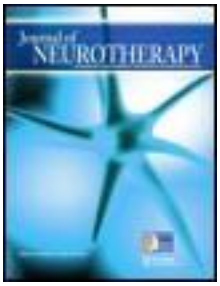

Journal of Neurotherapy: Investigations in Neuromodulation, Neurofeedback and Applied Neuroscience

Eyes-Closed and Activation QEEG Databases in Predicting Cognitive Effectiveness and the Inefficiency Hypothesis

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Published online: 26 Feb 2009.

To cite this article: Kirtley E. Thornton PhD & Dennis P. Carmody PhD (2009) Eyes-Closed and Activation QEEG Databases in Predicting Cognitive Effectiveness and the Inefficiency Hypothesis, Journal of Neurotherapy: Investigations in Neuromodulation, Neurofeedback and Applied Neuroscience, 13:1, 1-21

To link to this article: http://dx.doi.org/10.1080/10874200802429850

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Journal of Neurotherapy, 13:1–21, 2009

ISSN: 1087-4208 print/1530-017X online
DOI: 10.1080/10874200802429850

SCIENTIFIC ARTICLES

Eyes-Closed and Activation QEEG Databases in Predicting Cognitive Effectiveness and the Inefficiency Hypothesis

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ABSTRACT. *Background*. Quantitative electroencephalography (QEEG) databases have been developed for the eyes closed (EC) condition. The development of a cognitive activation database is a logical and necessary development for the field.

Method. Brain activation was examined by QEEG during several tasks including EC rest, visual attention (VA), auditory attention (AA), listening to paragraphs presented auditorily and reading silently. The QEEG measures obtained in the EC and simple, non-cognitive attention task that were significantly related to subsequent cognitive performance were not the same variables which accounted for success during the cognitive task.

Results. There were clear differences between relative power, microvolt, coherence and phase values across these different tasks.

Conclusions. The conclusions reached are (1) the associations among QEEG variables are complex and vary by task; (2) the QEEG variables which predict cognitive performance under task demands are not the same as the variables which predict to subsequent performance from the EC or simple, non-cognitive attention tasks; (3) a cognitive activation database is clinically useful; and (4) an hypothesis of brain functioning is proposed to explain the findings. The coordinated allocation of resources (CAR) hypothesis states that cognitive effectiveness is a product of multiple specific activities in the brain, which vary according to the task; and (5) the average response pattern does not involve the variables that are critical to success at the task, thus indicating an inefficiency of the normal human brain.

KEYWORDS. Attention, coordinated allocation of resources, eyes-closed and activation databases, memory, QEEG

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The relations between quantitative electroencephalography (QEEG) and clinical and cognitive problems have been investigated for several decades (Evans & Abarbanel, 1999; John & Prichep, 2006). Individuals with cognitive deficits have shown brain activation patterns that are related to the type and severity of their deficit (Thornton, 2002). A goal of the investigations has been to identify the deviations in the underlying electrophysiological measures from normative databases so that interventions directed towards these deviations will ameliorate or improve the clinical condition. Problematic in this assumption is the frequent lack of consistent empirical documentation that the specific cognitive deficits are directly related to the deviations from the database employed. One part of this problem resides in the eyes-closed (EC) QEEG data that have been employed. For example, in understanding memory performance within a normal population, the weakness has been the lack of a well defined set of specific QEEG variables which define how success is achieved during a task. Different EC databases (Lubar, 2003) have been developed as well as databases that engage in subject in simple attention tasks with eyes-open. Developments in the field have led to the inclusion of cognitive tasks in database development (Brain Resource Company, 2007; Skil 3 http://skiltopo.com/). A subject is compared to the normative databases on the QEEG values for the task, without reference to the variables that are critical for the task. These databases ask the question what happens rather than what makes it work.

The EC database provides a set of values that describe the resting state of brain activity for individuals who are engaged in a 'resting' state. While the assumption is that the resting state is a default baseline, the subjects may be engaging in any of a wide range of 'default' states. This issue is of concern to those in the field of neuroimaging (Buckner & Vincent, 2007; Raichle & Snyder, 2007). When subjects have no clear task, the resting brain shows large variations of activity that are not ascribed to performance (Gonzalez-Hernandez, 2005). Thus, the resting state is at best, an estimate of how individuals 'idle' when not required to attend, process, and remember information.

In contrast, an activation database is one that is developed while control subjects are engaged in tasks that require attention, processing, and memory (Thornton, 2001). Under activation conditions, variations in brain activation are related to the specific task. In addition, subject performance on cognitive tasks allows an examination of the associations between brain activation patterns and performance. For example, scores on tests of immediate and delayed recall on a reading task are related to measures of relative power and coherence in specific locations (Thornton, 2002).

There are differences of opinion on the relative value of the EC and activation databases (Thatcher, 1998; Thornton, 1999, 2000). An argument in favor of the EC database is the simple, relative uniformity of the EEG recording conditions (Thatcher, 1999) and high reliability values between evaluations (Niedermeyer, 1987; Oken & Chiappa, 1988). The reliability values across all frequencies for the EC condition have been shown to average around .7 (McEvoy, Smith, & Gevins, 2000).

In contrast to the passive EC condition, active tasks are dependent on many variables including the task difficulty, the motivation of the subject, and the physical characteristics of the recording environment such as the intensity of the stimuli and the room lighting. The reliability values of the activation approach for working memory and attention is .93 across the frequencies (McEvoy et al., 2000).

In addition, QEEG EC databases do not typically collect data above the 32 Hertz range. The Thornton activation database (Thornton, 2001) assesses the subject performing cognitive challenges that are difficult, in order to avoid a ceiling effect and extends the frequency range to 64 Hertz, which offers considerable advantages in certain clinical situations. For example, Thornton (1999, 2000, 2003) was able to distinguish between normals and subjects with mild traumatic brain injury (TBI) primarily on the basis of coherence patterns in the high frequency range (32–64 Hz) in the EC, simple non-cognitive visual (VA) and auditory attention (AA) tasks as well as the task of listening to paragraphs. The results emphasized, as in the Thatcher et al. (1989) study, the importance of the phase and coherence values in obtaining successful discrimination between the groups.

The issue of using as a reference the QEEG from either a passive eye-closed measure or from an active task measure has a parallel in the field of neuroimaging where there is a debate over the default state of the brain that is often used as a baseline for comparison of brain activity during tasks (Morcom & Fletcher, 2007; Raichle & Snyder, 2007). As Gonzalez-Hernandez et al. (2005) indicated, the pre-task 'resting' condition is never truly 'at rest.' McKiernan et al. (2006) found in functional neuroimaging task induced deactivation (TID), which is a local decrease in blood flow during an active task, relative to a "resting" baseline. TID may occur when resources shift from ongoing, internally generated processing typical of "resting" states to processing required by an exogenous task. The major components of the intrinsic system have been identified by various investigations. For example, one group found the intrinsic system to include medial prefrontal areas, the posterior cingulate and the precuneus, lateral inferior parietal cortex and the anterior aspect of infero-temporal cortex (Golland et al., 2007; Golland, Golland, Bentin, & Malach, 2008). Another group found that the intrinsic system involves four left hemisphere regions, including posterior parieto-occipital cortex, anterior cingulate gyrus, fusiform gyrus, and middle frontal gyrus (McKiernan, D'Angelo, Kaufman, & Binder, 2006).

In this study we examine two methods of understanding the relations between the QEEG variables and cognition and added a third method. The first two methods are examining (1) the relation between EC data and cognitive performance data collected at a different time and (2) the examination of the relation between cognitive performance and the QEEG variables during a task. The third method employs the results of the second method to guide the clinical QEEG protocols to improve performance in the cognitive problems of the reading disabled, memory impaired and traumatic brain injured (TBI) patients. We propose the coordinated allocation of resources (CAR) hypothesis which states that cognitive effectiveness is a product of multiple specific QEEG activities in the brain for specific tasks which can involve activities of different frequencies at a location as well as coherence and phase activity between locations.

