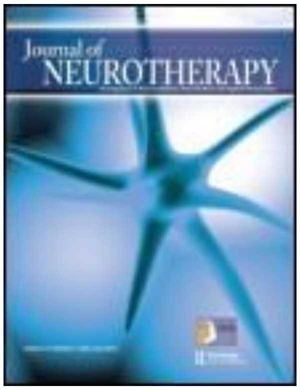

Journal of Neurotherapy: Investigations in Neuromodulation, Neurofeedback and Applied Neuroscience

The Role of Slow-Wave Electroencephalographic Activity in Reading

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Published online: 08 Sep 2008.

To cite this article: Efthymios Angelakis MA , Joel F. Lubar BS and PhD , Jon Frederick PhD & Stamatina Stathopoulou BA (2001) The Role of Slow-Wave Electroencephalographic Activity in Reading, Journal of Neurotherapy: Investigations in Neuromodulation, Neurofeedback and Applied Neuroscience, 5:3, 5-25

To link to this article: http://dx.doi.org/10.1300/J184v05n03_03

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The Role of Slow-Wave Electroencephalographic Activity in Reading

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The authors want to thank their lab colleagues Philip Vanlandingham, Kerry Towler, Jared Blackburn, and Noland White for contributing to the collection and analysis of their data, as well as Mr. Robert Muenchen for his statistical advice.

Journal of Neurotherapy, Vol. 5(3) 2001

ABSTRACT. *Background*. Although slow-wave EEG activity has traditionally been associated with either deep sleep or brain pathology, recent studies have revealed a relationship between this neuronal activity and cognitive functions. The present study explored the slow-wave EEG amplitude differences between resting and reading states in a group of 19 non-clinical young adults.

Methods. EEG was recorded during an eyes-open resting baseline, and three different reading tasks selectively engaging the visual, phonetic, and semantic reading modalities. Frequency spectra between 1 and 8 Hz were analyzed in two frequency bands, 1-4 Hz (delta) and 4-8 Hz (theta).

Results. Multiple t-test analyses comparing the three reading tasks with the baseline showed significant amplitude increases during reading mostly in the 1-4 Hz and some in the 4-8 Hz band. These changes were topographically different among the three reading tasks. During visual reading, amplitude increased at C3, C4, T3, T4, and T5 for the 1-4 Hz band, and at T5 and T6 for the 4-8 Hz band. During phonetic reading, amplitude increased at T3, T4, F3 and F7 for the 1-4 Hz band, and at T5 and FP1 for the 4-8 Hz band. During semantic reading, amplitude increased at T3, T4, C3, C4, F3, F7, F8, CZ and FZ for the 1-4 Hz band and at T5 for the 4-8 Hz band.

Conclusions. Amplitude increases in slow-wave EEG are part of the normal reading process and it appears at scalp electrodes close to cortical areas expected to be involved according to different reading modalities. Implications for neurofeedback involve tentative models for cognitive processes.

KEYWORDS. EEG, reading, adults, delta, theta, slow wave EEG

INTRODUCTION

Background and importance. The reading process involves several brain mechanisms that may be manifested in functional neuroimaging. For example, Positron Emission Tomography (PET) shows differential brain metabolism when participants look at false fonts, letter strings, pseudowords, or real words (Posner & Raichle, 1994, pp. 76-81). Several PET and functional magnetic resonance imaging (fMRI) studies have been extensively used to explore the neuroanatomical correlates of reading functions (for a review, see Cabeza & Nyberg, 2000). Electroencephalographic (EEG) studies have also shown differentiation of cortical electrical activity between reading and other visual processing tasks using evoked response potentials (ERPs) or computer quantified EEG (QEEG) (e.g., Rumsey, Coppola, Denckla, Hamburger, & Kruesi, 1989; Galin et al., 1992; Ackerman, Dykman, Oglesby, & Newton, 1994), as well as between different reading tasks (Ackerman, McPherson, Oglesby, & Dykman, 1998).

One reason that such neuroimaging techniques of the reading process are important is their potential contribution to the accuracy, specificity, and objectivity of diagnostic processes for various forms of reading difficulty (RD). Many studies based on childhood samples have shown distinct QEEG differences between reading disabled and non-disabled readers (Fein et al., 1985; Rumsey et al., 1989; Marosi et al., 1992; Ackerman et al., 1994; Harmony et al., 1995; Marosi et al., 1995) as well as between children with reading disabilities of different types (Duffy, Denckla, Bertels, & Sandini, 1980; Flynn, Deering, & Rahbar, 1992; Ackerman et al., 1998), mostly during active tasks including reading. Another reason for the importance of such studies is their potential contribution to the development of neurofeedback protocols for the neurobehavioral treatment of reading difficulties. Several reports have shown the effectiveness of neurofeedback for the treatment of learning disabilities due to attention deficit disorders (e.g., Nash, 2000; Lubar & Lubar, 1999; Thompson & Thompson, 1998).

