EEG Spectral Power and Coherence: Differentiating Effects of Spatial–Specific Neuro-Operant Learning (SSNOL) Utilizing LORETA Neurofeedback Training in the Anterior Cingulate and Bilateral Dorsolateral Prefrontal Cortices

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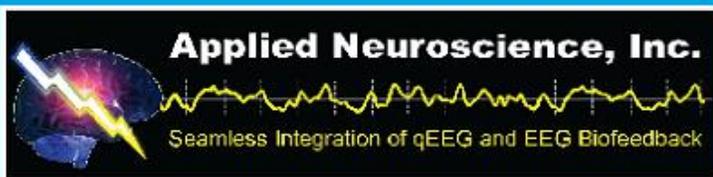Published online: 08 Sep 2008.

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EEG Spectral Power and Coherence: Differentiating Effects of Spatial–Specific Neuro-Operant Learning (SSNOL) Utilizing LORETA Neurofeedback Training in the Anterior Cingulate and Bilateral Dorsolateral Prefrontal Cortices

Rex Cannon, MA
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ABSTRACT. *Introduction.* This study investigated differences in topographical spectral power and coherence resulting from Spatial-Specific Neuro-Operant Learning utilizing low-resolution electromagnetic tomographic (LORETA) neurofeedback in three regions of the cortex: the cognitive division of anterior cingulate (AC, BA 32) and right (RPFC) and left (LPFC) dorsolateral prefrontal cortices (BA 8).

Method. This study was conducted with 14 nonclinical participants. All completed 20 sessions of LORETA neurofeedback in specific regions of the cortex in which they received visual and auditory reward for increasing 14 to 18 Hz activity in the region of training (ROT). We compared all training rounds for each ROT.

Results. There are significant effects resulting from training in each ROT in both spectral power and coherence.

Conclusions. Training in the AC appears to elicit activation patterns significantly different from training in both the RPFC and LPFC; similarly, the training in the AC and RPFC influence regions different than the LPFC. These patterns also appear in coherence. More important, the AC influences differentiation and integration effects significantly different from both prefrontal regions.

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INTRODUCTION

This work is part of an ongoing effort to determine the efficacy of spatial-specific neuro-operant learning (SSNOL) in cortical regions shown to be active in attentional, cognitive, affective, memory, and executive processes (Bench et al., 1993; Cannon, Lubar, Congedo, Thornton, & Wilson, 2005; Carr, 1992; Devinsky, Morrell, & Vogt, 1995; Fazio et al., 1992; Heyder, Suchan, & Daum, 2004; Kondo et al., 2003; Markela-Lerenc et al., 2004; Ortuño et al., 2001; Pardo, Pardo, Janer, & Raichle, 1990; Posner & Petersen, 1990) and to possibly uncover regions vital to a network of executive attention. In previous work, low-resolution electromagnetic tomographic (LORETA) neurofeedback (LNFB) was found to be an efficacious methodology for training individuals to increase 14 to 18 Hz activity in a seven-voxel cluster of neurons in the anterior cingulate gyrus (AC; Cannon et al., 2007; Cannon et al., 2006). We evaluated the cortical effects of this training in six other regions of the cortex; subsequently, we selected a five-voxel cluster of neurons within the right dorsolateral prefrontal cortex (RPFC) and a three-voxel cluster of neurons in the left dorsolateral prefrontal cortex (LPFC) for LNFB training to compare with the training in the AC, with the premise that training in each of the regions would elicit different effects in cortical pathways and that executive attention is moderated by the relationship between the AC and RPFC.

