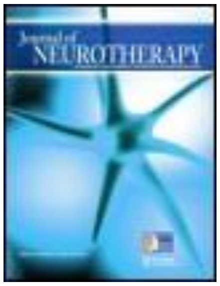

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EEG Changes in Traumatic Brain Injured Patients After Cognitive Rehabilitation

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EEG Changes in Traumatic Brain Injured Patients After Cognitive Rehabilitation

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ABSTRACT. *Background*. Little research has addressed cognitive rehabilitation and changes in the electroencephalogram (EEG) following training of traumatic brain injured (TBI) patients suffering from attention deficits because of their injury. This study focuses on changes in relative and absolute power in frontal, central and posterior regions of the TBI patients' brain following training on attention skills using a software program called Captain's Log.

Methods. The five participants–aged 20 to 45 years–received 22 sessions of training on their attention skills. Their attention skills were assessed at the beginning and end of the research study through a variety of psychometrics as well as through scaled self-reports. Their EEG was also recorded before and after training, during eyes-open resting baseline, eyes-closed resting baseline, eight cognitive tasks and a post-tasks eyes-open resting condition. Only the first two baselines were analyzed in the present study. (The rest of the conditions will be analyzed in another study.) The hypotheses that the participants' delta, theta, and alpha relative and absolute power would decrease and that their beta power would increase following training were analyzed.

Results. Although there were significant post-task changes in four out of the five case studies in relative and absolute power, both in eyes-closed

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and eyes-open conditions, the most systematic change was the decrease of alpha in the eyes-closed condition.

Conclusion. These new findings link training in cognitive processes with EEG changes.

KEYWORDS. Traumatic brain injury, EEG, cognitive rehabilitation, attention deficits, software programs

INTRODUCTION

Despite the fact that research already exists concerning electroencephalographic (EEG) changes followed by behavior changes (Kuhlman & Kaplan, 1979; Lantz & Sterman, 1988; Lubar & Lubar, 1984), little research has addressed the issue of behavior changes followed by EEG changes. The purpose of this study is to investigate this relatively new area–one type of cognitive rehabilitation for traumatic brain injured (TBI) patients.

Traumatic Brain Injury

The National Head Injury Foundation (1985) defines head injury as a "traumatic insult to the brain capable of producing physical, intellectual, emotional, social, and vocational changes." This definition implies brain damage and associated dysfunction such as the inability to coordinate movements, speech, memory, reasoning, or modulation of behavior. While not denying that pathology may be diffuse, research suggests that lacerations, contusions and hemorrhages as well as diffuse axonal injury (DAI), which is the diffuse degeneration of the cerebral white matter, are more prominent in the frontal and temporal regions (Sohlberg & Mateer, 1989). Finally, the shearing, tearing, and stretching of axons may also result in true disconnections between prefrontal, limbic, and association cortices leading to disturbances of the cognitive and executive processes (Langfitt & Gennarelli, 1982). Executive and cognitive disturbances can be treated with different kinds of therapy, cognitive rehabilitation training being the most commonly cited successful training (Prigatano, 1986; Adamovich, Henderson & Auerbach, 1985; Goldstein & Ruthven, 1983).

Cognitive Rehabilitation and Spontaneous Recovery

Cognitive rehabilitation refers to the therapeutic process of increasing or improving an individual's capacity to process and use incoming information so as to allow increased functioning in everyday life. This includes both methods to restore and compensate for cognitive functions. Assessment of a treatment's efficacy constitutes a difficult task with the most fundamental obstacle arising from individual differences in spontaneous recovery. The individual differences most relevant to recovery include intraspecies differences in brain organization, location of lesion, rate of improvement immediately following injury, premorbid level of functioning, extent of neurological damage, time post-onset and age at injury (Sohlberg & Mateer, 1989).

A primary executive function in need of cognitive rehabilitation is attention. Mild to severe dysfunction of the attention skills of the individual constitutes one of the main complications due to damage to the frontal and temporal lobes (Finlayson & Garner, 1994).

Types of Attentional Dysfunction and Their Representation in the Brain

There are different types of attention that may be disrupted. *Sustained attention* involves the duration over time one is able to maintain performance, as well as the consistency of performance over that period. *Selective attention* is defined as the ability to focus on relevant stimuli in the presence of distracting stimuli and select information for conscious processing. *Divided attention* is defined as the ability to either do more than one activity simultaneously, or to attend multiple stimuli. *Alternating attention* constitutes the ability to switch from one stimulus or activity to another (Ashley & Krych, 1995).

Starting with sustained attention, it has been noted that prefrontal and parietal areas, preferentially in the right hemisphere, are frequently engaged (Lewin et al., 1996; Pardo, Fox & Raichle, 1991; Haxby et al., 1994). Coull, Frackowiak, and Frith (1998) confirmed earlier reports of fronto-parietal-thalamic network associated with sustained attention and prefrontal cortex and anterior cingulate activation associated with selective responding. Their work showed that the right inferior frontal and parietal cortices are differentially activated by increasing time on task during the selective (S) vs. non-selective (NS) task. Specifically, they showed that regional cerebral blood flow (rCBF) decreases with increasing time spent performing the NS task but not the S task. Thus, it seems that Coull et al. identified the neuroanatomical correlates of each process separately, and provided the neuroanatomical location of the functional interaction between sustained attention and the process of selectively monitoring for target objects.

Selective attention is characterized by increased activity in posterior regions involved in stimulus processing. Different regions seem to be involved depending on the specific attribute that is attended to (Corbetta, Miezin, Dobmeyer, Shulman & Petersen, 1990). Recent examples of attentional modulation of auditory regions are provided in Woodruff et al. (1996) and Pugh et al. (1996) where the role of parietal cortex, especially the inferior parietal lobe, is suggested to control selective attention. Several of the studies on selective attention are based on the Stroop test, which is associated with activations in the anterior cingulate cortex and the left prefrontal cortex (Taylor, Komblum, Lauber, Minoshima & Koeppe, 1997). Studies by Rees and Lavie (2001), as well as Saenz, Buracas, and Boynton (2002), point to the role of the occipital cortex in selective attention. Other studies suggest that the cerebellum may be part of the selective attention network as well (Vandenberghe, Gitelman, Parrish & Mesulam, 2001; Sevostianov, Fromm, Nechaev, Horwitz & Braun, 2002).