Most of the above QEEG imaging studies have focused on children and adolescents from 6 to 16 years of age (Rumsey et al., 1989; Ackerman et al., 1994; Marosi et al., 1992; Harmony et al., 1995; Marosi et al., 1995; Duffy et al., 1980; Flynn et al., 1992), comparing different reading tasks (Ackerman, et al., 1998). However, little research has focused on the QEEG of the reading processes in adults. Moreover, despite the wealth of studies with PET, fMRI, or ERPs in this area, very little is reported on the QEEG manifestation of different reading tasks in non-clinical individuals.

One of the problems in correlating recorded brain activity with complex cognitive functions, such as reading, is the fact that such complex functions involve the cooperation of various cognitive mechanisms. The reading process in particular involves visual, phonetic, and semantic decoding of printed stimuli into words. The words of the text are kept in working memory while the reader attempts to associate them with words stored in long-term memory. Moreover, grammar and syntax are processed at the same time, and main ideas are extracted out of chunks of text (Leong, 1986; Bias & Roser, 1977). One of these mechanisms, working memory, is found to play a critical role in reading. Since the 1970s, several studies have shown that phonological span of working memory is positively correlated to reading comprehension (Kintsch & van Dijk, 1978; Baddeley, Logie, & Nimmo, 1985). One of the most supported models for working memory is that of Baddeley (1981; 1982). In this model, working memory comprises of three major components: the phonological loop, the visuospatial sketchpad, and the central executive. The *phonological loop* refers to the retention of pronounceable material into working memory through the use of phonetic rehearsal. The *visuospatial sketchpad* refers to the retention of visual material into working memory through the use of eidetic storage. The *central executive* refers to the coordination and allocation of attentional resources between the first two components.

Due to this complex network of processes, it is of great interest to isolate (as much as possible) such distinct mechanisms when recording brain activity, in order to be able to derive and test specific hypotheses associated to pathology, such as different subtypes of dyslexia. Several studies have shown that dyslexia, the difficulty one has with reading due to presumed brain dysfunction, is not a single syndrome, but may have diverse loci of origin, according to which subtypes are derived. For example, visual dyslexia refers to difficulties with whole-word recognition, phonological dyslexia refers to difficulties with letter-by-letter pronunciation, and semantic dyslexia refers to difficulties with recognizing the meaning of words (Licht, 1994; Posner & Raichle, 1994, pp. 45-46). Although different models and investigators of dyslexia use different terms and definitions to derive subtypes of dyslexia, many of them seem to agree on the differentiation between a phonetic and a visual subtype. Moreover, many models of dyslexia consider a semantic subtype (also termed "deep"). Therefore, this study will use the terms *visual, phonetic,* and *semantic,* to refer to different modalities of the reading process.

Slow-wave EEG correlates. Cerebral blood flow (CBF) measures, like PET and fMRI, support the association of slow-wave EEG with brain deactivation. Cognitive neuroimaging studies using CBF measures have shown increases in cerebral metabolism at brain areas responsible for different reading modalities. For example, occipital areas have been shown to increase their metabolism during perception of false fonts (Posner & Raichle, 1994, p. 80). Increases in cerebral metabolism have been correlated with increases in *fast* frequency EEG amplitude; and decreases in cerebral metabolism have been correlated with increases in *slow* frequency EEG amplitude (for a review, see Carlson, 1998, p. 260; Kirsch, Koehler, & Traystman, 1999).

Rhythmic slow-wave 4-8 Hz (theta) EEG activity has traditionally been considered as a correlate of drowsiness or attention deficit disorder (e.g., Makeig, Bell, Jung, & Sejnowski, 1996; Lubar & Lubar, 1999), and rhythmic very slow-wave 1-4 (delta) EEG activity has been considered as a sign of either deep sleep or brain pathology (Niedermeyer, 1999a; 1999b; 1999c; Sharbrough, 1999). However, several recent studies have associated slow-wave brain activity with working memory and stimulus detection functions. For example, Klimesch and colleagues have suggested that 4-8 Hz activity is correlated to working memory functions and may manifest cyclic reciprocal communication between the cortex and the hippocampus (Klimesch, Schimke, & Schwaiger, 1994; Klimesch, 1998). Gevins and colleagues have suggested that during tasks involving short-term retention of visual stimuli, 4-8 Hz activity is elevated in amplitude in frontal midline regions (Gevins et al., 1998).

In a separate analysis of the dataset used for the present study, we found that both 1-4 Hz and 4-8 Hz frequency bands increased in amplitude during reading as compared to a resting baseline. Specifically, two-way ANOVAs (task × location) showed significant main effects for task (amplitude increases from a resting baseline) for a number of reading tasks (Angelakis et al., 1999). Although this analysis did not investigate single electrode effects, significant interactions between task and location were found for both the 1-4 and 4-8 Hz bands, implying a differential distribution of the phenomenon across locations. Others have also reported amplitude increases in the 1-3.5 Hz and 4-7 Hz bands during silent reading in a group of female participants, over the entire scalp (Petsche & Etlinger, 1998, p. 265). In addition, ERP studies of auditory and visual discrimination have found responses to target stimuli to evoke almost pure delta (0.5-3.5 Hz) oscillations (Basar-Eroglu, Basar, Demiralp, & Schuermann, 1992; Schuerman, Basar-Eroglu, Kolev, & Basar, 2001).