In this paper we demonstrate how the QEEG measures obtained under EC, resting and simple attention tasks are not the same as the QEEG predictors of performance during the memory tasks. In addition, QEEG studies that measure brain activity with bandwidths from 1 to 64 Hz show a different set of relations between the QEEG variables and cognitive functioning than the studies that restrict the measures of brain activity to 32 Hz and less. We want to know the ongoing QEEG variables during the task which predict success.

RELATIONS BETWEEN MEASURES

As the research frequently examines microvolts, relative power, coherence and phase relations, it is important to understand the empirical relations between these measures. Corsi-Cabrera et al. (1989) summarized the relations between power and coherence across a number of studies by noting that changes in coherence occur independently from changes in EEG power.

Measures

Over the years research studies have generally defined the frequency ranges according to standard practice and have employed the scalp locations defined by the 10–20 system (Jasper, 1958). The frequency definition ranges have been: delta: 0 to 4 Hertz; theta: 4 to 8 Hz; alpha: 8 to 13 Hz; beta: 13 to 25 Hz. The ranges have been dependent upon hardware and software definitions as well as the preferences of individual researchers. Some studies have examined frequencies above 32 Hz (Thornton, 2000, 2001, 2002; von Stein et al., 2000).

There are two types of data available to QEEG analysis. The first involves the activity at a scalp location and examines the different frequencies in terms of measures such as amplitude, relative power, peak frequency, and peak amplitude. The second measure quantifies the association between locations with concepts of phase and coherence. This article will employ the presented bolded capitalized letters to represent the variables.

Activation Measures

M: Absolute Magnitude/Microvolts: the average absolute magnitude (as defined in microvolts) of a band over the entire epoch (one second).

RP: Relative Magnitude/Microvolt or Relative Power: the relative magnitude of a band defined as the absolute microvolt of the particular band divided by the total microvolt generated at a particular location by all bands.

PA: Peak Amplitude: the peak amplitude of a band during an epoch in microvolts.

PKF: Peak Frequency: the peak frequency of a band during an epoch defined in hertz.

S: Symmetry: the peak amplitude symmetry between two locations in a particular bandwidth-, i.e., defined as (A−B)/ (A+B).

Connectivity Measures

The coherence and phase values obtained in this research were generated by the algorithms employed in the Lexicor software. Different hardware and software companies have employed different algorithms in calculating these values. Neither the relations between these different algorithms nor the relations between the algorithms and cognitive effectiveness under activation conditions have been studied. It is not assumed that the results reported in this paper for coherence and phase relationships using the Lexicor software would be the same for the algorithms provided by other equipment manufacturers.

C: Coherence: the average similarity between the waveforms of a particular band in two locations over the one-second period of time, and conceptualized as the strength or number of connections between two locations. Although labeled by Lexicor as coherence, from a mathematical point of view it would more appropriate to refer to it as a cross spectral correlation.

P: Phase: the time lag between two locations of a particular band as defined by how soon after the beginning of an epoch a particular waveform at one location is matched in a second location.

The algorithms for coherence and phase, which were provided by Lexicor Medical Technologies, were employed in the activation database by Thornton (2001). There have been several conceptually and mathematically different approaches to describing the relationships of the frequencies between locations. Collura (2008) has provided a conceptual and mathematical discussion of these different approaches. There are 2944 variables for each subject in each task when combining all available Lexicor measures. In order to reduce the large number of variables and to be consistent with the generator concept in the EEG literature Thornton (2002) developed the flashlight calculation.

The concept of a flashlight assumes that a particular location emits a signal, in defined frequencies, which is projected to all cortical locations. The value for a flashlight variable at a specific location, and in a specific bandwidth, is calculated by summating the coherence values with the remaining 18 locations. References will employ a combination of the shorthand letters presented. For example, **CA** will refer to coherence alpha and **RPA** will refer to relative power of alpha.

There are several problems inherent in the research in the area of examining the associations between QEEG variables and cognition.

1. The first problem has been the implicit assumption that certain QEEG variables relate uniformly to all cognitive abilities. This assumption has been challenged in previous research (Thornton, 2000, 2002).
2. The second problem is the assumption that the degree of activation or changes of the brain from a relevant baseline are related to success at a cognitive task. This assumption is involved in neuroimaging studies including positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) when brain activation during a cognitive task is related to activation at rest.
3. The third problem is the modality of the information presented to the participant, whether auditory or visual.
4. The fourth problem is the assumption implicitly made by developers of EC databases that subject's relative standing, with respect to their QEEG values and a relevant database, will remain roughly the same when comparing values obtained under an EC condition and a task condition. In addition, it would be assumed that the deficits observed under the eyes closed (EC) condition will be present during the activation condition.

This study examines these problems and the associations between cognitive functioning, assessed by reading and auditory memory, and QEEG measures in order to lay the necessary empirical groundwork to identify effective treatment intervention protocols.

METHODS

Participants

Forty-two right-handed participants (age range 14 to 77 years, *M*=38.4, *SD*=15.98; 43% female) with no previous history of ADHD, LD, or TBI participated after signing consent forms. The participants under age 18 signed assent forms and the parents signed consent forms. None of the participants had a history of neurological problems, and four participants were taking medications (anti-hypertensive, anti-depressants). It is assumed that this small percentage (9.5%) of the sample would have no appreciable effect on the overall patterns. Participants were compensated financially and were free to drop out of the study at any time or to refuse participation in the research.

Tasks

The participants completed several tasks in one session. Participants first engaged in an EC resting task for five minutes. This was followed by an AA task with eyes closed for three minutes. The participants then opened their eyes and performed a VA task for three minutes. This was followed by listening and recalling four paragraphs with eyes closed for five minutes. Following each paragraph the subject engaged in silent eyes closed recall (one minute) for each of the four paragraphs while the QEEG is measured. Then they give a verbal report of the paragraphs with no QEEG monitoring. The next task was reading a full page of text for 100 seconds and then silently, with eye closed, recalling of the text. Then with eyes-closed, participants engaged in two delayed recall tasks. The first was a quiet eyes-closed recall of the paragraph and the second a similar approach to recall of the reading material while the QEEG is recorded. The participants then give a verbal report without QEEG recording.

EEG Recording

Brain activity was recorded using a 19 channel QEEG hardware device (Lexicor Medical Technology, Inc.). Bandpass filters were set between 0.0 and 64 Hz (3 dB points). The signals that passed were subjected to a Fast Fourier Transform (FT) using Cosine-tapered windows, which provides spectral magnitude in microvolts as a function of frequency. The sampling rate was set to 256 to allow an examination up to 64-Hz. The bandwidths were grouped according to the following divisions: Delta: .00–4 Hz, Theta: 4–8 Hz, Alpha: 8–13 Hz, Beta1: 13–32 Hz, Beta2: 32–64 Hz. An Electro-Cap was fitted to the participant. The electrodes were positioned at 19 scalp locations according to the standard 10–20 system (Jasper, 1958) with ear linked references. The scalp was prepped with rubbing alcohol and Nu-Prep and the 19 electrodes were filled with Electro-gel. The earlobes and forehead were prepped with rubbing alcohol and Nuprep. Impedances were maintained below 10 K Ohm (and within 1.5 K Ohm of each other) at all locations. Gain was set to 32000, and the high pass filter was set to off. The measurements available through the software provided by Lexicor Medical provided the numeric values of the QEEG variables. The data were artifacted for eye movements and EMG activity as well as other possible sources of contamination (Thornton, 1996).

RESULTS

The results are presented first by describing the associations among the tasks of EC, listening, and reading. Then the results are shown for the changes in brain activity as the participants progress from the EC task to the attention tasks then to the cognitive tasks of listening and reading.

Associations Among Measures

To aid in understanding the research presented it is important to understand how commonly used measures relate to one another and to empirically describe their associations. Two very commonly employed measures are microvolts and relative power. Table 1 presents the correlations between the values of relative power (**RP**) values and absolute microvolts (**M**), which were averaged across the 19 scalp locations for the three tasks of EC, listening, and reading. This study included the beta2 (32–64 Hz) in addition to the commonly used beta frequency range here named beta1 (13–32 Hz). Although many of the relations are significant, it is clear that the measures cannot be considered the same. The lowest associations between **RP** and **M** measures are in the delta frequency and the highest are in the alpha and beta2 frequencies. The relations between the alpha values decreases during the reading task.

