significant at $p < .05$; **SEX** = negative correlations indicate direction towards female sex; **ED** = Education; **RAWV** = raw score of Shipley Verbal Scale; **RAWA** = raw score of Shipley Abstraction Scale; **VIQ** = Verbal IQ; **AIQ** = Abstraction IQ; **SPEED** = number of seconds spent reading divided by number of lines read, smaller number reflects faster speed; **LINES** = number of lines read; **STM** = Short-Term Memory; **LTM** = Long-Term Memory; **MPL** = memory per line, calculated as number of lines read divided by memory score; **SAV** = savings, calculated as long-term memory divided by short-term memory; **TMEM** = Total Memory Score.
* Employed Paulson, M. J. and Lin, T. (1970) formulas in estimation of verbal and abstraction IQ

Shipley and negatively to abstraction IQ. Total memory is also significantly related to speed (faster reading speed), number of lines read, and the memory per line score.

Table 3 presents the analysis of the relationships between demographic variables, memory scores, and the degree of activation of the QEEG variables for the reading condition. There were no significant relationships between the QEEG variables and the demographic variables, indicating no significant relationship between education, verbal IQ, sex, or age with the ability to activate the relevant parameters for successful reading.

DISCUSSION

A complete understanding of the mind involves integration among biochemical, blood flow, electrical events, psychological events and anatomical structures. This research addressed relationships between anatomy, electrical events, and conscious recall of information.

Reading is a complex task as delineated by previous PET studies. Results of this study coincide exceptionally well with previous blood flow studies, which have indicated a frontal activation focus (Bookheimer et

TABLE 3. Significant Relationships Between QEEG Variables, Reading Recall and Demographic Information at Time of Reading Task (Degree of Activation from Visual Attention)

	F2CA	FZCA	C3CA	T5CA	P3CA	P4CA	O1CA	O2CA
SEX	.13	.07	.01	−.12	−.05	−.02	−.06	−.14
ED	−.05	.13	.19	.06	.12	.06	.23	−.03
RAWV	.15	.02	−.03	−.04	−.04	.01	.08	−.07
RAWA	−.08	−.15	−.11	.11	.09	−.04	−.02	−.18
VIQ*	.05	−.09	−.09	.04	.04	−.02	.04	−.16
AIQ*	−.13	−.16	−.08	.06	.07	−.12	−.14	−.23
SPEED	−.10	−.28	−.14	−.17	−.03	−.13	−.27	−.12
LINES	.05	.22	.12	.26	.09	.22	.32	.16
STM	.27	**.37**	.29	.31	.30	.21	.24	.16
LTM	**.45**	**.46**	**.39**	**.37**	**.39**	**.35**	**.33**	**.33**
MTOT	**.40**	**.44**	**.36**	**.35**	**.37**	**.30**	**.33**	**.33**
MPL	.21	.19	.16	.06	.23	.05	−.02	.06
SAV	**.37**	.21	.20	.11	.21	.24	.22	.27
AGE	.06	.02	.05	−.12	−.06	−.11	−.01	−.23

All correlations in bold are significant at $p < .05$; **SEX** = negative correlations indicate direction towards female sex; **ED** = Education; **RAWV** = raw score of Shipley Verbal Scale; **RAWA** = raw score of Shipley Abstraction Scale; **VIQ** = Verbal IQ; **AIQ** = Performance IQ; **SPEED** = number of seconds spent reading divided by number of lines read, smaller number reflects faster speed; **LINES** = number of lines read; **STM** = Short-Term Memory; **LTM** = Long-Term Memory; **MTOT** = total memory; **MPL** = memory per line, calculated as number of lines read divided by memory score; **SAV** = savings, calculated as long-term memory divided by short-term memory.
* Employed Paulson, M. J. and Lin, T. (1970) formulas in estimation of verbal and abstraction IQ

al., 1995; Pugh et al., 1996) and an occipital/temporal/parietal focus (Petersen & Fiez, 1993; Petersen et al., 1990; Bookheimer et al., 1995; Pugh et al., 1996) during the reading task. A right frontal/right hemisphere activation focus during immediate recall (Cabeza et al., 1997) was also supported by the present QEEG measures. However, both the immediate and delayed recall tasks resulted in F8 and F4 activations versus the F8 and FP2 activations indicated by the Cabeza group. The relevant comparisons are the degree of activation measures since PET studies are designed with this type of methodology. The posterior beta activations in the delayed recall task evident in this research were not studied in the earlier PET studies.

A contrast found in earlier research between delayed recall of visually presented reading material being dependent upon right frontal/right hemisphere activity and delayed recall of verbally presented material dependent upon left frontal generator activity (Thornton, 2001a) may help explain the divergence of results from some PET studies.