Goals of the study. One of the goals of this study was to determine if slow-wave EEG reflects only brain deactivation during reading. If so, areas responsible for the different reading modalities should show decreased amplitude of slow-wave EEG during reading when compared to a resting baseline. In addition, areas *least* involved in the particular reading task might show increased amplitude of slow-wave EEG during reading, due to differential allocation of resources. If, on the other hand, slow-wave EEG during reading reflects cognitive processing, then brain areas involved should show increases in slow-wave amplitude.

Another purpose of the present study was to explore the potential of slow-wave QEEG to identify topographically differential cortical activity during different reading tasks that selectively engage the visual, phonetic, and semantic modalities of reading. It was hypothesized that different processing modalities may manifest as EEG activity at relevant cortical areas. Recognition of visual stimuli is found to involve occipito-temporal and occipito-parietal neural pathways, named *ventral* and *dorsal streams of vision*, respectively (Carlson, 1998, p. 172). The ventral stream involves recognizing *what* the stimulus is, and is localized at the middle and inferior posterior temporal gyri (somewhat ventrally to EEG 10/20 channels T5 and T6). The dorsal stream of vision is mostly involved in recognizing *where* the stimulus is, and is localized at the superior-posterior parietal areas (underlying EEG 10/20 channels P3 and P4). Production of oral speech has been associated with the posterior part or the left inferior frontal gyrus (Broca's speech area/ Broadman's areas 44 and 45 underlying EEG 10/20 channel F7, Carlson, 1998, pp. 479-481), and recognition of phonetic stimuli has been associated with the superior temporal gyri (Paulesu, Frith, & Frackowiak, 1993, underlying EEG 10/20 channels T3 and T4). Attentional mechanisms are found to involve the anterior cingulate gyrus, and vigilance functions are found to involve right parietal and frontal areas (Posner & Raichle, 1994, pp. 168-176). Comprehension of meaning is related to Wernicke's area and the left occipito-temopo-parietal junction (Carlson, pp. 486-488, in between 10/20 EEG channels C3, T3, P3, T5; for electrode-to-cortical area correspondences, see Homan, 1988). Attentional processing has been associated with midfrontal channels, including F3, FZ, and F4, and some investigators suggest that amplitude increases in slow-wave EEG (4-8 Hz) reflect the underlying cingulo-cortical loops (Gevins et al., 1998). Based on these suggestions, visual processing was predicted to show slow-wave amplitude increase primarily in occipito-parietal and occipito-temporal areas, whereas phonetic processing was predicted to show slow-wave amplitude increase primarily in temporal and left inferior frontal areas. Semantic processing was predicted to show slow-wave amplitude increase at the occipito-temporo-parietal junction. Finally, all tasks were expected to show slow-wave amplitude increase at midfrontal areas, due to attentional mechanisms, and at right parietal and frontal areas due to vigilance.

METHOD

Participants. Nineteen psychology college students were included, 12 male and 7 female, all volunteering for extra credit. These were selected from an initial sample of 23 (14 male and 9 female) from which four participants (two male and two female) were eliminated from further analysis. It was determined from the self-reports that no participant had any neurological or psychological history that would significantly affect the QEEG. To cross-validate this decision, relative power reports from the Thatcher Lifespan Normative Database (LND, Thatcher, Walker, Gerson, & Geisler, 1989) were inspected. Two of them showed increased alpha (7-13 Hz) activity in 10 frontal locations from the LND; one scored more than one standard deviation below norms on six psychometric tests (IVA scores and five out of six Woodcock-Johnson scores, indicating a possible attention deficit with a reading difficulty); and one had excessive muscle artifact contamination of the EEG. Because of clear deviations from normative data, these four students were excluded from the study in order to avoid confounding effects, reducing the initial sample to nineteen participants.

Materials. A self-report form was administered to collect data on neurological and psychological history. Nine psychometric tests were administered in order to control for possible cognitive deviations that would exclude participants from a non-clinical sample. These subtests included the Integrated Visual and Auditory Continuous Performance Test (IVA), which measures various aspects of attention (Turner & Sandford, 1995); the Vocabulary and Block Design subtests of the Weschler Adult Intelligence Scale III (WAIS-III), measuring linguistic and visuospatial skills (Weschler, 1981); six subtests from the Woodcock-Johnson Achievement Battery Revised (WJ-R), specifically the Letter-Word Identification subtest for the assessment of pronunciation and paralexic reading, the Passage Comprehension subtest for the assessment of reading comprehension skills, the Word Attack subtest for the assessment of phonic, structural and auditory processing skills, the Reading Vocabulary subtest for the assessment of word semantic/conceptual skills, the Calculation subtest for assessment of arithmetic operations skills, and the Quantitative Concepts subtest for the assessment of knowledge of mathematical concepts (Woodcock & Johnson, 1977).