Table 2 addresses the relations between the **RP, M, C** and **P** variables by presenting the correlation matrix for the EC, listening (eyes-closed) and reading (eyes open) tasks for these variables. The only significant associations involved delta and alpha. There are positive relations between **RPA, MA** and **CA** and negative relations with **PA** during the two eyes-closed tasks. These relations cease when participants open their eyes to begin reading. It is unclear why there are these inverse relations between **CA, PA** and the **RPA** and **MA** variables.

Table 3 presents the intercorrelations between the phase and coherence values. As the table indicates there are strong associations between the coherence and phase values of the frequency measures, except for the alpha frequency under both eyes-closed tasks.

Table 4 presents the relations between age and the **RP, M, P** and **C** values across the three cognitive tasks. As the table indicates age has effects on all **RP** values (strongest for beta1) except alpha depending upon the task; age has no effect on microvolt measures, except for **MT** under reading tasks. Coherence theta (**CT**) was the only coherence variable that was directly associated with age under the listening task. The phase values that were directly related to age were

TABLE 1. Interrelations between microvolts and relative power.

	Eyes Closed	Listening	Reading	Average
MD/RPD	0.10	**0.32**	0.21	0.21
MT/RPT	**0.50**	**0.57**	**0.42**	0.50
MA/RPA	**0.86**	**0.87**	**0.53**	0.75
MB1/RPB1	**0.53**	**0.38**	**0.43**	0.45
MB2/RPB2	**0.72**	**0.69**	**0.71**	0.71

Note. Bold numbers are significant at .05 level, R: Relative Power, M: Microvolt, D: delta, T: theta, A: alpha, B1: beta1, B2: beta2.

TABLE 2. Relations between relative power, microvolts, coherence, and phase.

	Eyes Closed		Listen	(Eyes Closed)	Read	(Eyes Open)
	CD	PD	CD	PD	CD	PD
RPD	**0.45**	**0.36**	**0.57**	**0.51**	**0.41**	0.29
MD	−0.02	−0.02	0.12	0.14	**0.38**	0.16
	CT	**PT**	**CT**	**PT**	**CT**	**PT**
RPT	0.24	0.07	0.2	−0.05	0.07	−0.09
MT	−0.03	−0.1	−0.05	−0.16	−0.2	−0.1
	CA	**PA**	**CA**	**PA**	**CA**	**PA**
RPA	**0.64**	**−0.48**	**0.76**	**−0.39**	0.03	−0.08
MA	**0.45**	**−0.45**	**0.61**	**−0.42**	−0.04	−0.05
	CB1	**PB1**	**CB1**	**PB1**	**CB1**	**PB1**
RPB1	0.01	0.05	−0.02	−0.04	0.27	0.26
MB1	−0.1	−0.22	−0.1	0.02	−0.11	0
	CB2	**PB2**	**CB2**	**PB2**	**CB2**	**PB2**
RPB2	−0.13	−0.01	−0.01	0.08	0.11	0.19
MB2	−0.25	−0.2	−0.13	−0.12	0.04	0.12

Note. Bold numbers are significant at .05 level, R: Relative Power, M: Microvolt, D: delta, T: theta, A: alpha, B1: beta1, B2: beta2, C: Coherence, P: Phase.

the **PA** value under EC and listening tasks as well as **PT** under listening.

In summary, the associations between **RP** and **M** measures are strongest for alpha and beta2 and weakest for delta across the three tasks reported in the Table 1 (EC, listening and reading). The relations between **RP, M, C** and **P** values reflect non-significant relations in the theta, beta1 and beta2 bandwidths. Coherence and phase delta show positive relations to relative power of delta measures. Relative power and microvolt measures show positive relations to coherence alpha and negative relations to phase alpha. The alpha pattern doesn't exist in the reading task (Table 2).

Associations between coherence and phase values are high within all frequencies, except for the alpha frequency during the EC and listening tasks (Table 3). The beta2 frequency has one of the highest associations between the **M** and **RP** values as well as between the **C** and **P** values. Some of these phenomena have no clear explanation at this point in the development of this field.

Activation Patterns and Predicting Cognitive Success

From a clinical point of view it is helpful to understand what specifically occurs in the QEEG variables as the participants move from an EC task to a simple non-cognitive activation task, and to identify the QEEG variables that are related success or failure at a cognitive task. The following analysis will examine these changes as the

TABLE 3. Interrelations between coherence and phase values in three tasks.

Eyes Closed	Tasks				
		Listen	(Eyes Closed)	Read	(Eyes Open)
CD	**PD 0.96**	**CD**	**PD 0.91**	**CD**	**PD 0.80**
CT	**PT 0.92**	**CT**	**PT 0.72**	**CT**	**PT 0.71**
CA	**PA** 0.03	**CA**	**PA** 0.04	**CA**	**PA 0.77**
CB1	**PB1 0.83**	**CB1**	**PB1 0.53**	**CB1**	**PB1 0.87**
CB2	**PB2 0.94**	**CB2**	**PB2 0.96**	**CB2**	**PB2 0.86**

Note. D: delta, T: theta, A: alpha, B1: beta1, B2: beta2, C: Coherence, P: Phase.

TABLE 4. Relations among age, relative power, microvolts, coherence and phase in three tasks.

	RPD	RPT	RPA	RPB1	RPB2
Age (EyesClosed)	−**0.34**	−0.29	−0.17	**0.47**	**0.34**
Age (Listening)	−0.29	−0.17	−0.12	**0.41**	0.25
Age (Reading)	−**0.57**	−**0.60**	−0.08	**0.47**	**0.48**
	MD	**MT**	**MA**	**MB1**	**MB2**
Age (Eyes Closed)	0.00	−0.22	−0.17	0.14	0.23
Age (Listening)	0.02	−0.27	0.21	0.05	0.06
Age (Reading)	0.04	−**0.38**	−0.25	0.02	0.21
	CD	**CT**	**CA**	**CB1**	**CB2**
Age (Eyes Closed)	0.13	0.21	−0.01	0.05	0.19
Age (Listening)	0.14	**0.51**	0.03	0.23	0.11
Age (Reading)	0.07	0.14	0.22	0.17	−0.08
	PD	**PT**	**PA**	**PB1**	**PB2**
Age (Eyes Closed)	0.11	0.22	**0.32**	0.16	0.20
Age (Listening)	0.11	**0.45**	**0.34**	0.10	0.15
Age (Reading)	−0.05	0.20	0.26	0.11	−0.05

Note. RP: Relative Power, M: Microvolt, D: delta, T: theta, A: alpha, B1: beta1, B2: beta2, C: Coherence, P: Phase, Bold numbers are significant at .05 level.

participants (1) move across tasks from EC to AA to listening to paragraphs and (2) move across tasks from EC to VA and then to reading. The analysis of the data will also (1) examine the problem of predicting from the EC and simple AA and VA tasks to cognitive success and (2) provide a description of the state changes in brain functioning for a group of normal individuals.

CHANGES IN QEEG VARIABLES WITH CHANGES IN TASK

We report the changes in QEEG variables as the group of participants progresses from one task to the next. Selection of the variables of interest was based on a criterion of a standard deviation (SD) change of .50 or greater, using the SD of the relevant baseline task. Almost all of the changes were in the range of 0.50 to 1.00 SD for the auditory task changes and up to 2.00 SD for the visual task changes. Specifically, the QEEG obtained during AA is the relevant baseline for auditory encoding and auditory memory. Similarly, the QEEG obtained during VA is the relevant baseline for visual encoding and reading recall. In the first analysis, we examine the changes in QEEG variables when participants move from the EC task to the tasks of AA and VA and subsequently to the listening and reading tasks.