One prominent theory proposes that the AC detects the need for executive control and signals the PFC to execute the control (Markela-Lerenc et al., 2004); similarly, researchers propose that the AC is in effect a gating mechanism between the cortex and subcortical regions (Pizzagalli, Oakes, & Davidson, 2003). These two ideas are supported given that the AC receives inputs from regions involved in memory, emotion, reward, nociception, and autonomic functioning along with other subcortical nuclei (Bush & Posner, 2000). Persons with lesions to the frontal lobes or removal of frontal regions may continue to perform within 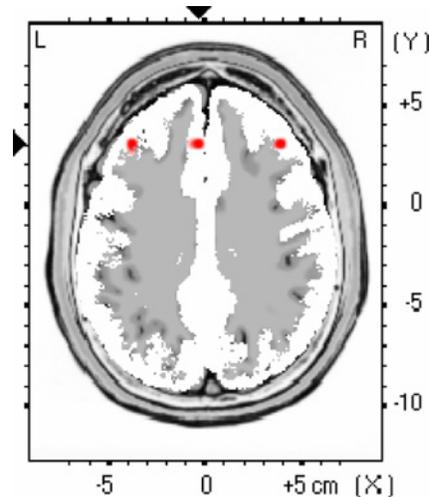normal range on standardized intelligence tests but also do better on perceptual or memory tasks than persons with left or right temporal lesions, and persons with frontal lobe lesions are responsive to external stimuli but are distracted by them and experience difficulty utilizing these stimuli as cues for behavioral regulation (Milner, 1995). If we were to combine these theoretical concepts, it is reasonable to infer that the AC maintains a presidential role in executive attention; however, the attentive processes are governed in the right hemisphere, mainly in the RPFC, whereas the LPFC is more the governing force of working memory and reclamation memory processes, given that many of the regions active during working memory and episodic retrieval are also active during other types of tasks including visual attention (Cabeza et al., 2003; Cabeza & Nyberg, 2000). The AC is divided into cognitive and affective divisions, and research indicates that persons with attention-deficit hyperactivity disorder (ADHD) fail to activate the cognitive division during Stroop interference tasks. Similarly, research suggests the cognitive division of the AC is activated during divided attention tasks and the affective division is decreased in activation during cognitive tasks and vice versa (Bench et al., 1993; Bush, Luu, & Posner, 2000). Thus, we would conclude that there is an underlying network involving DLPFC, AC, and numerous other regions in which the AC deciphers, directs, and blends memory and attention to form and maintain executive attention (Cannon, Congedo, & Lubar, 2008).

Neurofeedback techniques have been utilized in clinical and research settings for treatment of neurological and psychiatric disorders (Lubar, 1997; Lubar & Lubar, 1999; Peniston & Kulkosky, 1989, 1990, 1991; Sterman, 2000; Sterman & Lantz, 2001) and continue to be a focal point for development of possible treatments for psychological disorders as well as discovery of functional processes. For complete reviews of NFB and quantitative electroencephalography (EEG); see Kaiser (2006) and Hammond (2006). A recent fMRI study reports neurofeedback techniques initiating blood oxygenated level dependent changes in the AC, caudate and substantia nigra in children

with ADHD (Levesque, Beauregard, & Mensour, 2006). LNFB is a recent advancement in the neurofeedback method (Congedo, 2003; Congedo, Lubar, & Joffe, 2004), offering the possibility to influence regions deep in the medial temporal lobes, limbic regions, and regions at the base of the brain, such as the insular cortex, parahippocampal, lingual, fusiform, and orbital-frontal gyri, to which the contribution to surface EEG is poor. LORETA (Pascual-Marqui, 1995, 1999; Pascual-Marqui, Esslen, Kochi, & Lehmann, 2002a, 2002b; Pascual-Marqui, Michel, & Lehmann, 1994) is an inverse solution estimating cortical electric current density originating from scalp measurements, utilizing realistic electrode coordinates (Towle et al., 1993) for a three-concentric-shell spherical head model co-registered on a standardized MRI atlas (Talairach & Tournoux, 1988) allowing a reasonable approximation of anatomical labeling within the neo-cortical volume, including the ACC and hippocampus (Lancaster et al., 1997; Lancaster et al., 2000).