Apparatus. EEG was recorded with a Lexicor NeuroSearch-24 analog to digital system, and all data were stored and visually artifact rejected using a Pentium 120 MHz computer, and Lexicor’s v41e software. Nineteen-channel electrode caps using the 10/20 international electrode placement system by Electro Cap Inc. were used, with linked ear lobe references. The EEG data were collected with a band-pass filter set at 0.5-32 Hz for 128 samples per second recordings and at 1-64 Hz for 256 samples per second recordings. Digital EEG was processed by Fast-Fourier Transformation (FFT) with cosine tapering (Hanning window).

Reading materials for the three experimental tasks were developed in our laboratory. Three pieces from Homer's *Odyssey* translated into English were used to selectively engage participants in visual, phonological, and semantic processing. Participants were asked to identify target words following different rules for each processing modality. Visual reading required the identification of four-letter words that include at least one "a" (e.g., *have*); phonological reading required the identification of words that included the sound "k" (as in *cross* or *peak*); and semantic reading required the identification of nouns that refer to a non-animate material object or entity (e.g., *table* or *ocean*). Texts were selected so that they were narrative, easy to read, and with a minimum number of names. Moreover, all three texts contained 20 (±1) target words for all three reading requirements, but in randomly different positions. Reading materials were presented with a Pentium computer with a 17″ color screen. In order to identify possible distinct EEG abnormalities, the Thatcher Lifespan Normative Database (LND) was used to compare participants' eyes closed resting EEG recordings to a normative sample of non-clinical individuals of similar sex and age.

Procedure. All data were collected in a quiet windowless laboratory room with fluorescent lighting and no other persons present except for the participant and the experimenter. Participation was completed in two sessions on two different days. All EEG recording was completed within the first day of participation. On this day, participants were first asked to complete a self-report form concerning personal history on any psychological or neurological diagnosis (including reading difficulties), current prescription medication usage, head injuries, age, sex, and handedness (left or right). Then participants were fitted with the Electro Cap, and impedance at all channels was measured to be below 5 kOhms.

Participants were seated in an armchair with their eyes toward a computer screen at a distance of 60 cm. Nineteen-channel EEG activity was recorded in the following order: first, during an eyes-closed resting condition (ECB); second, during an eyes-open resting condition (EOB), where participants were instructed to focus on the notepad window on the computer screen, while no text was running; then, five reading tasks (the three Odyssey texts, a list of misspelled words and a list of numbers) and a post-task eyes-open resting condition (PTR) were administered in a counterbalanced order across participants, during which EEG was recorded.

All target items were randomly distributed within the texts. The three Odyssey texts were always presented in the same order, but for different reading requirements (i.e., visual, phonological, or semantic), according to the counterbalanced order. In addition, the two reading lists and the PTR were included in the counterbalanced procedure; however, they were not included in the present analysis. This varied presentation order was employed to avoid confounding of order effects and text related effects.

In order to minimize eye movements and control speed of stimulus presentation, reading materials were computerized and presented in a self-running mode through a 1×5 cm Notepad window (Microsoft Windows 95), with the aid of Keyboard Express (Insight Software Solutions), which programmed the DELETE key of the computer to continuously strike every 100 milliseconds, “pulling” the text into the left side of the notepad window. This resulted in texts moving from right to left, at a pace of two words per second. The distance between the Notepad window and the participant’s eyes was approximately 60 cm. This setting obliged participants to focus on a limited area to read, while the text was moving at a constant speed.

Each recording lasted 3.3 minutes, between which participants had the opportunity to rest, stretch, and relax for one minute. Before recording each reading task, a practice task was administered for 30 seconds, which enabled the participants to become familiar with the tasks. All reading was silent. While reading, participants were responding to target word identification by pressing a key on the computer keyboard with their right hand. This key put a marker on the EEG recording, which was later compared (during data analysis) with a timed key of correct responses. This was done by visually inspecting the raw EEG files for markers at specific times according to the timed keys, with ± one-second allowance for differential reaction time and synchronization of the EEG and the Keyboard Express. The procedure was completed within 120 minutes. During the second day of participation, within one week after the EEG recording, participants were measured using the psychometric tests.

ANALYSIS

First, the self-reports were inspected for any neurological or psychological history that would significantly affect the QEEG. To cross-validate this decision, relative power reports from the LND were inspected. The criterion for exclusion was set at more than four neighboring locations deviating for any particular frequency band. Moreover, psychometric data were scored and evaluated for extreme deviancies. Criteria for exclusion were set at more than four (out of nine) psychometric measures falling below one standard deviation from the norms.