As far as divided attention is concerned, it seems that when two tasks are performed simultaneously, performance often deteriorates, with simultaneous increases in reaction time and error rate. Klingberg (1998) considered three potential neurophysiological mechanisms behind this deterioration in performance: (a) dual-task performance requires additional cognitive operations and activation of cortical areas in addition to those active during single-task performance, (b) two tasks interfere if they require activation of the same part of cortex, and (c) cross-modal inhibition causes interference between two tasks involving stimuli from different sensory modalities. Klingberg concluded that there is no separate cortical area that gets activated due to any dual task, but that the area activated depends on the type of the specific cognitive process. In addition, according to the studies of Le, Pardo and Hu (1998) and Ravizza and Ivry (2001), the cerebellum has been implicated in alternating attention. Another brain structure which gets also activated during alternating attention is the prefrontal cortex (Ravizza & Ciranni, 2002; Koski & Petrides, 2001). Table 1 summarizes the three types of attentional dysfunction, their representation in the brain and the best tests to measure these specific types of attention.

Figure 1 depicts the three types of attention portrayed on the brain represented in the right and left hemisphere.

Cognitive Tests and EEG as Assessment Measures for TBI and ADD

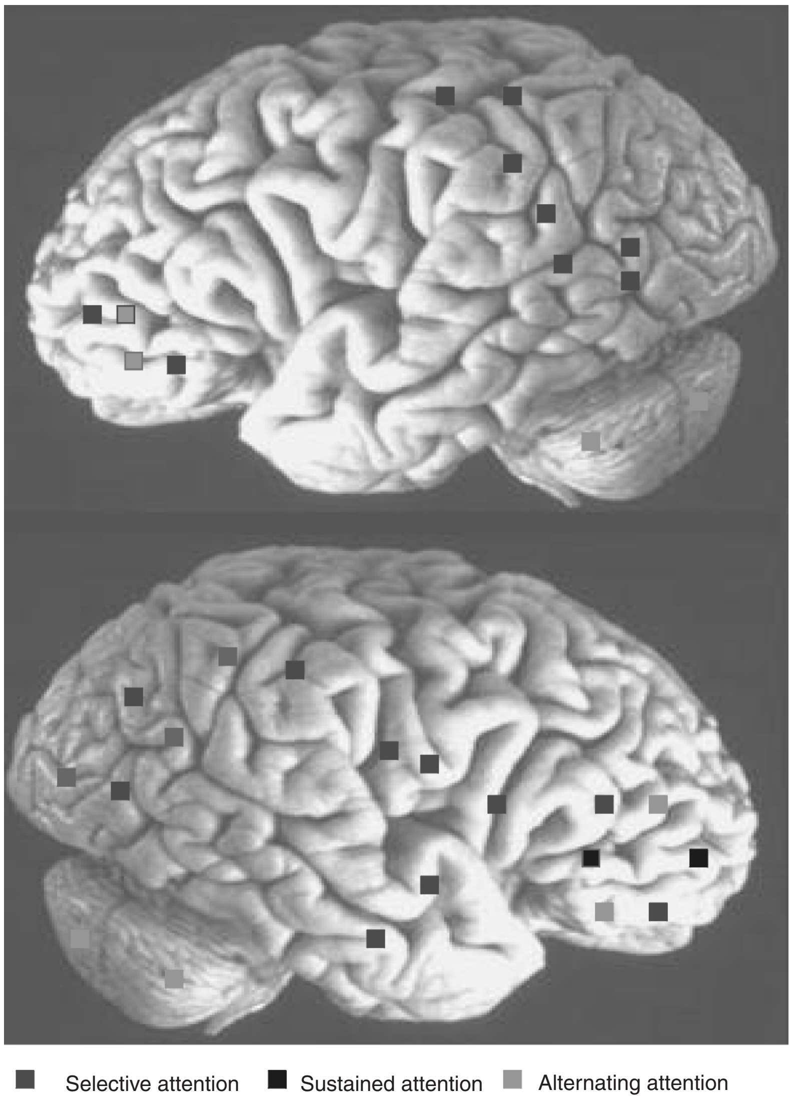
Several kinds of cognitive tests or subtests are currently used in order to assess attention. The WAIS-R Digit Span subtest (Weschler, 1981) is commonly used to test immediate or working memory, the WAIS-R Digit Symbol subtest (Weschler, 1981) to test information processing speed performance, the Paced Auditory Serial Addition Test (PASAT; Gronwall, 1977) to assess divided attention skills, and the Stroop Test (Stroop, 1935), to test distractibility attention capacities. The Integrative Visual and Auditory Continuous Performance Test (IVA CPT; Sandford & Turner, 1995) tests all types of attention deficits (Solberg & Mateer, 1989).

On the other hand, the quantitative electroencephalogram (QEEG)–the recordings from electrodes of the electric brain potentials–constitutes different methodology for the study of the dynamic functional aspects of brain function (Hudspeth & Pribram, 1992). QEEG is a highly validated method for assessing attention deficit disorders.

TABLE 1. Types of Attention, Associated Brain Regions and Related Psychometrics

Types of attention	Representation on the brain	Tests
Sustained	Prefrontal/Parietal right hemisphere	IVA-Scales on Consistency, Focus, Stamina; Digit Span and PASAT
Selective	Parietal cortex, inferior parietal lobe prefrontal, occipital	IVA-Scales on Prudence, Vigilance, Comprehension; Digit Symbol
Divided	Depends on cognitive task	IVA-Scales on Prudence and Speed
Alternating	Prefrontal, cerebellum	IVA-Scales on Speed, Balance, Readiness, Consistency and Focus; PASAT

FIGURE 1. Types of attention represented on two hemispheres. Upper image: Left hemisphere. Lower image: Right hemisphere.



Chabot, Orgill, Crawford, Harris, and Serfontein (1999) studied a sample of 130 children with attention disorders. The children were evaluated with the Conners and DSM III rating scales and with Neurometric QEEG before and 6 to 14 months after treatment with stimulants. Significant QEEG differences were found between the non-clinical control group and the children with attention problems ($p < .001$) before treatment. QEEG abnormalities involved increased theta or alpha power greatest in frontal regions, frontal theta/alpha hypercoherence, and posterior interhemispheric power asymmetry. Coherence is analogous to a cross-correlation coefficient in the frequency domain and thus is a metric of the amount of shared activity between the two regions. The degree of correspondence between behavioral and QEEG changes after the stimulant treatment was 78.5 percent. Research on Attention Deficit Disorder (ADD) patients has shown an increase of the slow wave theta and more specifically an increase in the theta-beta ratio in the frontal or central regions, depending on the age of the patient (Monastra et al., 1999).