In this study, we used the three-shell concentric spherical head model implementation made available from the Key Institute for Brain-Mind Research, Zurich, Switzerland. In this implementation, the current density was mapped for 2394 voxels of dimension $7 \times 7 \times 7$ mm covering the entire neocortex plus the AC and hippocampus. In conventional neurofeedback, EEG activity is recorded at a particular scalp location. The physiological measurements are extrapolated from the signal and converted into auditory stimuli or visual objects that animatedly covary with the magnitude of a specified frequency or frequency bandpass region. Similarly, LNFB correlates the physiological signal with a continuous feedback signal; however, the physiological signal is defined as the current density in a specified region of training (ROT). This allows the continuous feedback signal to become a function of the intracranial current density and to covary with the intracranial current density. The advantage over traditional neurofeedback is increased specificity of the training. Figure 1 shows the ROT for this study. It is important and necessary to keep in mind that when we refer

FIGURE 1. Horizontal view of the brain at z plane = 29 showing each of the ROT for this study.

to each of the respective ROT (i.e., AC, RPFC, and LPFC), we are referring to regions delimited by a number of discrete brain volume elements (voxels) as defined by the standard head model we employed. Thus, the ROT (Table 1) may be displaced as much as 3 to 4 cm from the aimed ROT. The resolution of this issue is the topic of a recent investigation (Congedo, 2006).

METHOD

Participants

This study was accomplished with 14 participants, 6 male and 8 female nonclinical students, with a mean age 21.21 ($SD = 2.39$, range = 18–26). Thirteen of the participants were right handed and 1 was ambidextrous. All participants read, signed, and agreed to an informed consent to protocol approved by the University of Tennessee Institutional Review Board. Participants received extra course credit for participating in this study. Exclusionary criteria for participation included previous head trauma, history of seizures, recent drug or alcohol use, and any previous psychiatric diagnosis.

Participants were prepared for EEG recording using a measure of the distance between the nasion and inion to determine

TABLE 1. Regions of neurofeedback training.

Region of Training	Talairach (Voxel) X, Y, Z Coordinates	Brodmann Area Anatomical Label
AC	(−3 31 22) (−3 24 29) (−10 31 29) (−3 31 29) (4 31 29) (−3 38 29) (−3 31 36)	BA 32, anterior cingulate, limbic lobe.
LPFC	(−38 31 36) (−38 31 43) (−31 31 43)	BA 8, middle frontal gyrus, frontal lobe
RPFC	(39 31 36) (39 24 36) (39 24 43) (32 31 43) (39 31 43)	BA 8, middle frontal gyrus, frontal lobe

Note. AC-LPFC = left dorsolateral prefrontal cortex; RPFC = right dorsolateral prefrontal cortex.

the appropriate cap size for recording (Electrocap, Inc; Blom & Anneveldt, 1982). The head was measured and marked prior to each session to maintain consistency. The ears and forehead were cleaned for recording with a mild abrasive gel to remove any oil and dirt from the skin. After fitting the caps, each electrode site was injected with electrogel and prepared so that impedances between individual electrodes and each ear were less than 6 KΩ. The LNFB training was conducted using the 19-leads standard international 10/20 system (FP1, FP2, F3, F4, Fz, F7, F8, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, and O2). Data were collected and stored with a band pass set at 0.5–64.0 Hz at a rate of 256 samples per second. All recordings and sessions were carried out in a comfortably lit, sound-attenuated room in the Neuropsychology and Brain Research Laboratory at the University of Tennessee, Knoxville. Lighting and temperature were held constant for the duration of the experiment. Each session required approximately 60 min to complete.

Neurofeedback Protocol

Twenty training sessions composed of four 4-min rounds were conducted three times per week. Following standard protocol (Cannon et al., 2007; Congedo et al., 2004), we designed to improve attentional processes by training individuals to increase 14 to 18 Hz (low-beta) power activity in one of three ROTs: a three-voxel cluster of neurons in the left dorsolateral prefrontal cortex and a five voxel cluster of neurons in the right dorsolateral prefrontal cortex (see Table 1) and compared them to a seven-voxel cluster of neurons in the cognitive division of the AC (Bush & Posner, 2000; Cannon et al., 2007; Devinsky et al., 1995). In a preliminary session, the participants were instructed to control tongue and eye movements; eye-blinks; and muscle activity from forehead, neck, and jaws. This enabled the participants to minimize the production of extra-cranial artifacts (Electromyogram, Electrooculogram, etc.) during the sessions. At the end of the preliminary session, they were informed of the inhibitory and reward aspects of the training. Standardized thresholds were then set and maintained for each participant. For the standardized protocol used, see Tables 1 and 2.