Raw EEG data were visually inspected and all epochs including artifacts were removed from further analysis. Given the sensitivity of slow frequencies to be affected by eye movements, especially in the frontal channels, qualitative criteria of rejection were set as follows: epochs with slow-wave activity that was seen primarily in FP1 and FP2 were rejected, being interpreted as vertical eye or eyelid movements; and epochs with convergence between F7 and F8 were rejected, being interpreted as lateral eye movements. All artifact-free epochs (regardless of whether they contained marked responses or not) were reported in peak-to-peak microvolts (amplitude) averaged for each 3.3-minute recording. EEG amplitude was reported for two frequency bands of 1-4 and 4-8 Hz, separately for each recording and each scalp location. The present article reports data from the three reading tasks (out of five) and the EOB.

Each reading task was compared to the EOB in a repeated measures analysis. Since QEEG data do not usually fall under a normal distribution, a fact also confirmed by testing for normality on the present data, all values were squared and then transformed to their natural logarithm. This transformation yielded a significant normalization of the distribution of the data, as confirmed by less than five percent rejections of normality using both the Kolmogorov-Smirnov and the Shapiro-Wilkinson tests (Shapiro, Wilkinson, & Chen, 1968) independently. This transformation has universally been found to adequately normalize QEEG data (John et al., 1980; Gasser, Bacher, & Mocks, 1982).

Given the large number of variables (two frequencies, three tasks, 19 scalp locations making 114 variables), statistical tests were corrected for multiple comparisons using a sequential Bonferroni adjustment of the alpha level of probability. This technique increases the power of the standard Bonferroni adjustment, reducing the probability of type-II error (Rice, 1988; Miller, 1981; Holm, 1979). First, the alpha level 0.05 (two-tailed = .025) was divided by the total number of comparisons (0.025/114 = 0.000219). Then, all p-values were rank-ordered, and the smallest p-value was compared to the corrected alpha level (0.000219). If the p-value was smaller, it was considered significant. Then, the next smaller p-value was compared to an adjusted alpha level for the remaining number of comparisons (0.025/113 = 0.000221, 0.025/112 = 0.000223, etc.) until the p-value became greater than the adjusted alpha level.

RESULTS

Performance on all reading tasks was found to be above 50% correct for all participants (i.e., at least 10 out of 20 targets were identified) and for the purposes of the present analysis we considered this success rate as acceptable. However, significant differences were found in both omission (misses) and commission (false alarms) errors, when comparing the semantic task with any of the other two. Visual and phonetic tasks did not differ significantly in either omission or commission errors (see Table 1).

Table 2 summarizes the significant findings (p-values smaller to a-level corrected for multiple comparisons). Reported values are significant *amplitude increases* during reading as compared to the EOB. Numbers are *mean differences* of transformed amplitude (transformation: ln[uV^2]) with their respective *standard errors* (in parentheses).

During visual reading, amplitude increased at C3, C4, T3, T4, and T5 for the 1-4 Hz band, and at T5 and T6 for the 4-8 Hz band. During phonetic reading, amplitude increased at T3, T4, F3 and F7 for the 1-4 Hz band, and at T5 and FP1 for the 4-8 Hz band. During semantic reading, amplitude increased at T3, T4, C3, C4, F3, F7, F8, CZ and FZ for the 1-4 Hz band and at T5 for the 4-8 Hz band.

DISCUSSION

Slow-wave EEG and processing. The present data support previous studies that relate amplitude increases in slow-wave EEG with cogni-

TABLE 1

	OMISSIONS				COMMISSIONS		
ERRORS	VISUAL	PHONETIC	SEMANTIC		VISUAL	PHONETIC	SEMANTIC
MEAN	3.05	4.37	**1.89**		1.37	1.84	**8.37**
STD. ERR.	0.55	0.62	0.37		0.38	0.30	1.18

Means and standard errors for omission (misses) and commission (false positives) errors during visual, phonetic, and semantic reading. Semantic reading produced significantly less omission and more commission errors compared with visual and phonetic reading. Visual and phonetic reading did not differ significantly in the amount of errors. (Bold typed numbers refer to significantly different means from the rest in their group.)

TABLE 2

		VISUAL		**PHONETIC**		**SEMANTIC**	
		1-4 Hz	**4-8 Hz**	**1-4 Hz**	**4-8 Hz**	**1-4 Hz**	**4-8 Hz**
FP1					.15 (.03)		
FZ						.19 (.04)	
CZ						.16 (.03)	
F3				.21 (.04)		.22 (.04)	
F7				.24 (.04)		.28 (.06)	
T3		.23 (.05)		.17 (.03)		.18 (.03)	
C3		.20 (.04)				.19 (.04)	
F8						.13 (.03)	
T4		.22 (.04)		.16 (.03)		.17 (.03)	
C4		.18 (.04)				.18 (.03)	
T5		.18 (.03)	.22 (.04)		.21 (.03)		.21 (.04)
T6			.15 (.03)				

Significant ***amplitude increases*** *during reading as compared to the EOB. Numbers are* ***mean differences*** *of transformed amplitude (transformation: ln[uV^2]) with their respective* ***standard errors*** *(in parentheses). Reported results are corrected for multiple comparisons.*