In a study conducted by Thatcher, Cantor, McAlaster, Geisler, and Krause (1991), a number of variables were used to study the development of prognostic equations for patients with closed-head injury one year after the accident. The variables studied were: EEG recording from 19 scalp locations, Computed Transaxial Tomography (CT) scan, Glasgow Coma Scale (GCS) and the Rappaport Disability Rating Scale (DRS). According to the results, the best predictors of outcome in both the discriminant analyses and the regression analyses were the EEG measures, coherence, and phase. More specifically, in another study conducted by Thatcher, Walker, Gerson and Geisler (1989), head injured patients showed increased coherence and decreased phase in frontal and frontal-temporal regions, decreased power differences between posterior and anterior cortical regions and reduced alpha power in posterior cortical regions.

On the other hand, prior research regarding QEEG and TBI (Randolph & Miller, 1988) has shown that the head injured group displays higher amplitudes, except in the alpha band of 8-12 Hz, and greater variance than the control group in the occipital and especially the temporal placements. The increased amplitudes, amplitude variance, and reduced correlation coefficients at the temporal sites of the closed-head injured patients are presumed to reflect areas of dysfunctional cortex. The same patients when asked to participate in cognitive tasks demanding increased arousal showed increases in amplitude in delta (0-4 Hz) and beta bands (12-32 Hz) and decreases in alpha and theta (4-8 Hz) bands.

Increased theta power in brain-injured patients was also reported by Montgomery et al. (1991) even after a six-month period following the accident. A predominance of slow waves was also reported by Enomoto, Ono, Nose, Maki and Tsukada (1986) from 280 cases of minor head-injured patients.

EEG Biofeedback

Almost 25 years ago, a treatment procedure called EEG biofeedback was developed. It constitutes an operant conditioning procedure, where the individual modifies the amplitude, frequency or coherence of the neurophysiological dynamics of his/her own brain (Lubar, 1989). It has been found to be effective in treating attention deficit problems both in ADD individuals (Shouse & Lubar, 1979; Lubar & Lubar, 1984; Linden, Habib & Radojevic, 1996; Tansey, 1993; Lubar, Swartwood, Swartwood & O' Donnell, 1995) and TBI patients with attentional problems (Ramos, 1998). Different paradigms have been used including Sensory Motor Rhythm (SMR) biofeedback (Tansey & Bruner, 1983; Lubar & Lubar 1984), alpha training (Nall, 1973), hemisphere-specific biofeedback (Patmon & Murphy, 1978) and theta-beta training (Lubar et al., 1995; Alhambra, Fowler & Alhambra, 1995). Theta-beta training, where individuals are trained to increase beta and decrease theta, seems to give the most promising results (Ramirez, Desantis & Opler, 2001). Effective results were also seen in the training of TBI patients with attentional deficits. In Ramos' (1998) study, TBI patients were trained to decrease their theta and increase their beta waves, leading in less than 20 sessions to a significant improvement in their attention deficit problems. Similarly, in Hamilton's research study (1997), 23 TBI participants were trained using EEG biofeedback to increase beta and decrease theta wave activity, leading in 24 sessions to an increase in their level of vigilance and an improvement in their global functioning.

Software Programs for Training Attention Skills

EEG biofeedback is not the only method for treating attention deficits. Computerized attention training is another promising approach. A number of studies have found evidence for the efficacy of a microcomputer-based approach to the rehabilitation of attention skills in brain injury (Baribeau, Ethier & Braun, 1989; Skinner & Trachman, 1985; Sohlberg & Mateer, 1989). Most of the programs used in these studies use the Process-Specific Approach to cognitive rehabilitation, where repeated administration of hierarchically organized treatment tasks target distinct, theoretically derived components of a cognitive process. Initial studies on the Process-Specific Approach are encouraging (Solberg & Mateer, 1987). Microcomputer use fits well within the context of the Process-Specific Approach. Furthermore, some of the advantages of microcomputer use in cognitive rehabilitation are: consistent, often adjustable, rate of stimulus presentation; automatic collection and tabulation of performance data; efficient administration of tedious practice tasks; objective feedback; freeing of clinicians to observe and record valuable qualitative data that may be lost or forgotten in the course of administration (Solberg & Mateer, 1989).

Using a group experimental design, Baribeau et al. (1989) examined the effects of computerized cognitive rehabilitation on selective attention in closed-head injury patients using auditory event related potentials (ERP) as a dependent variable. Improvements on ERP measures as a function of computerized cognitive rehabilitation were attributed to "improved motivation, more effort, and better capacity to follow experimental instructions" as opposed to improvement in selective attention mechanisms. Skinner and Trachman (1985) also found improvements in motivation which could, in part, explain the increases in attention that were found. On the other hand, Tinius and Tinius (2000) found significant improvement on full scale attention and full scale response accuracy of a continuous performance task in the TBI and ADHD group following EEG biofeedback and cognitive retraining with a software program, The Captain's Log.

The equivocal results in this area of computerized cognitive rehabilitation have been attributed to differences in the definition and measurement of attention skills, as well as various treatment and patient parameters (Ponsford & Kinsella, 1988).

Rationale, Purpose and Hypotheses of the Study

The literature on EEG biofeedback (mentioned above) suggests that improvement of attentional deficits follows training of different frequency bands. This training consists of either increasing or decreasing those frequencies that are outside of the normative range based on QEEG with a normative database. The rationale behind this study is that while EEG biofeedback constitutes a direct way to alter brain waves, computerized cognitive rehabilitation may achieve the same results in a more indirect way: the training of attentional deficits will evoke modification of the amplitude of frequency bands. The purpose of this study is to test the relationship between cognitive rehabilitation and changes in the EEG patterns of TBI patients with attentional deficits.

There are indications that people with attentional problems have increased power in delta, theta and alpha frequency bands (i.e., the bands involved in drowsier conditions) and decreased power in the beta frequency band (i.e., the band more active during cognitive processes). By training TBI patients with attentional deficits with a software program called Captain's Log, effectively used by Tinius and Tinius (2000), reduction in the patients' delta, theta and alpha relative and absolute power is expected as well as an increase in beta in both relative and absolute power. These changes are expected to be seen both in eyes-closed and eyes-open conditions. The psychometrics as well as their scaled self-reports have been used in order to assess the participants' post-training improvement or deterioration in different types of attention.

METHOD

Participants

The proposal was distributed to the Association of Brain Injured Patients of Knoxville, to the Disability Service of the University of Tennessee and to the local newspaper, the *Knoxville News-Sentinel*. The five patients who participated in the project were instructed regarding the scope and the procedures of the study, signed the consent form and agreed to participate in exchange for the free therapy sessions offered to them. Their ages ranged from 20 to 45. There were two males and three females. The participants who were accepted for the study had experienced the accident causing their brain injury at least one year prior to their selection for this study. The experimenter wanted to avoid any effects resulting from spontaneous recovery, which usually occur during the first six months after the accident. Their accidents had occurred at different time periods, starting from one and a half to twenty-three years before coming to the study. None of the participants were engaged in any therapy or medication during the period of the study. All of the post-injury information mentioned below comes from medical records.