The participants were provided visual and auditory feedback, and points were achieved when they were able to simultaneously maintain all conditions specified in Table 2 (A *and*

TABLE 2. The inhibit and reward parameters for LORETA neurofeedback training.

(A)	Electro-oculogram < 15.0 (Microvolts) Decrease 1–3 Hz activity in a linear combination of six frontal channels, FP1, FP2, F3, F4, F7, F8	SUPPRESS
(B)	Electromyogram < 6.0 (Microvolts) Decrease 35–55 Hz activity in a linear combination of six temporal and occipital channels, T3, T4, T5, T6, O1, and O2	SUPPRESS
(C)	Region of Interest (ROI) > 5.0 (Current Density) Increase current source density (14–18 Hz) in the ROI.	ENHANCE

B *and* C) for 0.75 sec achieved one point. Following Congedo et al. (2004) we made use of both auditory and visual feedback. The auditory stimuli provided both positive and negative reinforcement—an unpleasant splat sound when the conditions were not met and a pleasant tone when they were. Similarly, the visual stimuli were activated when the criteria were being met (e.g., a car or a spaceship driving faster and straighter). Alternatively, a slower car driving in the wrong lane or the spaceship flying slow and crooked occurred when the criteria were not being met. The score for meeting the criteria was also seen by the participants in a small window of the game screen.

Data Collection

Three-minute eyes-opened and eyes-closed baselines were collected before and after the neurofeedback training for pre–post brain imaging comparison. Likewise, three-minute eyes-opened baseline recordings were collected before and after each session. In contrast with studies utilizing traditional neurofeedback, the whole-head EEG data were continuously stored during the sessions. In addition, the participants in this study provided a written record of their experience, strategies, and mental processes employed to obtain points for each session during this training. The data were collected utilizing the following frequency band-pass regions: Delta (0.5–3.5 Hz), Theta (3.5–8.0 Hz), Alpha 1 (8.0–10.0 Hz), Alpha 2 (10.0–12.0 Hz), Beta (12.0–32.0 Hz), and trained frequency (TF: 14–18 Hz).

Data Analysis

The obtained data were rigorously artifact rejected, with extra attention given to the frontal and temporal leads. All episodic eye blinks, eye movements, teeth clenching, jaw tension, body movements, and possible electrocardiogram were removed from the EEG stream. We then imported the artifacted, Lexicor files into NeuroGuide (Applied Neuroscience) version 2.4 for group analysis. We compared the training rounds for each

ROT between groups. We conducted an analysis of variance for the obtained pre- and post psychometric scores controlling for participant as a random factor. The statistical procedures in NeuroGuide utilize the following parameters. The EEG values are computed to z scores, the FFT parameters are 2 s epochs at a sample rate of 128 samples per second or 256 digital time points at a frequency range from 0.5 to 40 Hz with a resolution of 0.5 Hz using a cosine taper window to minimize leakage. Each 2-sec FFT consists of 81 rows (frequencies 0–40 Hz) by 19 columns (electrode locations) that equates to a 1,539 element cross-spectral matrix for each participant. To minimize the effects of windowing, the FFT (Sterman & Kaiser, 2001) an EEG sliding average of the cross-spectral matrix is computed for each normal participant, editing the EEG by advancing in 64-point steps. The FFT is recombined with the 64-point sliding window of 256-point FFT cross-spectrum for the entire EEG record. Each of the 81 frequencies for each 19 channels is $\log_{10}$ transformed to better approximate a normal distribution. The total number of 2-sec windows is entered into the analysis of variance, t test, and used to calculate the degrees of freedom for a given statistical test. The mean, variance, standard deviation, sum of squares, and squared sum of the real (cosine) and imaginary (sine) coefficients of the cross-spectral matrix are computed across the sliding average of edited EEG for all 19 leads for the total number of 81 and 1,539 log transformed elements for each participant. NeuroGuide utilizes independent t tests, assuming population variances are not equal (Winer, 1962).