Effect Size Analysis

We will use effect size analysis to evaluate whether the task changes QEEG measures (Cohen, 1988). In order to obtain an effect size statistic (*ES*), it is necessary to have the means and standard deviations on QEEG measures from both the EC assessment and the task assessment. The *ES* for the task is calculated using the formula: the task mean score minus the EC mean score, divided by the standard deviation of the EC distribution. This provides a change score in QEEG from EC to task in standard deviation units, thus allowing an evaluation of changes in QEEG due to the task. In addition, the *ES* is bias-adjusted for the size of the sample (Hedges & Olkin, 1985). In addition to the *ES*, we obtained confidence intervals that allow us to determine if the change from EC assessment to the task assessment is significant. Using a cutoff of 95% confidence intervals for a sample size of 42 subjects, we calculated the minimum *ES* required to be sure that the QEEG measures obtained under task conditions differed from those collected under eyes-close conditions, with 95% confidence. An *ES* of 0.5 meets these conditions. For more information, as well as more details on how to calculate effect size as applied to QEEG, see Thornton and Carmody (2008).

Changes from EC to AA

As the participants move from an EC state to an AA state there are increases in left temporal lobe activity (T3) in beta variables (**RPB2, PKFB1, SYMB2**) and **F3PA**.

Changes from AA to Listening

Figure 1 shows the changes in QEEG variables from the AA task to the listening task. The changes include increases in frontal locations of delta (**RPD, PKAD, MD**) and theta (**MT, PKAT**) and occipital (O2) beta2 activity (**MB2, PKAB2**). The variables which decreased included frontal **RPB1, PKFT** and **F3PA**. The increases in delta probably represent artifacting issues due to eye movements.

PREDICTING LISTENING PERFORMANCE FROM PREVIOUS TASKS

Predicting from EC to Listening

Figure 2 shows the predictors of auditory memory under task, which indicate a predominant pattern of left hemisphere coherence alpha flashlights (F7, T3, C3, P3) and right frontal (F8) as well as **PKFB1** at T5 and Cz (Thornton, 2000). These results are a recalculation of the Thornton (2000) published results employing the flashlight metaphor. This is the example of the examination of the relations between cognitive performance and the QEEG variables during a task.

Data obtained during an activation QEEG evaluation were used to develop protocols for clinical patients on a case by case basis for EEG biofeedback that was designed to improve memory. The remediation efforts improved auditory memory (2.44 standard deviations or 296%) with a group of 20 children who had learning-disabilities and

FIGURE 1. The changes in quantitative electroencephalography (QEEG) variables from the auditory attention task to the listening task.

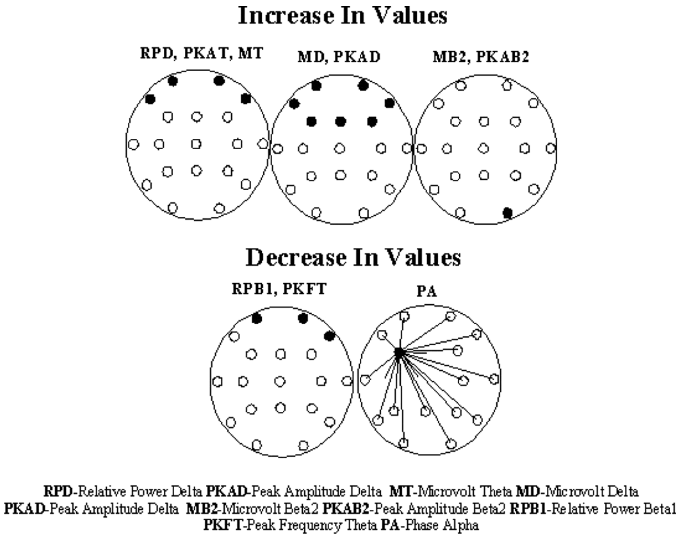
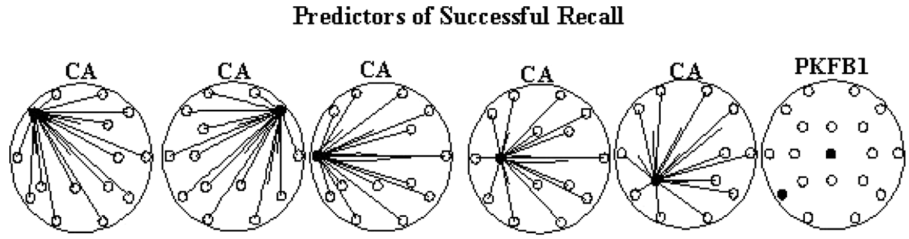


FIGURE 2. The predictors of auditory memory under task.

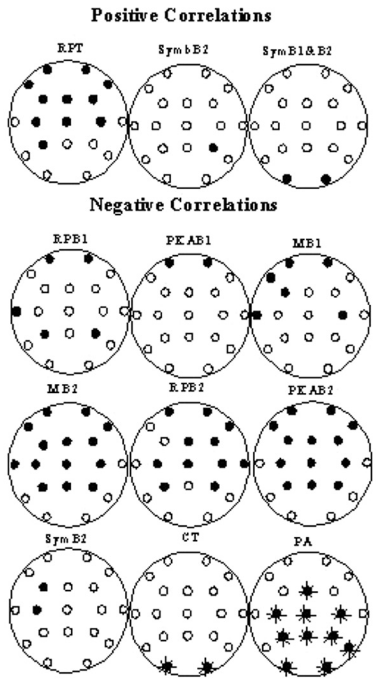


CA: Coherence Alpha PKFB1: Peak Frequency Beta1

ADHD (Thornton, 2006a; Thornton & Carmody, 2005). In a separate study, 19 participants with TBI improved auditory memory by 2.62 standard deviations (Thornton & Carmody, 2008). This is an example of the third method, the effects of intervention on cognition (Thornton & Carmody, 2009).

Figure 3 illustrates the predictors of auditory memory from the EC task. This is an example of the first method, predicting from EC to a cognitive measure collected at a different point in time. The positive predictors involve frontal and central **RPT** and posterior symmetry beta measures while the negative predictors are diffusely evident in the beta2 frequency (**RPB2, MB2**), frontal beta activity and posterior and central connection projections. As evident in this comparison none of the subsequent task predictors of memory performance were evident in the

FIGURE 3. The predictors of auditory memory from the eyes-closed task.



RPT: Relative Power Theta SymB1: Symmetry Beta1 SymB2: Symmetry Beta2
RPB1: Relative Power Beta1 PKAB1: Peak Amplitude Beta1 MB1: Microvolt Beta1 MB2: Microvolt Beta2 RPB2:
Relative Power Beta2 PKAB2: Peak Amplitude Beta2
✱ indicate flashlight origin effects of CT: Coherence Theta PA: Phase Alpha

EC task. It would be expected that a participant's relative value, compared to the other participant's values, would be maintained as the tasks change. In this auditory memory task, the coherence alpha (**CA**) values of the subsequent better performers should be higher in the EC task, and thus be a predictor of recall under task. This association was not demonstrated in the data because the EC alpha coherence values did not correlate with subsequent recall performance.

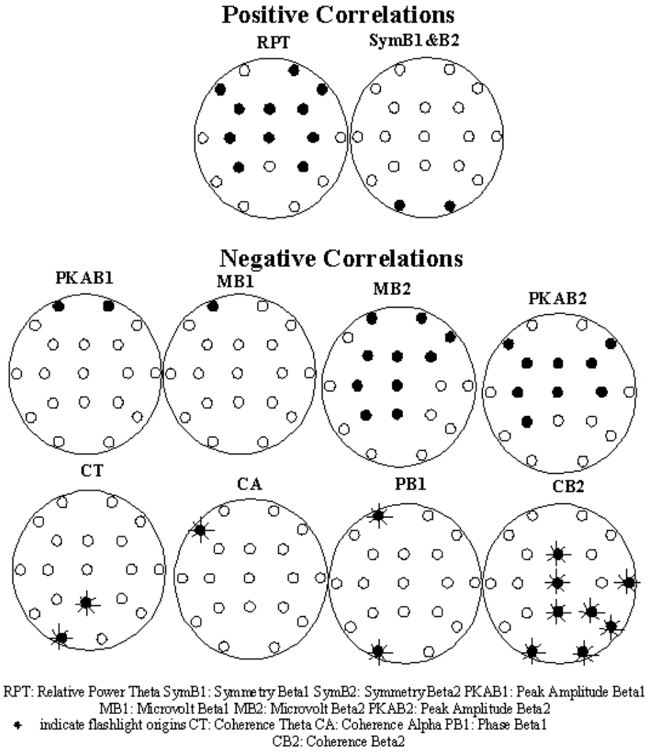
Predicting from AA to Listening

Figure 4 shows the predictors of paragraph recall score from the AA task. The positive relations between AA variables and subsequent paragraph recall ability were very similar to the patterns in the EC data: diffuse **RPT** values, occipital symmetry beta measures while the negative indicators involved the beta2 frequency in diffuse locations in addition to frontal beta measures. In addition, the **CB2** activity from the right posterior and central locations proved to be an additional negative predictor of recall ability. In summary, brain activity during the EC or the AA tasks was unrelated to the subsequent predictors of auditory recall ability.