M. F. was a 48-year-old female. She had a motor accident one and a half years prior to the study. Her left hemisphere was injured. She did not stay in a coma. She was in the emergency room for four hours and in the hospital for two and a half months. She had post-traumatic amnesia for the first two months following the accident.

D. S. was a 38-year-old female. She had a motor accident 23 years ago. Damage occurred in her frontal lobe, especially the left frontal, and the left temporal. She also had some lacerations in the occipital area. She did not stay in coma but she had post-traumatic amnesia and was not aware of her surroundings for seven days. She stayed in the Intensive Care Unit for seven days and in the hospital for 14 days.

S. M. was a 40-year-old male. He had a motor accident eight years ago. Damage occurred in the left temporal/hippocampal area. He stayed in coma for three months and in the hospital for four and a half months. He reported still having post-traumatic amnesia.

R. M. was a 32-year-old male. He had his motor accident 14 years ago. Damage occurred to the right hemisphere, frontal lobe and optical nerve. He had a massive right to left shift, with a right subdural hematoma two cm in diameter. He later developed a small subdural hydroma in the left frontal region and in the right occipital region. He stayed in coma for 10 weeks, in an emergency room for six weeks and in the hospital for a year and a half. At the time of the study he suffered both from anterograde and retrograde amnesia.

R. Q. was a 20-year-old female. She had a motor vehicle accident six years ago. Damage occurred mainly in the right posterior lobe and left thalamic area. She stayed in coma for 24 days, in the emergency room for three hours, in the Intensive Care Unit for 72 hours and in the hospital for four months. She reported still having post-traumatic amnesia.

Assessment

All participants took the WAIS-R Digit Span subtest (Weschler, 1981), the WAIS-R Digit Symbol subtest (Weschler, 1981), the PASAT (Gronwall, 1977), and the Integrated Visual and Auditory Continuous Performance Test (IVA CPT; Sandford & Turner, 1995). Digit Span assesses working memory, short-term memory, sequential processing, learning ability, sustained and selective attention. Digit Symbol assesses perceptual organization, sequential processing, learning ability, visual short-term memory, visual-motor coordination, sustained and selective attention. PASAT assesses information processing skills, sustained and selective attention and the IVA CPT assesses all different types of attention capacities for both audition and vision. More specifically, the IVA CPT scales for Prudence and Vigilance assess focused attention; the scales for Stamina, Consistency and Focus assess sustained attention; the scales for Prudence, Vigilance and Comprehension assess selective attention; the scales for Speed, Balance, Readiness, Consistency and Focus assess alternating attention, and the scales for Prudence and Speed assess divided attention.

In the WAIS-R Digit Span subtest, the administrator orally presents numbers and the test-taker repeats them. In the first part, the numbers have to be repeated in the same order as presented; however, in the second part they have to be repeated backwards. In the WAIS-R Digit Symbol there are nine symbols paired with nine digits. The examinee has one and a half minutes to fill in as many symbols as he can under the numbers on the answer sheet. In the PASAT numbers are orally presented from a tape; the individual has to add each number he/she hears to the previous number and orally present the total. In the IVA CPT test, the participant hears or sees on the screen either the number "1" or the number "2" and must click the mouse only when he hears or sees number "1."

A scaled self-report (questionnaire) regarding attention and memory skills was given to each participant individually during the first session. The possible answers ranged from one to five, with "one" meaning "no problem at all" and "five" meaning "severe problem." The experimenter created this questionnaire based on a review of different types of attention and memory by Solberg and Mateer (1989).

The four different assessment tools and the scaled self-report were administered in order to assess different kinds of attention and the actual improvement or deterioration of the participants' attention skills after intervention. The cognitive rehabilitation software program used to train the TBI patients with attentional deficits for the remediation of their attentional deficits was the Captain's Log program, Version 1992 (Sandford, 1992).

In the Captain's Log "Attention Skills Tasks," different kinds of tasks were involved. They included tasks on vigilance, inattention, prudence, impulsivity, focus, variability and speed. The participants usually have to accurately select, discriminate or match visual pictures or sounds.

Apparatus

EEG was recorded with a Lexicor Neuro-Search 24 channel EEG recorder, using an Electro-Cap with electrodes set according to the 10/20 international standard. The Captain's Log program was presented on a computer screen 50 cm from the participants' eyes. The participants responded using the computer mouse. Speakers with adjustable volume were also used.

Procedure

A series of five single-subject experiments was conducted. During the first session, the participants signed the consent form, took their assessment tests and their scaled self-reports. The assessment tests and the scaled self-reports together lasted for about two hours. The experimenter also examined their medical records to verify and get information about their brain injury condition. During the second session, an eyes-open/eyes-closed EEG baseline, a recording during eight cognitive tasks and a second post-task eyes-open recording took place. EEG activity was recorded using a 19-channel electrode cap to measure the participants' brain electrical activity for deviations from a normative database. EEG was recorded according to the 10/20 system connected to a Lexicor Neuro-Search 24 EEG recorder. Cap electrodes were filled with electrolyte gel, gently rubbed into the scalp until impedance reached less than 5K ohms. Recording was referenced to the two ear lobes with additional electrodes. In the eyes-open baseline recording, the participants had to fixate their eyes on a point on the screen for three minutes, while in the eyes-closed baseline they just had to close their eyes and relax. The setup up period lasted for 40 minutes, the learning period to familiarize the participant with the eyes-open and eyes-closed baseline recording lasted for about five minutes, and the actual recording for about 35 minutes.

Training started in the third meeting. Twenty-two training sessions were given individually to each one of the participants. They were trained three times per week for the remediation of their attention skills, 50 minutes per session.

For each TBI participant his/her degree of attentional deficit differed slightly from the others. However, the five participants show all four types of attentional deficits: sustained, selective, divided and alternating attention. These deficits were assessed through the use of the psychometric tests and scaled self-reports. Thus, all five of them were trained principally on the same tasks of the Captain's Log program. More specifically, the skills they were trained on were: visual spatial memory, visual motor skills, visual alternating attention, verbal memory, auditory memory, working memory, memory for figures, choice reaction time, auditory discrimination and perceptual skills.

The EEG recording, the psychological assessments and the training were conducted in the Brain Research Laboratory of the University of Tennessee, Knoxville. The two rooms used for the study were specifically designed to be free of visual and auditory distraction. There were no windows. Two chairs, a table and a computer were placed in the room. During assessment, recording and training no one else was allowed in the room except the participant and the experimenter.