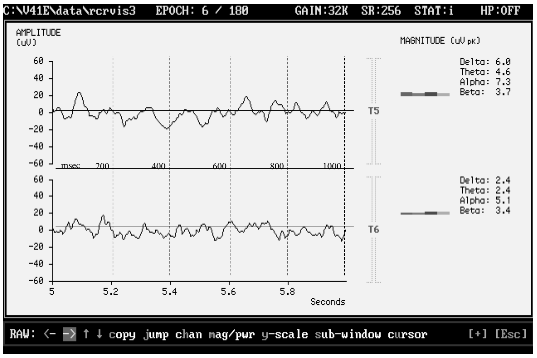
tive processing. Not only did slow-wave EEG amplitude increase in areas expected to be involved, but it also did not decrease at any area. This suggests that, during reading tasks in awake, non-clinical young adults, increased amplitude in slow-wave EEG may illustrate cognitive processing. We propose that slow frequency EEG is a form of brain *activity*, rather than inactivity. Schuerman and colleagues relate the "delta" component (0.5-3.5 Hz) of the P300 ERP to decision making and matching during cognitive tasks like, for example, during detection of auditory stimuli close to the hearing threshold (Schuerman et al., 2001). What may be correlated with slow frequency EEG and inactivity is the lack of activity in *other* parts of the EEG spectrum (i.e., faster than 4 Hz), which seems to be the case with most reported findings in the literature that relate slow frequency EEG to inactivity and pathology. This absence of higher EEG rhythms, then, may let the slow frequency loops dominate at the cortical surface. The form of slow-wave EEG being different between pathology/sleep and healthy cognitive functions supports this conclusion. In the first case (pathology/sleep), slow waves are dominant, rhythmic and of high amplitude. In the latter case (healthy cognitive functions), however, slow waves are non-dominant, arrhythmic and of low amplitude (see Figure 1).

Moreover, some studies report EEG amplitude for each selected frequency band as a proportion of the total EEG amplitude (relative amplitude/power), rather than as an absolute independent measure. Relative amplitude, however, for any frequency band, will increase if amplitude in some of the other bands decreases. In other words, in some reports, increases in slow frequency EEG may not be real, but an artifact of decreases in higher frequency bands (for a related discussion, see Fein et al., 1986).

Topographical distribution. The next point of interest with the present results is the topographical distribution of the very slow frequency, which suggests that it may be more specific than the 4-8 Hz in localizing specific processing modalities.

Compared to the EOB, all three reading tasks showed increased amplitude in the 1-4 Hz band in bilateral temporal areas (T3, T4), the visual task showed selective involvement of the left postero-temporal area (T5), the phonetic task showed selective involvement of the left frontal area (F7, F3) and the semantic task showed selective involvement of central and frontal areas (C3, CZ, F3, F7, F8 and FZ). Although it has been suggested that linked ear referenced EEG does not always reflect activity of the underlying cortical areas (see Rosenfeld, 2000), it is of interest that these localizations fall over areas expected for the nature of each reading task. First, being a process of language, reading was expected to show activity primarily in the left hemisphere, as it did (see Figure 2). Moreover, visual reading involving visual pattern recognition was expected to involve primarily visual association areas, and it did (T5). Phonetic reading, involving articulation (although silent) was expected to involve primarily Broca's area and auditory areas, which was also observed (F7, F3, T3, T4). Semantic reading was expected to

FIGURE 1. Examples of raw data showing lateral asymmetry of delta (1-4 Hz) activity between homologous pairs: T5-T6 (visual reading, top); F7-F8 (phonetic reading, middle); and C3-C4 (semantic reading, bottom).

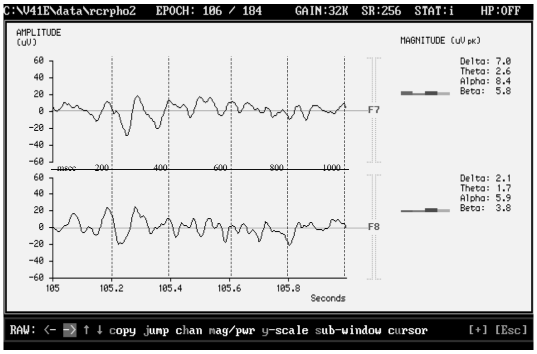


```
C:\V41E\data\rcrvis3   EPOCH: 6 / 180      GAIN:32K  SR:256  STAT:i    HP:OFF

MAGNITUDE (uV pk)
T5   Delta: 6.0
     Theta: 4.6
     Alpha: 7.3
     Beta:  3.7
T6   Delta: 2.4
     Theta: 2.4
     Alpha: 5.1
     Beta:  3.4
```