Psychometric Pretraining Measures

We administered the Weschler Adult Intelligence Scale–Third Edition (WAIS–III) for a pretraining measure. Table 3 contains the pretesting results for each of the three groups. The Working Memory Index (WMI) score consists of the sum of scaled scores in the Arithmetic, Digit Span, and Letter-Number Sequencing subtests. The Processing Speed Index (PSI) score consists of the sum of scaled scores in Digit-symbol Coding (CD)

TABLE 3. The group average and standard deviation for pretraining Weschler Adult Intelligence Scale–Third Edition Working Memory Index (WMI), Processing Speed Index (PSI), and Full Scale Intelligence Quotient (FSIQ) scores.

Group	WMI	SD	PSI	SD	FSIQ	SD
AC	117.5	16.44	106.62	11.13	124.25	6.79
RPFC	96.67	8.33	114.00	9.85	111.33	1.53
LPFC	97.67	4.04	111.33	2.52	106.00	8.72

Note. AC = anterior cingulate gyrus; RPFC = right dorsolateral prefrontal cortex; LPFC = left dorsolateral prefrontal cortex.

and Symbol Search (SS). We used these combinations of subtest scores following the recommendation of Sattler (2001).

RESULTS

Absolute Power Figure Descriptions

The topographical maps calculated in Neuroguide show the probability for the obtained *t* value for the comparison between groups. The red in the images indicates probabilities toward zero, whereas the blue indicates probabilities toward or above .05. In these images (A) shows the frequency bands in 1 Hz increments, 1 to 20 Hz from top to bottom and left to right, whereas (B) shows the frequency bands in 1 Hz increments, 21 to 40 Hz from top to bottom and left to right. Figure 2a shows the results for the comparison of all training rounds in the AC compared to LPFC. Training in the AC appears to elicit global increases in absolute power as compared to the LPFC. There are significant increases in theta and alpha frequencies globally and specific to superior frontal regions. The trained frequency shows increased power specific to frontal and parietal regions; however, centro-parietal regions show no increase. Figure 2b shows the higher beta frequencies increase primarily involving parieto-temporal-frontal regions in the higher beta range.

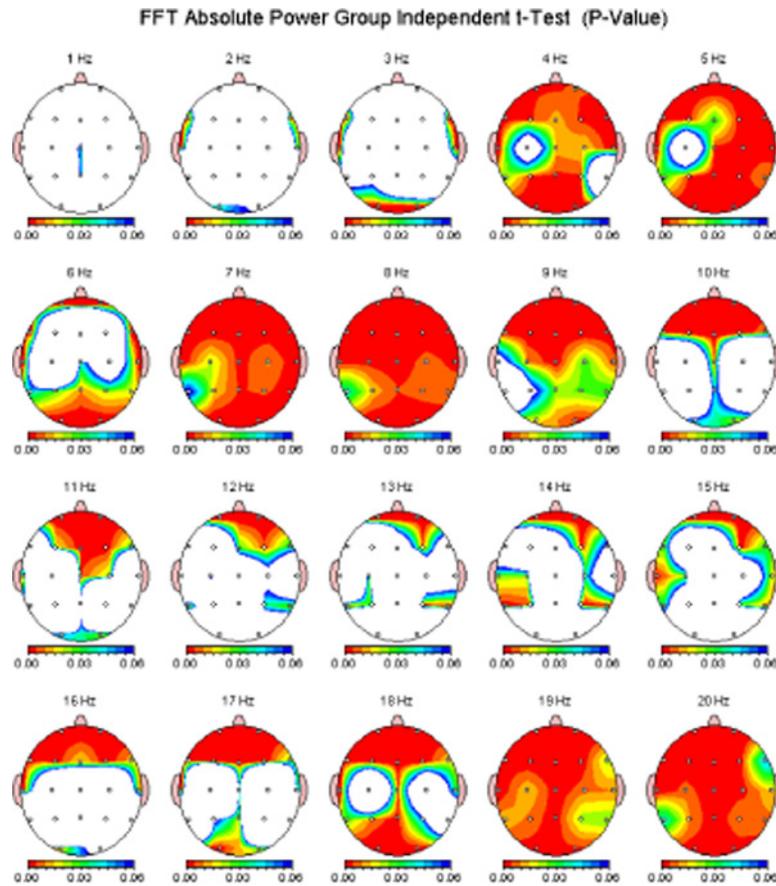Figure 3a shows the results for the comparison for all training rounds in the AC compared to RPFC. Training in the AC shows increased low delta power as compared to the RPFC and increases in theta power in specific regions, mainly in temporal and central midline regions. The low alpha frequency shows increased power in 8 Hz in frontal midline regions, whereas the higher alpha frequency shows increased power over the entire frontal region. The trained frequency shows increased power in left frontal and centro-parietal regions. Figure 3b shows significant differences between the AC and RPFC that appear specific to central midline, parietal, and right frontal regions.