At the end of the intervention, all the assessment tests and scaled-self reports were administered again. In the next two meetings, two EEG recordings took place. In the pre-training EEG recording as well as in the first post-training EEG recording, the participants' eyes-open and eyes-closed baselines were measured and they were also engaged at the "beginner" level (level 1) of the Captain's Log cognitive tasks. On the second post-training recording, they were engaged in the "advanced" level (level 3) of the cognitive tasks.

Independent Variable

The variable to be manipulated was the time period before and after training.

Dependent Variables

The dependent variables are the differences in psychometrics and scaled self-reports before and after training. The psychometrics used were the WAIS-R Digit Span Subtest (Weschler, 1981), the WAIS-R Digit Symbol Subtest (Weschler, 1981), the PASAT (Gronwall, 1977), and the IVA CPT (Sandford & Turner, 1995). Other dependent variables were the differences before and after training in the frequency bands delta, theta, alpha and beta, relative and absolute power in the frontal, central and posterior regions during eyes-open and eyes-closed baseline conditions. In order to avoid influence by the main confounding factor in EEG recording (i.e., muscle artifact) the peripheral electrode sites were not included in the analysis of the results. Only the central sites were included. Thus, when the frontal areas were compared F3, F4 and FZ were averaged together and compared before and after training. The same holds true for the central areas (C3, C4 and CZ) as well as for the posterior areas (P3, P4 and PZ). The rest of the EEG recording conditions (cognitive tasks and second eyes-open resting condition) will be analyzed in another paper. The purpose of this study is to determine whether EEG differences are obvious just by comparing the eyes-open and eyes-closed resting conditions before and after treatment.

Statistical Analyses

Multiple t-tests were used comparing the average of all epochs before and after training for each subgroup of recording areas (frontal, central, posterior) and frequencies (delta, theta, alpha and beta) for both relative and absolute power for eyes-closed and eyes-open conditions: frontal-delta, frontal-theta, frontal-alpha, frontal-beta, central-delta, central-theta, central-alpha, central-beta, posterior-delta, posterior-theta, posterior-alpha, and posterior-beta. Since there were 240 combinations of variables (five case studies, three cortical areas, four frequencies, absolute and relative power, eyes-open/eyes-closed conditions) the alpha level 0.05 was corrected with the Bonferoni method by being divided by 240, thus giving a p-value of 0.0002. A two-tailed t-test was performed with a p-value of 0.0001.

The results of the psychometrics were also examined and their standard deviation differences were reported. Significant results were considered any differences that were two or more standard deviations below or above their pre-training scores. The scaled self-report differences before and after training were also examined and reported but were not statistically analyzed.

RESULTS

Individual Case Study Results

Following training M. F. showed a significant decrease in theta (in central and posterior areas) in eyes-closed absolute power and an alpha decrease in eyes-closed absolute and relative power. She also showed a significant decrease in delta frontal areas in eyes-open absolute power and a decrease in beta in frontal and central areas in eyes-open relative power. She also showed an increase in beta in frontal areas in eyes-open absolute and relative power (Tables 2 and 3). According to her self-rated questionnaire, choice reaction time and alternating attention were the types of skills improved after training. According to psychometrics, sustained attention was the type of attention that improved the most after training (Table 12).

Following training D.S. showed a significant decrease in theta (in central and posterior areas) in eyes-closed absolute power and an alpha decrease in eyes-closed absolute and relative power. She also showed a significant decrease in beta (in central and posterior areas) in eyes-closed absolute power

TABLE 2. M. F. Eyes-Open

EYES-OPEN					
	ABS. POWER (uV2)		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta **3.35**	*2.39		**7.34**	**5.43**	*3.92
Theta					
Alpha					
Beta −**2.01**	*−0.85		−**2.72**	*−1.48	

Bold: p-value < 0.0002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value < 0.001
Minus (−) significant increase after training
No significant decrease after training

TABLE 3. M. F. Eyes-Closed

	EYES-CLOSED				
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta *2.75	*2.23	*1.94			
Theta 1.50	**2.13**	**23.44**			
Alpha 5.09	**7.27**	**1.35**	**5.25**	**6.48**	**10.27**
Beta **1.52	*1.68	**1.83			−1.52*

Bold: p-value < 0.0002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value < 0.001
Minus (−) sign: increase after training
No sign: decrease after training

and in all areas in eyes-closed relative power. She also showed an increase in delta in central and posterior areas in eyes-closed relative power (Tables 4 and 5). According to her self-report questionnaire, selective and divided attention were the types of skills improved after training According to psychometrics, alternating attention and information processing were the skills that improved the most after training (Table 12).

Following training S. M. showed a significant decrease in alpha in the posterior areas in eyes-closed absolute power, an increase in theta and a decrease in alpha in the frontal area in eyes-closed relative power (Tables 6 and 7). According to the self-rated questionnaire, choice reaction and simple reaction time were the types of skills improved after training. According to psychometrics, selective attention was the type of attention that improved the most after training (Table 12).

Following training R. M. showed a significant increase in delta in central and posterior areas in eyes-closed relative power (Tables 8 and 9). According to the self-rated questionnaire, simple reaction time, divided, sustained and selective attention was the types of skills improved after training. According to psychometrics, sustained, alternating and selective attention constituted the types of attention that improved the most after training (Table 12).

Following training R. Q. did not show any significant EEG changes (Tables 10 and 11). According to the self-report questionnaire, choice reaction time and divided attention were the types of skills improved after training. According to psychometrics, sustained, alternating attention and information processing constituted the skills that improved the most after training (Table 12).

General Results for All Five Cases

Psychometrics. Three out of the five case studies showed sustained attention as their first (or among their first) ability to show improvement. Exactly the same results (three out of the five cases) held for alternating attention. Third was selective attention, with five out of five cases showing improvement, but only as second in order. Divided attention (three out of the five cases) and finally focused attention (two out of the five cases) constituted the last measured skill to show changes. Auditory working memory (two out of the five cases), auditory short-term memory and processing of numerical sequences (one out of five cases) and visual short-term memory as well as visual-motor coordination, (one out of five cases) constituted the last measured skills to improve after training (Table 12). Improvement was equally divided in the visual and auditory field for all five case studies.

Questionnaire (Scaled Self-Report)

In their self-reports participants scored higher by one point (indicating improvement) in choice-reaction time (three subjects), divided attention (three subjects), selective (two subjects), confusion (two subjects), simple-reaction time (two subjects), alternating attention (one subject), verbal memory (one subject), non-verbal memory impairment (one subject), long-term memory (one subject), sustained attention (one subject), and anterograde memory (one subject).