ACTIVATION PATTERNS AND SUBSEQUENT AUDITORY RECALL

Another way to examine the data is an analysis of the activation patterns in relation to subsequent task performance. A question that arises is whether the participants are increasing the value of the variables that are critical to task success? Examining the changes in QEEG from both the EC to AA and from the AA to listening tasks reveals no significant activation of the coherence alpha flashlights. While the change from EC to AA is not expected to induce an increase in coherence alpha values, it certainly would be expected as the participants move from the AA to listening task. An additional analysis was undertaken to determine if there was a significant change in coherence alpha

FIGURE 4. The predictors of paragraph recall score from the auditory attention task.



relationships as the participants moved from the EC to listening state. None of the coherence alpha relationships showed a significant increase and almost all were in the negative direction, thus negating the possibility that the analysis was overlooking smaller increases as the participants moved from EC to AA to listening, which may be, in aggregate, significant if combined.

STABILITY OF RESPONSE PATTERN ACROSS DIFFERENT TASKS

Table 5 presents the correlations between the EC and listening tasks to describe the stability of the variables across different tasks for the relative power and microvolt measures. Table 6 presents the data for the subsequent coherence alpha predictors. As the tables indicate there are significant positive correlations between the variables under the different tasks. However, it does not appear that this stability is sufficient to employ the EC task for prediction purposes due to variability of the response pattern across these tasks. For example, the **T3CA** correlation is .78, providing an R^2 value of .61, leaving a large amount of unexplained variance.

Changes from EC to VA

Figure 5 presents the significant changes as the participants move from the EC to the VA task. As there were many changes involving only a few locations, the description of the results will focus on the most dominant patterns. The change from EC to VA results in large increases in relative power in beta2, right hemisphere microvolts of beta2, lateral locations for peak frequency beta1, and symmetry beta1 and beta2 measures while the decreases in values involved broad decreases in **PKFT, PKAT, RPA, PKAA, MA** and posterior **PKAB1 and PKAB2** and more centrally located and posteriorly located **SYMB1** and **SYMB2** measures. Connection activity decreased in **CA** at all locations, in **CB1** for frontal and central locations, in **PA** frontal locations and in **PB1** frontal and temporal locations. Thus the act of looking evokes the beta2 frequency, decreases all frequencies lower than 13 hertz, and decreases connection activity, both phase and coherence, from frontal locations and between all locations in the coherence alpha variable. The greatest changes (>1 SD) were the global decreases in alpha **(RP, PKA, CA, PKFT)** and increases in **RPB2**.

TABLE 5. Associations of relative power and microvolts in eyes-closed and listening tasks.

RPD	**0.79**
RPT	**0.72**
RPA	**0.90**
RPB1	**0.90**
RPB2	**0.82**
MD	**0.81**
MT	**0.86**
MA	**0.94**
MB1	**0.94**
MB2	**0.82**

Note. RP: Relative Power, M: Microvolt, D: delta, T: theta, A: alpha, B1: beta1, B2: beta2, Bold numbers are significant at .05 level.

TABLE 6. Reliability of coherence measures across the tasks of eyes-closed and listening tasks.

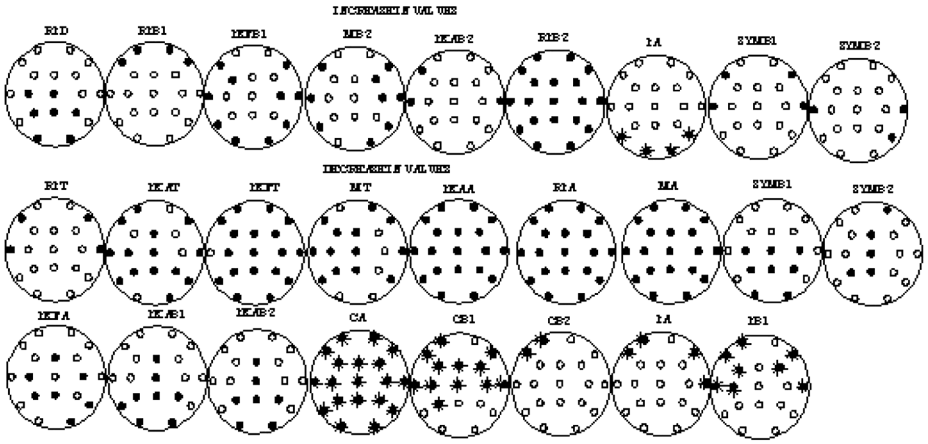
F7CA	**0.84**
F8CA	**0.84**
T3CA	**0.78**
C3CA	**0.75**
P3CA	**0.64**

Note. C: Coherence, P: Phase, D: delta, T: theta, A: alpha, B1: beta1, B2: beta2, Bold numbers are significant at .05 level.

Changes from VA to Reading

Figure 6 presents the significant changes as the participants move from VA to reading silently (RS). The change from VA to RS results in continued posterior increases in beta2 (**MB2, RPB2**) along with broad increases in theta (**PKAT**), frontal theta (**MT**) alpha (**PKAA, MA**) and beta1 (**PKAB1**), right frontal **SYMB1** measures along with **CB1** activity from posterior locations (P3, T6, O2, P4) and **CB2** from posterior locations (T5, P3, Pz, P4, T6, O1, O2).

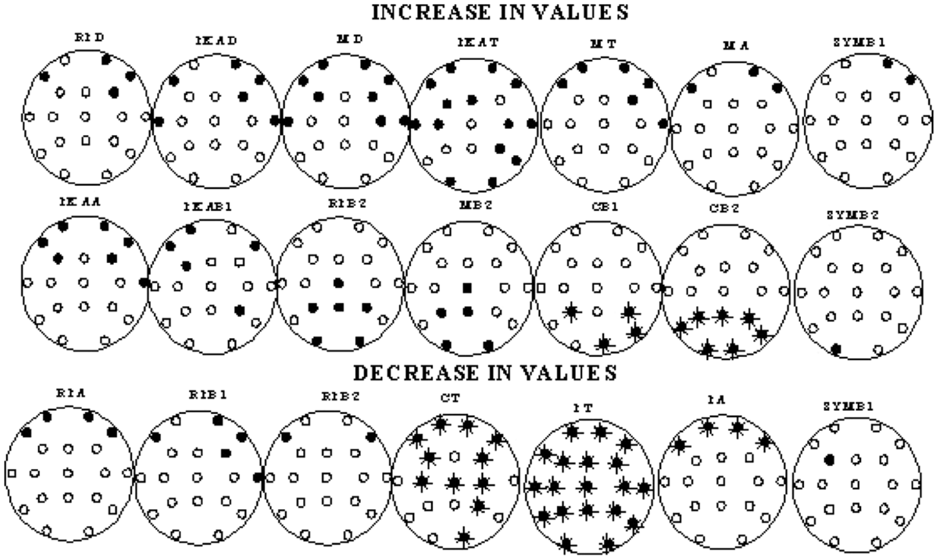
FIGURE 5. The significant changes as the participants move from the eyes-closed to the visual attention task.