VISUAL READING

T5 delta: 6.0 uV
T6 delta: 2.4 uV

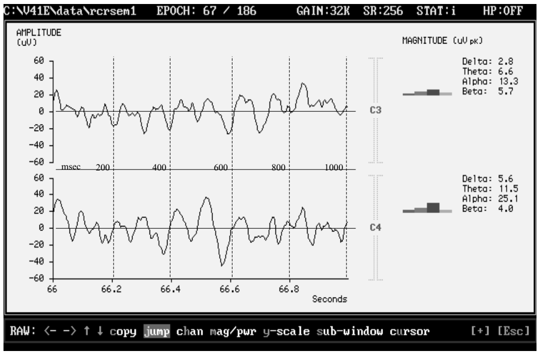


```
C:\V41E\data\rcrpho2   EPOCH: 106 / 184    GAIN:32K  SR:256  STAT:i    HP:OFF

MAGNITUDE (uV pk)
F7   Delta: 7.0
     Theta: 2.6
     Alpha: 8.4
     Beta:  5.8
F8   Delta: 2.1
     Theta: 1.7
     Alpha: 5.9
     Beta:  3.8
```

PHONETIC READING

F7 delta: 7.0 uV
F8 delta: 2.1 uV



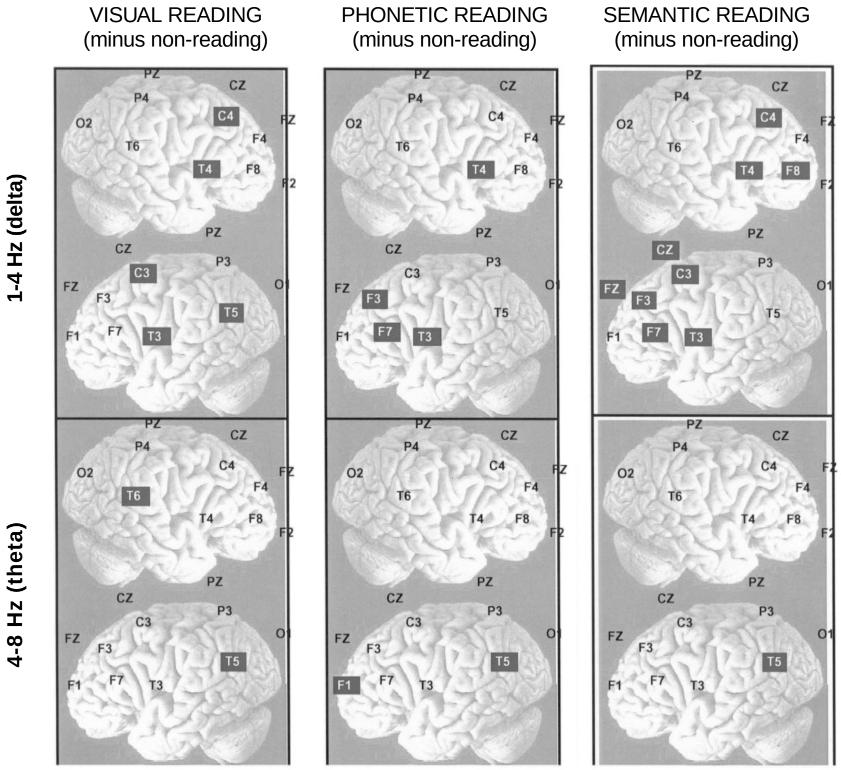
```
C:\V41E\data\rcrsem1   EPOCH: 67 / 186     GAIN:32K  SR:256  STAT:i    HP:OFF

MAGNITUDE (uV pk)
C3   Delta: 2.8
     Theta: 6.6
     Alpha: 13.3
     Beta:  5.7
C4   Delta: 5.6
     Theta: 11.5
     Alpha: 25.1
     Beta:  4.0
```

SEMANTIC READING

C3 delta: 2.8 uV
C4 delta: 5.6 uV

FIGURE 2. Amplitude increases (in colored square frames) during visual, phonetic, and semantic reading as compared to the eyes open baseline (EOB). Notice the bilateral temporal effects (T3 and T4) of all reading tasks, the left posterotemporal effects (T5) of visual reading, the left frontal effects (F7, F3) of phonetic reading, and the frontal midline effects (FZ) of semantic reading. Top row is for 1-4 Hz, and bottom row for 4-8 Hz. (Brain-electrode correspondence approximated from Homan, 1988.)



involve primarily the occipito-temporo-parietal junction and Wernicke's area, which, however, was not found. Finally, all tasks were expected to show some midfrontal engagement, which, however, was found only with the semantic task (FZ). One explanation is that the semantic task required more attentional resources, also supported by the higher incidence of false alarms, as well as by the increased amplitude at F8, possibly reflecting higher vigilance demands. It is of interest that the 4-8 Hz band showed some amplitude increases during reading, but not to the extent that the 1-4 Hz band did. Specifically, the visual task showed bilateral amplitude increase at occipito-temporal areas (T5 and T6), the phonetic task showed amplitude increase in the left prefrontal and occipito-temporal areas (FP1, T5), and the semantic task showed amplitude increase for the 4-8 Hz band in the left occipito-temporal area (T5).