Quantitative Electroencephalogram

Each of the four conditions: eyes-closed absolute power (Table 13), eyes-closed relative power (Table 14), eyes-open absolute power (Table 15), and eyes-open relative power (Table 16) have some cortical areas and frequencies that showed significant changes. For example, in the eyes-closed absolute power theta, alpha and beta frequencies showed the most prevalent significant

TABLE 4. D. S. Eyes-Open

EYES-OPEN					
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta					
Theta					
Alpha	*2.45				
Beta	2.24*				

Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value < 0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 5. D. S. Eyes-Closed

	EYES-CLOSED				
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta				**−6.04**	**−6.58**
Theta *2.67	**3.29**	**4.82**			
Alpha **8.07**	**8.08**	**11.52**	**4.85**	**3.42**	**4.38**
Beta **.341**	**6.41**	**7.35**	*1.49	**3.02**	**2.74**

Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value < 0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 6. S. M. Eyes-Open

EYES-OPEN					
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta					
Theta		*−1.58			*−2.07
Alpha					
Beta					

Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value < 0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 7. S. M. Eyes-Closed

	EYES-CLOSED				
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta					
Theta *−2.85	*−2.80	*−2.36	−**4.57**	−**4.32**	−**5.03**
Alpha **3.36	*2.13	**3.37**	**3.84**		*2.70
Beta		**2.01			

Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value <0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 8. R. M. Eyes-Open

EYES-OPEN					
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta			*3.41		
Theta *2.70			*2.39		
Alpha					
Beta *−1.53					

Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value < 0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 9. R. M. Eyes-Closed

	EYES-CLOSED				
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta	*−5.41		−2.64*	−**4.12**	−**4.34**
Theta					
Alpha					
Beta *−1.81			*		

Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value <0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 10. R. Q. Eyes-Open

EYES-OPEN					
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta					
Theta	*1.73			2.10*	
Alpha					
Beta *1.00					

Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value < 0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 11. R. Q. Eyes-Closed

	EYES-CLOSED				
	ABS. POWER uV2		RELAT. POWER		
Frontal	Central	Posterior	Frontal	Central	Posterior
Delta					
Theta					
Alpha					
Beta	1.94*		*		

Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value <0.001
Minus (−) sign: increase after training
No sign: decrease after training

changes. In the eyes-closed relative power, delta, alpha and posterior beta showed the most prevalent significant changes; the same was true for the eyes-open absolute power for frontal and central beta.

DISCUSSION

M. F., whose accident was the most recent, showed the most prominent EEG changes. Her results were also the ones most consistent with the experimenter's hypothesis, with the exception of the decrease in beta in absolute power eyes-closed recording. She was also the only one who showed significant changes in the eyes-open recording. Her psychometrics, however, in comparison to the remaining four cases showed the least significant results. D. S. who had similar age, same gender and area of brain injury as M. F.,

TABLE 12. Psychometrics Pre-Post

TBI Participants Psychometrics	**MF**		**DS**		**SM**		**RM**		**RQ**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
PASAT	129	144	106	**128 (a)**	103	120	166	152	67	**104 (b)**
Digit Span	11	11	11	11	11	11	7	7	6	7 a
Digit Symbol	10	10	9	**10 (a)**	9	9	7	7	8	8
Consistency Audit.	117	127	114	110	91	86	153	126	113	118
Consistency Visual	114	123	124	134	70	**91 (a)**	110	124	90	**106 (a)**
Stamina Audit	92	**107 (a)**	93	106	103	105	0	**114 (g)**	100	120*
Stamina Visual	94	94	96	93	83	92	88	101	108	103
Prudence Audit	118	118	109	109	37	45	117	82	109	115
Prudence Visual	84	**104 (a)**	92	104	38	**59 (a)**	85	71	106	106
Focus Audit	124	127	111	110	90	90	143	122	121	123
Focus Visual	97	**122 (a)**	121	131	89	85	79	107	97	**115 (a)**
Speed Audit	58	51	50	**73 (a)**	65	58	38	**86 (C)**	27	39
Speed Visual	80	77	83	84	75	80	88	100	34	**52 (a)**
Readiness Audit	109	106	104	95	102	103	0	**100 (f)**	106	112
Readiness Visual	107	103	107	107	77	84	88	65	103	111
Persistence Audit	104	100	100	95	98	106	97	96	97	90
Persistence Visual	107	95	108	99	100	104	86	**106 (a)**	106	97
Sensorimotor Audit	79	68	73	80	73	79	53	66	47	57
Sensorimotor Visual	92	86	72	76	87	84	93	86	68	66
Vigilance Audit.	105	105	94	103	86	65	0	**107 (g)**	83	106

Vigilance Visual.	106	106	100	104	105	105	80	80	105	105
Comprehension Audit	107	107	99	94	77	98*	0	**109 (g)**	99	110
Comprehension Visual	107	107	101	101	39	**110 (d)**	106	106	93	**109 (a)**
Scores Audit	125	125	123	123	121	122	2	**125 (h)**	123	125
Scores Visual	124	125	123	124	123	123	124	124	124	125
Balance		88	86	66	**87 (a)**	100	88	66	**86 (a)**	96
Hyperactivity	mild	**none (a)**	none	none	mild	**none (a)**	none	none	none	none

(a): 1 standard deviation difference after training
(b): 2 standard deviation difference after training
(c): 3 standard deviation difference after training
(d): 4 standard deviation difference after training
(e): 5 standard deviation difference after training
(f): 6 standard deviation difference after training
(g): 7 standard deviation difference after training
(h): 8 standard deviation difference after training

TABLE 13. Eyes-Closed Absolute Power: Significant Changes After Training for All Five Cases.

	Delta	Theta	Alpha	Beta
Frontal	m*	m*/m*/−s*	**m**/**d**/s**	m**/**d**/r*
Central	m*/−r*	**m**/**d**/−s*	**m**/**d**/s*	m*/**d**/q*
Posterior	m*	**m**/**d**/−s*	**m**/**d**/**s**	m**/**d**/s**

m: M.F.
d: D.S.
r: R.M.
q: R.Q.
s: S.M.
Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value <0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 14. Eyes-Closed Relative Power: Significant Changes After Training for All Five Cases.