RPD-Relative Power Delta **RPB1**-Relative Power Beta1 **PKFB1**-Peak Frequency Beta1 **MB2**-Microvolt Beta2
PKAB2-Peak Amplitude Beta2 **RPB2**-Relative Power Beta2 **PA**-Phase Alpha
RPT-Relative Power Theta **PKAT**-Peak Amplitude Theta **PKFT**-Peak Frequency Theta **MT**-Microvolt Theta
PKAA-Peak Amplitude Alpha **RPA**-Relative Power Alpha **MA**-Microvolt Alpha
SYMB1-Symmetry Beta1 **SYMB2**-Symmetry Beta2 **PKFA**-Peak Frequency Alpha
PKAB1-Peak Amplitude Beta1 **PKAB2**-Peak Amplitude Beta2 **CA**-Coherence Alpha **CB1**-Coherence Beta1
CB2-Coherence Beta2 **PB1**-Phase Beta1 ✱indicate flashlight origins

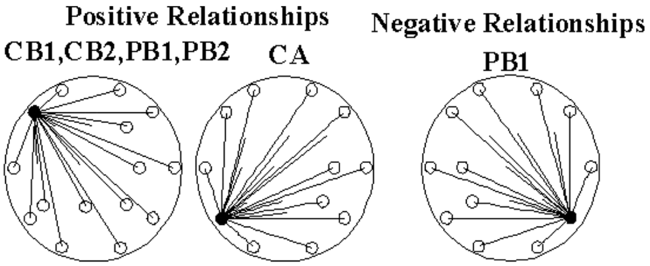
Decreases were evident in frontal alpha (RPA), frontal beta activity (**RPB1, RPB2**) and broadly located theta coherence and phase activity, as well as frontally located flashlights (**PA**). In summary, as the participant moves from VA to RS the clinically

FIGURE 6. The significant changes as the participants move from visual attention to reading silently.



RPD-Relative Power Delta **PKAD**-Peak Amplitude Delta **MD**-Microvolt Delta **PKAT**-Peak Amplitude Theta
MT-Microvolt Theta **MA**-Microvolt Alpha **SYMB1**-Symmetry Beta1 **SYMB2**-Symmetry Beta2 **PKAA**-Peak Amplitude Alpha **PKAB1**-Peak Amplitude Beta1 **RPB2**-Relative Power Beta2
MB2-Microvolt Beta2 **CB1**-Coherence Beta1 **CB2**-Coherence Beta2
RPA-Relative Power Alpha **RPB1**-Relative Power Beta1 **RPB2**-Relative Power Beta2
CT-Coherence Theta **PT**-Phase Theta **PA**-Phase Alpha ✱indicate flashlight origins

FIGURE 7. The correlates of reading recall under task in a normal population.



CB1: Coherence Beta1 CB2: Coherence Beta2 PB1: Phase Beta1
PB2: Phase Beta2 CA: Coherence Alpha

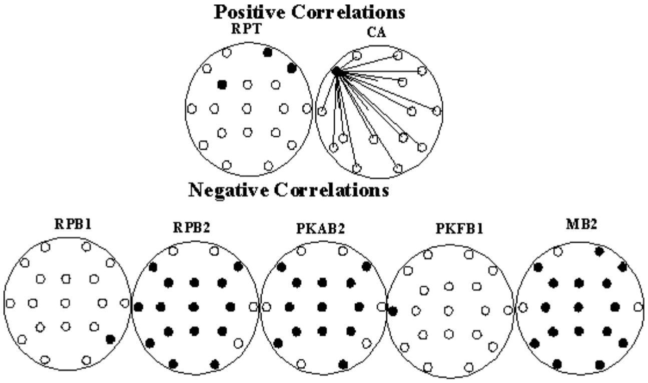
relevant results are the increased posterior **MB2** and **RPB2**, increased posterior beta coherence activity. Successful reading involves F7 coherence activity, a top down process (Figure 7). There were no variables whose averaged value (across all 19 locations) increased greater than 1 SD in this change. An additional analysis of the changes from EC to RS was undertaken to determine if smaller changes were occurring as the participants moved between these three states, which if taken in aggregate would be significant. As in the auditory situation, there were no significant positive changes in the critical variables (F7 coherence and phase activity; T5 coherence alpha relationships). As the participants moved from the EC to RS condition there were significant decreases in several of these critical variables: **T5CA**, −1.08 SD; **F7CB1**, −1.0 SD; **F7PB1**, −1.04 SD. However, much of this decrease can be explained by the change in state from an EC to an eyes open condition. Comparing the two attention measures (VA vs. AA) indicates that these values decrease as a result of opening the eyes. The following changes occur: **T5CA**, −.73 SD; **F7CB1**, −1.04 SD; **F7PB1**, −.77 SD.

PREDICTING READING MEMORY FROM PREVIOUS TASKS

Predicting from EC to Reading Memory

Figure 7 presents the correlates of reading recall under task (Thornton, 2002) in a normal population. As the figure indicates, the successful pattern is predominantly F7 beta1 and beta2 coherence and phase flashlight

FIGURE 8. The predictors of reading memory from the eyes-closed task.



RPT: Relative Power Theta CA: Coherence Alpha RPB1: Relative Power Beta1
RPB2: Relative Power Beta2 PKAB2: Peak Amplitude Beta2
PKFB1: Peak Frequency Beta1 MB2: Microvolt Beta2

patterns along with **CA** from the T5 location. Thus successful reading memory is primarily dependent upon left hemisphere coherence activity. This is another example of the third method that measures the effective variables under task conditions.

Figure 8 presents from the predictors of reading memory from the EC task. The positive predictors involve frontal theta (**RP**) and **F7CA**. The negative predictors involve diffuse sites and the beta2 frequency. This is a second example of the first method, predicting from EC to a later obtained cognitive measure.

Predicting Reading Memory from VA Task

Figure 9 presents the correlates from the VA task to subsequent reading recall. The positive predictors were the **MD** measure in central locations. Negative predictors involved **PB1** from O1 and O2 and **F4CA**. None of these predictors accurately identified the subsequent correlates under the task.

Visual Activation Patterns and Subsequent Reading Recall

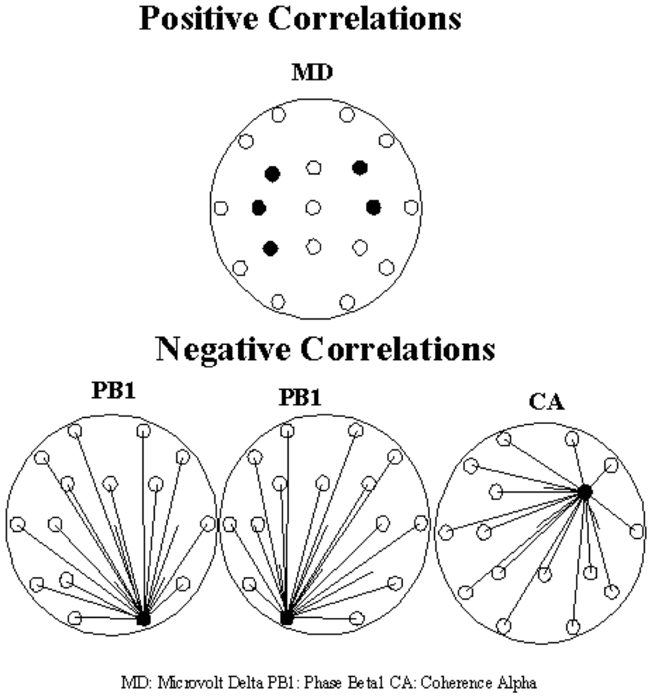
The analysis of the changes from EC to VA and from VA to reading revealed that as the participants changed from an EC to VA task they decreased the values of the predictors indicated in Figure 7. The change from VA to reading does not result in any significant improvement or decreasing of these values. As in the paragraph task, one conclusion that can be asserted is that the normal brain is not particularly effective at activating what it needs to be successful at the task, the "inefficient activation pattern."

QEEG DIFFERENCES BETWEEN TASKS

Differences in QEEG Variables Between AA and VA Tasks

It is of some clinical value to understand the differences between the two attention tasks and two cognitive tasks, as clinician's

FIGURE 9. The correlates from the visual attention task to subsequent reading recall.