This research and related discussion makes the assumption that if a single location is the focus of multiple significant correlations then it is the source or generator of a relevant signal (as a flashlight is the source of a beam of light) and the multiple significant relationships are the receiving end of that signal source. These results present a picture of a top-down and bottom-up interactive system. Ungerleider (1995) noted that object knowledge seems to be stored in a distributed cortical system in which information about specific features is stored close to the regions of the cortex that mediate the perception of those features. As the posterior/central/temporal regions are the predominant receptive regions for information, what then is the role of the frontal generator activity to these locations? Is its role to activate these regions? The answer is not self-evident and is not answerable by the data of this study. However, if memory is dependent upon activations at one or several locations, then it could be argued that increased connection activity serves to activate a location, as Damasio (1989) has argued.

Additional unanswered questions concern the nature of and relationships between the degree of EEG activation from a previous condition analysis and absolute level analysis. The absolute level analysis is an appealing approach, as it simply hypothesizes that the higher the base activation value the better the recall. One assumption behind this concept might be that with greater activation the information is being transferred more accurately. More theoretically problematic is the degree of activation from a priori condition analysis. Superficially, one could assume that the greater the degree of activation would indicate the system is employing the relevant locations to a greater degree, much as a car produces more power for greater speed. However, this assumption ignores the problem that individuals operate at different resting levels. If subject A has a resting level of beta activity (for example) which is higher than subject B, why is it required that subject A activate the region to improve his memory score. Wouldn't a certain level of activation be sufficient? During the input stage of this research the significant degree of activation variables are not beta measures (with one exception) but alpha coherence activity. However, alpha coherence activity was never seen as an important variable after the input stage, when coherence and phase beta activity become critical. Why does the system need to change frequencies to produce results? There are no specific answers to these questions now.

The results seem contrary to Damasio's (1989) hypothesis that memory is a recreation of the original physical storage process, as the parameters found relevant to effective input were not the same as the parameters found related to effective recall. The reading condition results indicated generator activity as critical. The immediate and delayed recall conditions showed mixed results with both activation and generator activity important to recall (as presented in results section). However, Damasio's theory that connective activity (coherence and phase) serve to activate regions (i.e., increase magnitudes of beta) is partially supported, especially in the delayed recall condition.

Many of the generator patterns are not associated with significant activations in the locations where they terminate. Activations (in certain locations and frequencies) are also negatively related to recall (see Figure 3). One implicit assumption behind PET studies is that activations are somehow related to successful functioning. Whether PET activations have their correlate in an increase in beta activity at a location or an increase in connectivity patterns emanating from a location or both is uncertain. This research can provide limited indirect support to the concept that the increased blood flow at a location is related to increased connectivity from that location as the Pugh et al. (1996) study indicated anatomical relationships to reading involving frontal, left temporal and occipital locations, a finding consistent with Figure 2 results for the generator activity.

Although previous research (Doyere et al., 1993; Larouche et al., 1990) has focused on the long term potentiation (LTP) changes in the prefrontal cortex and the relationship between the hippocampus theta rhythm and the prefrontal cortex, the results of this research point to a more complex pattern involving different frequencies and different locations across different tasks. The interplay between these frequencies and locations defies specific understanding, as there is no proposed model of brain functioning which can adequately account for these findings.

The statistical approach employed in this research is different than previously applied approaches addressing this type of data. The author is not aware of any mathematical/statistical procedure which can integrate findings across different fields of scientific inquiry. The validity of the statistical approach employed resides in the discoveries, which parallel the findings in PET studies. This overlap is evident in the author's previous research (Thornton, 2001a) on auditory memory, which strongly implicated left temporal lobe connectivity patterns, a location previously indicated by PET studies as critically involved in auditory memory. The discussion in the current article also points to consistent results between the QEEG results and previous PET and blood flow studies. An additional argument for the validity of the statistical approach resides in its applicability to remediation. In short, if the approach is not valid why do the interventions work? The effectiveness of the interventions for auditory memory have been reported in two separate peer reviewed articles (Thornton, 2000b and 2002). Parsimony of explanation has long been a valid scientific principle. Other explanations might be offered for the improvement in functioning. However, it is more parsimonious to state that the "cause" of improved memory is the increase in the values of the variables, which are positively correlated with memory.

It is hoped that this preliminary delineation of the electrophysiology of these memory-related mental states will lead to interventions that are more effective for individuals experiencing problems in these areas. As in any research in this area, replications using larger sample sizes are desirable. However, this type of information has proven useful in the rehabilitation/improvement of memory functioning in normal, learning disabled and head injured subjects by applying it to development of training protocols for neurotherapy training. Improvements in paragraph recall ranging from 39% to 181% (N = 10) have been obtained (Thornton, 2000b and 2002).

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