	Delta	Theta	Alpha	Beta
Frontal	−r*	−s	**m/d/s**	d*
Central	−**d/-r**	−s	**m**/**d**/	**d**
Posterior	−**d/-r**	−s	**m**/**d**/s*	−m**/**d**

m: M.F.
d: D.S.
r: R.M.
q: R.Q.
s: S.M.
Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value <0.001
Minus (−) sign: increase after training
No sign: decrease after training

shared with her the same EEG changes after training in direction, topography and frequency. D. S. also showed a significant increase in delta relative power eyes-closed. S. M., who had similar age, same area of brain injury, but different gender as M. F. and D.S., shared with them the same EEG changes after training in direction, topography and frequency. S. M. also recorded a significant increase in theta relative power eyes-closed. R. M., who had the most serious accident affecting the right hemisphere, portrayed the most significant changes in the psychometrics, but among the least significant changes in the EEG. His most significant change was the increased delta relative power eyes-closed. R. Q., the youngest participant (in her 20s), an undergraduate student, with right hemisphere damage showed no significant EEG changes at all, but showed the most significant changes compared to the other four cases in

TABLE 15. Eyes-Open Absolute Power: Significant Changes After Training for All Five Cases.

	Delta	Theta	Alpha	Beta
Frontal	**m**	r*		−**m**/−r*/q*
Central	m*	q*	d*	−m*/d*
Posterior		−s*		

m: M.F.
d: D.S.
r: R.M.
q: R.Q.
s: S.M.
Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value <0.001
Minus (−) sign: increase after training
No sign: decrease after training

TABLE 16. Eyes-Open Relative Power: Significant Changes After Training for All Five Cases.

	Delta	Theta	Alpha	Beta
Frontal	**m**/r*	r*		−**m**
Central	**m**			−m*
Posterior	m*	−s*		

m: M.F.
d: D.S.
r: R.M.
q: R.Q.
s: S.M.
Bold: p-value < 0.002 and significant after correction for multiple comparisons
*: p-value < 0.01
**: p-value <0.001
Minus (−) sign: increase after training
No sign: decrease after training

the psychometrics. Sustained and alternating attention improvement seemed to be more prevalent in the R. M. and R. Q. cases, whose accidents occurred on the right hemisphere.

One point of interest was the similarity in the EEG changes after training among M. F., D. S., and S. M (Figures 2, 3 and 4, respectively). All of them were similar in age (in their 40s), and their area of accident was the left hemisphere (the other two case studies were right hemisphere). M. F. and D. S. were also of the same gender (females) and shared the most common EEG changes after training. These common EEG changes after training for these three cases occurred mainly in the eyes-closed absolute power, in theta, alpha and beta, and in the eyes-closed relative power in alpha and posterior beta. An-

FIGURE 2. M. F. Eyes-closed absolute power.

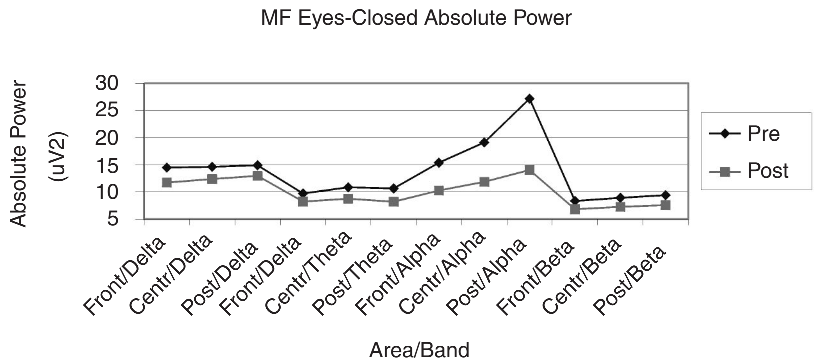
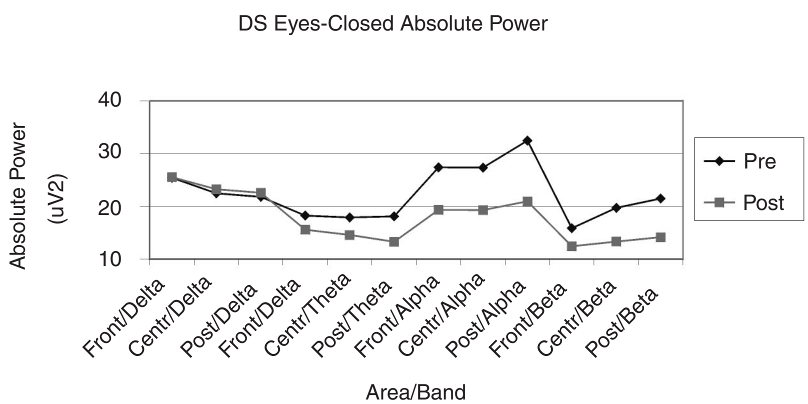


FIGURE 3. D. S. Eyes-closed absolute power.

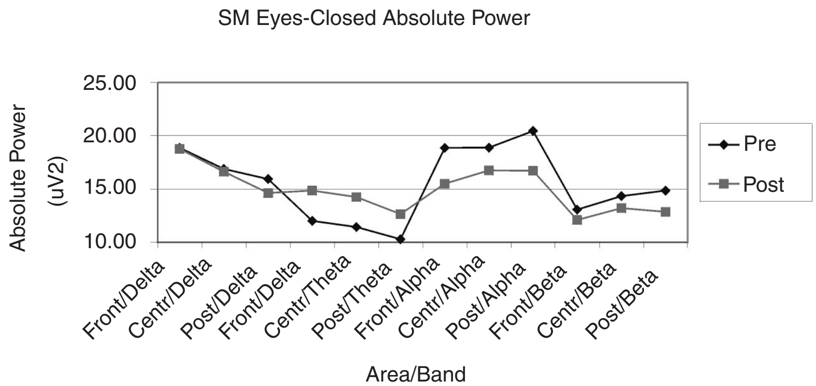


other aspect of similarity was between R. M. and S. M. (the two males in the study) who showed an increase in delta and theta in eyes-closed absolute and relative power, respectively.

It looks like the area of brain injury, age, gender and time of injury have some interaction with the EEG results, but less with the psychometrics. The person with the most significant changes in EEG after training was the person whose injury was the most recent. For the other participants, who had their accidents more than one and a half years ago, time did not seem to influence their rate of improvement.

According to the self-reporting questionnaires, the changes in different cognitive skills reported to have taken place after training did not coincide with the responses on the psychometrics. Moreover, the amount of significant

FIGURE 4. S. M. Eyes-closed absolute power.



EEG changes for each participant did not seem to be correlated with the amount of significant changes on his/her psychometric results. Two examples are M. F., who had the most prominent EEG changes but the least psychometric changes, and R. M., who had the most prominent psychometric changes but among the least EEG changes.