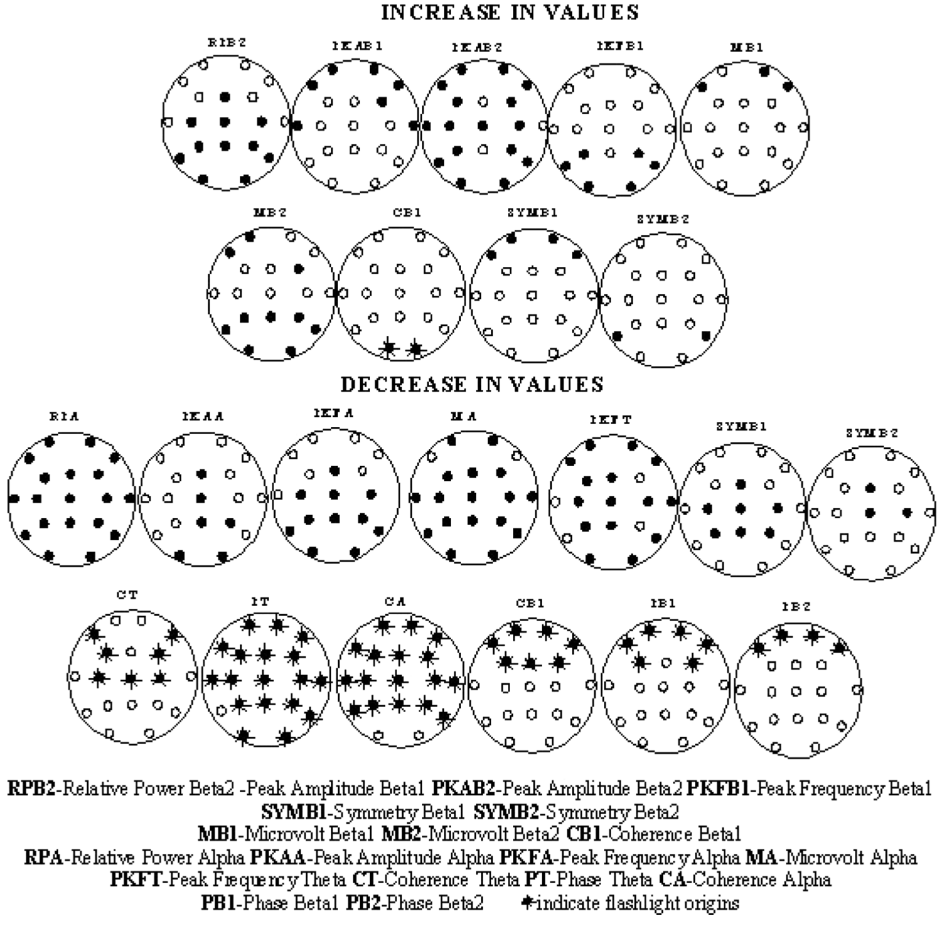
may have their patients in either an EC or eyes open condition during the training and may misinterpret the meaning of the change in values. In addition, as the clinician is viewing the EC as the comparison state, a clinical error of assuming improvement in a variable may occur when, in reality, the only reason for the change maybe due to the patient opening their eyes. Only the most dominant differences will be reported. The variables which are greater in the AA task compared to the VA task include alpha (**RP, M, PKA, CA**) and frontal beta1 flashlights (**CB1, PB1**), frontal phase alpha and left frontal **CB2** flashlights, symmetry beta1 measures at P3, P4, O1, Cz, Pz and **SYMB2** measures at Fz, Cz.. The VA task variables are higher in all **RPB2** values, frontal **RPB1**, **SYMB1** measures at F7, F8, T3, T4 and **SYMB2** at T6.

QEEG Differences Between Listening Silently (LS) and Reading Silently (RS)

Figure 10 displays the variables that are significantly greater in the reading silently task (RS) compared to the listening silently task (LS) and Figure 11 presents the variables that are greater during the listening compared to the reading task. Reading has greater values than listening in frontal beta activity (**RPB1, PKAB1, MB1, SYMB1**), posterior beta (**PKFB1, MB2, RPB2, SYMB2**) and diffusely located higher values for beta2 (**PKAB2**). The overall pattern is one of frontal beta1 values higher and posterior beta2 values higher than in the listening task as well as increased **CB1** from occipital locations.

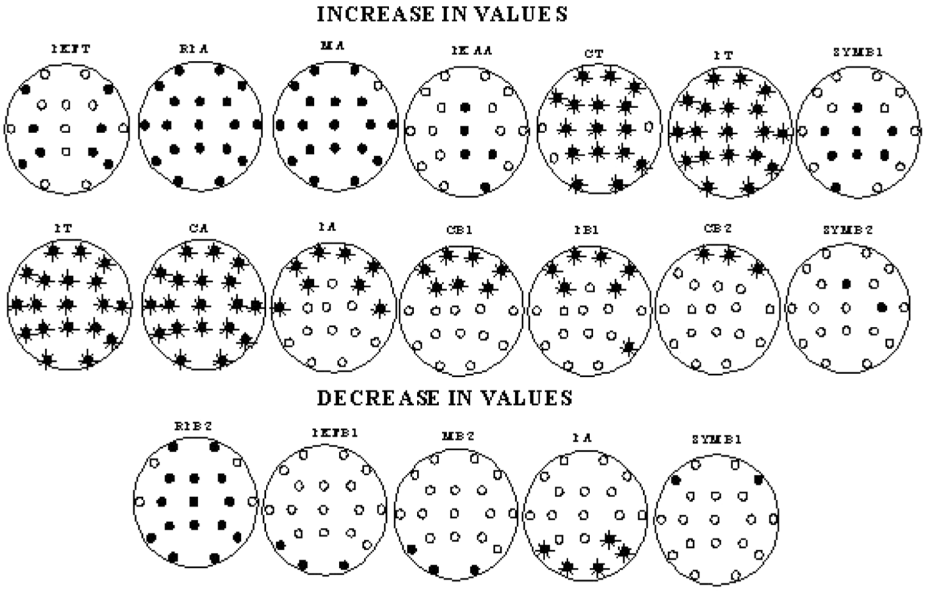
Listening silently exhibits greater values than reading for diffuse locations in the theta

FIGURE 10. Significantly greater variables in the reading silently task compared to the listening silently task.



RPB2-Relative Power Beta2 -Peak Amplitude Beta1 **PKAB2**-Peak Amplitude Beta2 **PKFB1**-Peak Frequency Beta1
SYMB1-Symmetry Beta1 **SYMB2**-Symmetry Beta2
MB1-Microvolt Beta1 **MB2**-Microvolt Beta2 **CB1**-Coherence Beta1
RPA-Relative Power Alpha **PKAA**-Peak Amplitude Alpha **PKFA**-Peak Frequency Alpha **MA**-Microvolt Alpha
PKFT-Peak Frequency Theta **CT**-Coherence Theta **PT**-Phase Theta **CA**-Coherence Alpha
PB1-Phase Beta1 **PB2**-Phase Beta2 ✱indicate flashlight origins

FIGURE 11. Significantly greater variables during the listening compared to the reading task.



PKFT-Peak FrequencyTheta **RPA**-Relative Power Alpha **MA**-Microvolt Alpha **PKAA**-Peak Amplitude Alpha
CT-Coherence Theta **PT**-Phase Theta **CA**-Coherence Alpha **PA**-Phase Alpha **CB1**-Coherence Beta1 **PB1**-Phase Beta1
CB2-Coherence Beta2 **SYMB1**-Symmetry Beta1 **SYMB2**-SymmetryBeta2
RPB2-Relative Power Beta2 **PKFB1**-Peak Frequency Beta1 **MB2**-Microvolt Beta2 **PA**-Phase Alpha
*indicate flashlight origins

frequency (**PKFT**), alpha (**RPA, MA, PKAA**), and increases in central and posterior symmetry beta1 measures. Of some interest to note is that the LS task evokes higher values in the broadly located connection variables in the lower frequencies (**CT, PT, CA**) and frontal located flashlights in the beta frequencies (**PA, PB1, CB1, PB2**) and increases in central and posterior symmetry beta1 measures. Thus the LS task engages the lower frequencies more as well as involving more activity in the coherence and phase associations. Both tasks involve semantic processing, which argues against the von Stein & Sarnthein (2000) hypothesis that the lower frequencies are involved in semantic processing.