Figure 4a shows the results for the comparison for all training rounds in RPFC compared to LPFC. There is decreased power in the left frontal region. There is increased power globally in the 7, 8, and 9 Hz bands similar to the results for the AC as compared to LPFC. The high alpha increases occur in frontal, central midline, and left parietal regions. The trained frequency shows increased power in superior frontal regions and central-parietal regions. Figure 4b shows the results for the comparison of 21 to 40 Hz. The beta increases occur in frontal regions and the inverse U often associated with attentional processes is pronounced in the 21 to 23 Hz, with 33 to 40 Hz increases occurring over the entire frontal cortices.

Coherence Figure Descriptions

Neuroguide computed the coherence values for interhemispheric electrode relationships and the output for analysis consisted of topographical maps with the probability of the obtained *t* value for the comparison. The blue indicates decreased coherence (*differentiation effect*), whereas the red indicates increased coherence (*integration effect*). The size of the line dictates the probability of the obtained *t* value. The thinner line represents α at less than or equal to .05. The middle size line indicates α less than or equal to .025, and the larger line indicates values with α less than or equal to .010.

FIGURE 2. Comparison between LNFB training 14–18 Hz in AC and LPFC: A = 1–20 Hz; B = 21–40 Hz.
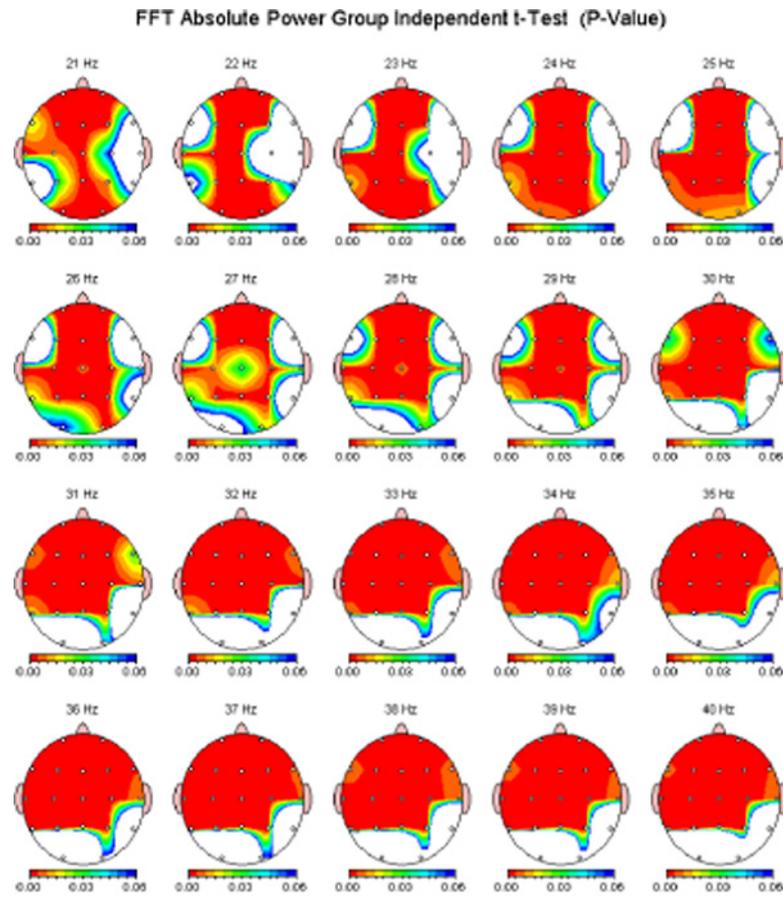

(a)

In all figures, the interhemispheric results are shown within the figure from top left to right, for the delta, theta, alpha, and beta frequencies and bottom left to right, high beta, beta 1, beta 2 and beta 3 frequencies respectively. Figure 5 (a, b, and c) shows the results for the comparisons between the regions of training for all training rounds.