These findings suggest a modality-specific property of the 1-4 Hz band, which shows involvement of phonetic processing pathways for all reading tasks, involvement of visual processing pathways only for the visual reading task, and involvement of attentional, cingulo-cortical pathways for the phonetic and semantic reading tasks. We think that this slow-wave activity is of brain origin, rather than an artifact of eye movements, for several reasons. One is that the presentation of the reading materials minimized eye movements. Another reason is that all data containing eye movements were rejected by thorough visual inspection. Figure 1 presents examples of raw data accepted in the analysis that show lateral asymmetry of low amplitude delta (1-4 Hz) activity in T5-T6 (visual reading, top), F7-F8 (phonetic reading, middle), and C3-C4 (semantic reading, bottom). Similar patterns of normal low amplitude delta in young adults can be seen in Blume and Kaibara's (1995) *Atlas of Adult Electroencephalography* (pp. 514-515). (For a similar discussion, see also Petsche & Etlinger, 1998, p. 265.) Last, but not least, this phenomenon was found in locations associated more with components of reading than with eye movements, or any other source of slow-wave artifact, such as tongue and head movements, or respiration.

As a caveat in the present study, we should note that the method employed for correcting the alpha level for the large number of comparisons (114) may be responsible for statistical Type-II error, meaning that there may be more locations showing slow-wave amplitude increases to the ones reported here. We can say with confidence that the ones reported are true, and that there may be more, but these were not reported because of our statistical design. Moreover, the use of linked-ear referenced EEG has been suggested to not always reflect activity of the underlying cortical areas (Rosenfeld, 2000). Finally, with the techniques and analyses used, it is not possible to attribute the slow-wave EEG activity to a specific brain network. If it reflects working memory, then it should be produced by cortico-cortical or cortico-subcortical loops related to working memory functions. One such source is cortico-hippocampal loops. Direct subcortical EEG recordings from the hippocampus in patients prior to surgery have shown peaks of 2-6 Hz activity during rest, and augmentation of 4-8 Hz activity during semantic word testing (Basar, 1998, p. 357). The hippocampus is a paleocortical structure that, in humans, is associated with transfer of working memory to long term memory, as well as with transient functions during encoding and retrieval (Milner, Corkin, & Teuber, 1968; Curtis, Zald, Lee, & Pardo, 2000). Damage to the hippocampus deprives the person of the ability to form new declarative memories or even retrieve memories formed during the period of time before the damage (among other effects), but leaves the ability to retrieve long term memories intact. Of course, these observations should be taken cautiously with respect to their validity in non-clinical individuals. However, the unique advantage of direct recording from the hippocampus provides a starting point in considering relating the hippocampus to working memory functions. Future studies may test this question by relating this neocortical activity to *concurrent* hippocampal activity. A recently developed technique of EEG data analysis called LORETA (Low Resolution Electromagnetic Tomography) has the potential to identify such interactions (Pascual-Marqui, 1999).

Implications for neurofeedback. A question that arises from the present findings as well as from other studies (e.g., Gevins et al., 1998) is why neurofeedback training to suppress amplitude of the slow frequencies (4-7 Hz) improves the attentional and cognitive abilities of children with attention deficit disorder when these frequencies seem involved in cognitive tasks in adults. One explanation is that such slow activity (4-7 Hz) in children may be equivalent to higher rhythms, between 7 and 9 Hz in adults. It has been shown, for example, that the posterior dominant frequency follows such a developmental pattern of frequency increase, starting from 6-9 Hz at preschool ages and reaching the adult level of 8-12 Hz around the age of 13 (Duffy, Iyer, & Surwillo, 1989; Niedermeyer, 1999a). In this case, children with attentional deficit disorder may be developmentally delayed, and what neurofeedback suppresses is the dominant oscillating rhythm. This model is supported by a recent study showing that adults with attention deficit disorder exhibit this rhythm at higher frequencies than children, between 7-10 Hz (White, Lubar, & Hutchens, 2000).

An alternative explanation would be limited attentional resources. Benham and colleagues found a widespread significant increase in the 4-8 Hz band when participants reported being engrossed in listening to a story, as opposed to when they reported not being engrossed (Benham, Rasey, Lubar, Frederick, & Zoffuto, 1997). Maybe children with attention deficit disorder engage in some internal engrossment (which some may call day dreaming) that occupies working memory resources. This would involve activation (and occupation) of the respective neural pathways for working memory, and thus not allow processing of external stimuli or events. It has been shown that engagement with working memory tasks impedes performance in concurrent attentional tasks (Posner & Raichle, 1994, p. 177). By teaching these children to suppress their internal processes, more attentional resources may become available.

Conclusions. In summary, we conclude that in non-clinical young adults, slow and very slow EEG rhythms are an index of brain activation, and that they can topographically differentiate reading tasks that engage different processing pathways. This low-amplitude slow-wave activity is an independent phenomenon from that of deep sleep or brain pathology, and may be one of the variables to consider when studying the components of the reading process and their relationship to reading difficulties.

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RECEIVED: 12/30/00
REVISED: 05/04/01
ACCEPTED: 06/01/01