DISCUSSION

The findings present a complex system that defies adequate scientific understanding at this point in the development of the field. However, the findings do have implications for how EEG biofeedback intervention protocols should proceed. The results indicate (1) tasks evoke a system response which involve different locations and different frequencies; (2) focusing on a particular location, such as Cz or frequency does not adequately address the complexity of the system; (3) the high beta2 frequency (32–64 Hz) is intimately involved in brain functioning; (4) EC and simple attention data are not sufficient to understand or predict what is required to improve cognitive functioning in normal individuals; (5) The figures and tables provided also indicate to the clinician that an improvement (from an EC database) on a variable may not relate to the effectiveness of the intervention but merely to a change in task; (6) improvement on a particular variable may have no relations to improvement of cognition; (7) interventions are generally conducted with eyes open and employ an EC database to determine interventions. However, merely opening of the eyes results in many reductions in the alpha frequency as well as other changes (see Figure 5 for specifics). The failure to suppress alpha under eyes open condition can be considered a clinical problem (Thornton, Carroll, & Cea, 2007).

More specifically when addressing problems in auditory memory in adults, the protocols should be directed towards increasing coherence alpha relationships. When addressing reading problems, the F7 coherence and phase flashlights (beta1 and beta2) and **T5CA** flashlight may require attention.

It is relevant to note, however, an additional comment. Thornton has been involved in cases where the subject's values on variables, which are not related to successful task performance, were several standard deviations below the norm and required addressing. One common pattern is low posterior coherence beta relationships during reading. There are two ways to conceptualize this issue. One way is to consider that variables are necessary but not predictive of good memory functioning. The second way is to consider that any variable (coherence values in particular) which is grossly deviant from the norm may function as a hindrance to effective cognitive functioning.

The preceding discussion has focused on the clinical value of having the subject undergo specific cognitive tasks to understand the subject's deficits in QEEG response pattern on the variables which relate to performance. In addition to the value of individual task QEEG analysis, there is relevant clinical information that can be obtained from the subject's response pattern across the different tasks. Two case studies illustrate the value of the activation database.

In the first case study, a woman with impaired reading had coherence alpha values well above the norm in the paragraph listening task and her levels of coherence beta1 and beta2 were below the norm at location F7, in addition to other locations (Thornton, 2006). The difference between her auditory and reading memory ability was 5.29 standard deviations. It is instructive in this case to ask whether the subject's beta coherence values under the reading condition reflect an underlying structural deficit in the myelinated fibers or a lack of appropriate allocation. An examination of her beta coherence values under the EC to the reading condition, indicated that the subject was increasing coherence values between the frontal locations and decreasing the beta coherence values within the posterior locations, while her **F7CB2** (both raw and standard deviation values) decreased as the tasks changed from VA to reading. This pattern would indicates (1) that the subject has the necessary physiological resources, but was not appropriately employing them and (2) knowledge of the subject's **F7CB2** standard deviation value in the VA task would not have allowed accurate prediction to the F7 value during the reading task.

In the case of a 21 year old male with a history of severe reading disability, the examination of the response pattern across different tasks proved critical to rehabilitation efforts. The subject's relative power of alpha was within normal limits under EC condition as well as all of the tasks which involved the EC. Only when the subject opened his eyes did the relative power of alpha values increase in their standard deviation value to approximately 3 standard deviations above the norm. Overall the subject's raw relative power of alpha value increased an average of .25 across all locations, thus indicating a failure to suppress alpha under visual task conditions. Once the rehabilitation protocols were set to address this problem, the subject improved significantly in his reading ability assessed by standardized testing. In this example, the subject's standard deviation value of alpha in the EC task would not have indicated the appropriate intervention. (Thornton et al., 2007).

The purposes of the research were to (1) examine the relative value of databases obtained under different conditions in improving cognition; (2) to understand how the brain responds to different task demands; (3) to understand how the QEEG variables relate to one another. To achieve this purpose, the changes in activity levels at locations and between locations were examined during several tasks including EC, AA, VA, as well the input stages of paragraphs presented aurally and reading presented visually. The brain response patterns in each task were associated with performance on memory tasks. The results showed that the QEEG variables measured in the recall tasks were more consistent with neuroscience research of memory response patterns than those measured in the EC and simple attention tasks. Specifically, the QEEG measures during recall show left hemisphere involvement, which has been shown by PET to be active in auditory memory (Mazoyer et al., 1993). These findings suggest that interventions using EEG biofeedback have an advantage in obtaining treatment success when selection is based on an activation database. For example, there are associations between QEEG measures taken under the EC condition and recall memory. Specifically, the relative power of the theta bandwidth is directly related to memory while there are inverse relations with microvolt and relative power values of beta2 bilaterally in central and anterior regions. However, the theta frequency in the EC condition has not been associated historically with effective cognitive performance (Harmony et al., 1990) and would not be a recommended protocol to improve auditory memory.

The locations that were most strongly associated with memory performance were identified using the flashlight concept. In the auditory memory task, the greatest associations to performance are with the coherence alpha flashlight activity in the left hemisphere and right frontal locations. Previous PET research has confirmed the role of the left temporal lobe (T3) and left frontal (F7) locations in auditory processing and auditory memory (Mazoyer et al., 1993), the role of the right frontal lobe (Henson, Shallice, & Dolan, 1999) during recall, as well as the dominant role of the left hemisphere in verbal processing.

The current study identifies coherence alpha as a contributor to the left hemisphere functioning. The predictors from EC (Figure 3) and AA (Figure 4) do not fit well with previous PET research, or with present neuroscience understanding of anatomical functioning and previous QEEG research which has identified theta activity as a negative predictor of cognitive abilities (Harmony et al., 1990, Lubar et al., 1995). In the reading task, improved performance is associated with sources of coherence in beta from left frontal region (F7) as well as sources of coherence in alpha from and **T5CA** activity. The previously researched identified role of the left hemisphere in language processing overlaps with these QEEG findings. The predictors from EC (theta) and VA (delta) do not fit well with previous QEEG research that indicated that elevated levels of left hemisphere theta and delta under EC condition predicted poor educational evaluations in children (Harmony et al., 1990).

There are also specific QEEG variables which have a negative correlation with recall scores (**T6 PB1**). In the reading task the increased phase beta activity from the T6 location is inversely related to memory. EC data or attention task data do not provide the relevant information to formulate effective interventions, while activation QEEG correlates of cognition provide the necessary information for highly effective interventions. Figure 6 indicates that reading is predominantly a bottom up processing task in a normal population with increased microvolts of beta2 in posterior locations and posterior flashlight activity (coherence beta1 and beta2). However, successful reading involves F7 coherence activity, a top down process (Figure 7).

The results presented in this paper suggest a coordinated allocation of resources (CAR) hypothesis of cognitive effectiveness. The CAR hypothesis states that effective cognitive functioning is determined by multiple specific variables acting in unison to achieve optimal performance and that these variables can be different in different tasks. The QEEG variables that are related to performance include activity in the beta frequency at specific locations as well as the coherence and phase relationships between locations in specific frequencies. While there are significant correlations between the attention tasks and memory performance, the QEEG variables identified in the attention tasks are not the variables that account for success during the memory task and thus are not sufficient to develop an appropriate intervention protocol using

EEG biofeedback. Both reading and auditory memory tasks require different sets of resources for success. We cannot assume that there is a single intervention protocol that will broadly affect reading and auditory memory as different tasks require allocation of different sets of QEEG variables.

In addition, the data document that the human brain does not activate the necessary variables for success in a task. For example, coherence alpha values in the auditory task do not increase as the subjects move from an AA task to the listening to paragraphs task. One conclusion that can be reached is that the normal brain is not efficient or effective in its activation response pattern. This phenomenon can most succinctly be called the "inefficient activation pattern." This conclusion, if validated in a larger sample, has significant implications for the EEG biofeedback field and education. If the resources are available but just not employed correctly, interventions become pragmatically easier to accomplish then trying to "build" connections which don't exist. The normal human mind is not efficient at activating the necessary correlates of effective cognitive functioning, as indicated by the cognitive inefficiency hypothesis.

There are, however, patterns of relations between variables across tasks which are clinically important to understand in determining protocol interventions. These patterns need to be understood in addressing the cognitive ineffectiveness of the LD, ADHD and TBI patient if we are to obtain the desired results.

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