The hypothesis that the low frequencies, delta and theta, would decrease after training, was partially supported since there were some mixed results. The two males, R. M. and S. M., contradicted the hypothesis by showing an increase after training. As far as beta is concerned, the hypothesis that it would increase after training was again partially supported, since there was a significant decrease in eyes-closed absolute power while in the three remaining conditions there were mixed results. Only M. F., the participant who had her accident the most recently, showed a consistent increase in beta in all four conditions, except in eyes-closed absolute power.

The decrease in alpha in the left hemisphere injured participants, in the eyes-closed condition and less in the eyes-open, was the most important finding of the research. This was even more obvious when the right versus the left hemisphere cases were averaged and compared together (Figures 5, 6 and 7). This decrease in alpha was much less prevalent in the right hemisphere cases. What is obvious looking at Figure 1 is that all three types of attention coincide in the right frontal area. A hypothesis which could be made is that for left hemisphere injured people, the right hemisphere is still intact and thus they are still able to use it and train their attention skills. This is not the case, however, with the right hemisphere injured patients who do not have the opportunity to train their right brain area.

Frontal and posterior alpha and posterior beta in eyes-closed absolute power, as well as frontal alpha in eyes-closed relative power, constituted the most prevalent EEG changes (decreases) after training. It seems that in gen-

FIGURE 5. All 5 cases: Eyes-closed absolute power.

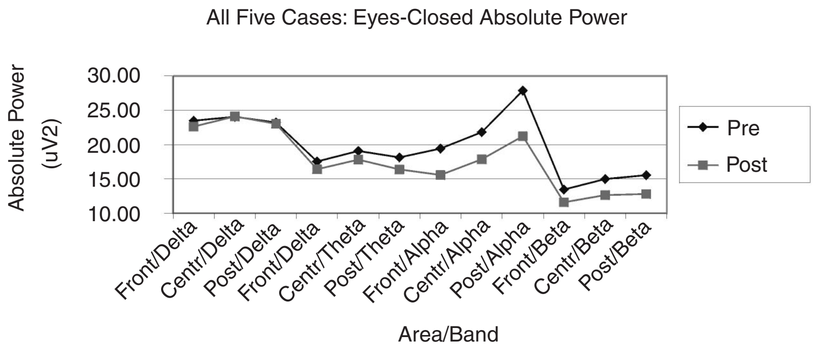
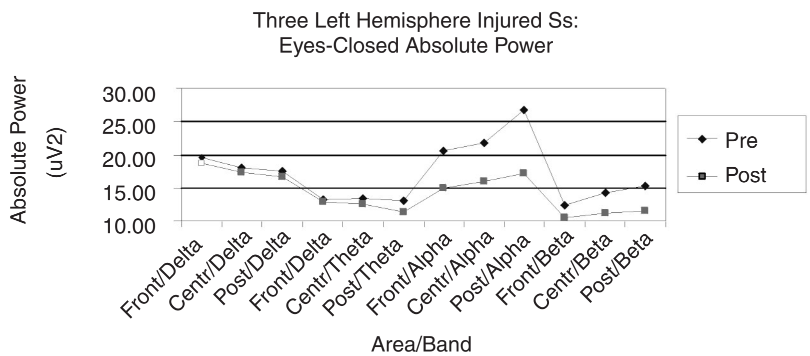


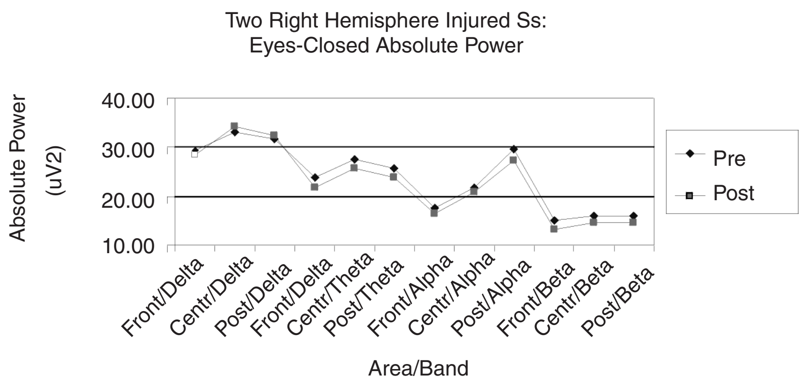
FIGURE 6. Left-hemisphere cases: Eyes-closed absolute power.



eral, eyes-closed more than eyes-open and mostly absolute rather than relative power gave the most significant results.

The fact that alpha frequency decreased after training coincides with Chabot's and Serfontein's study (1996) which identified that in children with attention problems QEEG abnormalities involve increased alpha power greatest in frontal regions. Logically then, when attention problems diminish, alpha decreases. These results coincide also with the study conducted by Jackson and Eberly (1982) that trained five mentally challenged adults, aged 22 to 29, to suppress alpha amplitude. The resulting attenuation in alpha was correlated with improvement in attention skills. The decreased alpha after training in frontal as well as in posterior regions coincides with the improvement in the attention abilities of the participants, shown through the psychometrics. According to the literature in the case of sustained attention, it has been noted that prefrontal and parietal areas are frequently engaged, while in the case of selec-

FIGURE 7. Right hemisphere cases: Eyes-closed absolute power.



tive attention, increased activity in posterior regions is involved (Lewin et al., 1996; Pardo et al., 1991; Haxby et al., 1994). Carlson (2001) has also cited numerous studies regarding the role of prefrontal cortex in attentional modulation. Moreover, the fact that improvement in attention skills are followed by changes on EEG, not just in the frontal areas, but also in the central and posterior ones may be explained by the neuropsychological theories of attentional processing by Mesulam (1981). This work considered the role of the reticular activating system and the cingulate gyrus in the regulation of information to be attended to, the posterior parietal lobe system in focusing conscious attention, and the frontal lobes in directing attentional resources.

Delta and theta frequencies are more prevalent in drowsy conditions while beta frequency is prevalent in more aroused, highly cognitive conditions. A common protocol for the improvement of attention deficit disorder in EEG biofeedback is the reduction of theta or delta frequencies and the increase of beta frequency. In this project it was expected that cognitive rehabilitation, through a software program designed to improve attention, concentration and memory skills, could achieve this improvement using the same brain wave patterns as the one achieved through operant conditioning technique (i.e., EEG biofeedback) when used to improve concentration and attention.

However, in this project, even though the psychometrics showed an improvement in attention for all participants, the EEG changes that followed, though significant, were only partially the ones expected. Only the reduction in alpha frequency was consistent with the hypothesis in most cases. White (2001) finds increased frontal alpha to be the most prominent difference between adults with ADD and the non-clinical population.

The decrease in alpha frequency after implementation of the cognitive rehabilitation as well as the other significant QEEG results constitute interesting findings. A larger sample size is needed in order to corroborate these results.

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