Figure 5a shows the interhemispheric results for all training rounds in the AC compared to the LPFC. There is a global differentiation effect for the delta, theta, and alpha frequencies, whereas the beta frequencies show an integration effect specific to anterior regions and differentiation effects in the posterior frontal lobes and the posterior regions in general. Figure 5b shows the result for all rounds of training in the AC compared to the RPFC. The differentiation effect appears less global in this comparison for the theta and alpha frequencies, whereas the delta frequency does appear to involve a larger region of the cortex. The theta and alpha frequencies appear to integrate in frontal, central and posterior regions, whereas differentiation occurs in temporal and occipital regions. The beta frequency shows differentiation in anterior regions and with high beta effects globally. The beta 1 and beta 2 frequencies appear to integrate central, temporal, and posterior regions similar to the theta and alpha frequencies. Figure 5c shows the coherence results for all training rounds in the RPFC compared to LPFC. The results are very similar to the comparison

FIGURE 2 (continued)

FFT Absolute Power Group Independent t-Test (P-Value)
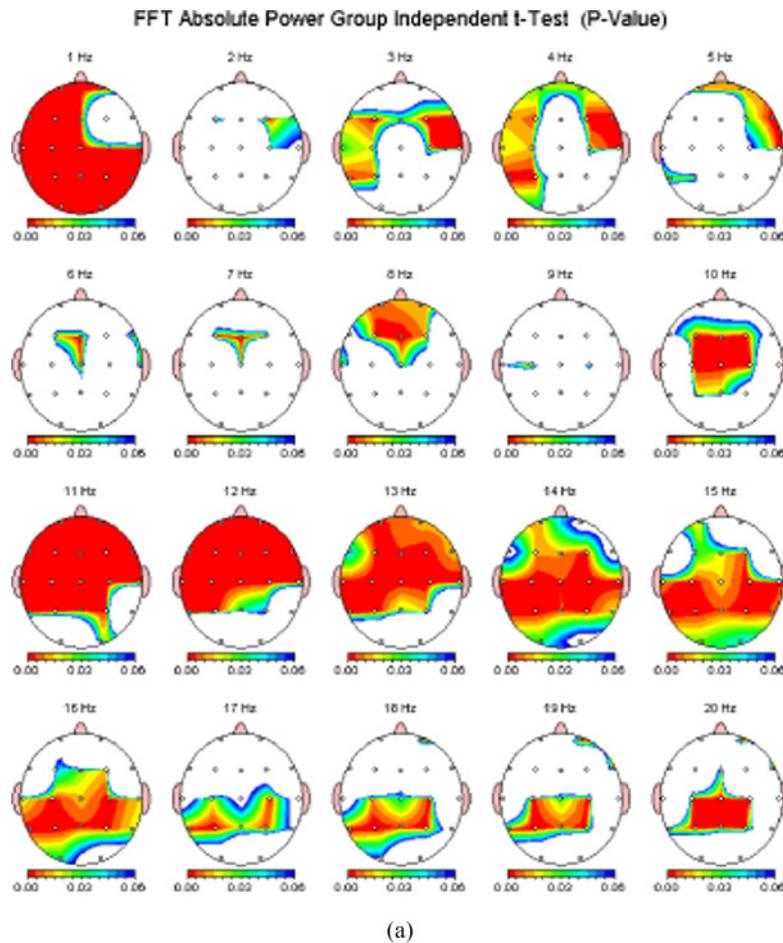

(b)

between the AC and LPFC with the exception of the beta frequency. The delta, theta, and alpha frequencies show a differentiation effect globally with integration occurring in the temporal and parietal regions. The beta frequencies appear to integrate more of the frontal regions as a result of training in the RPFC as compared to both LPFC and AC, whereas the increased integration effect in the central–posterior regions appears more central in this comparison than in the AC.

Psychometric Testing

The postpsychometric measures show significant increases in both WMI and PSI scores for all groups. The data indicate a mean increase of 10 points as a result of LNFB training. Figure 6a shows the results for the mean increase in both index scores as a result of LNFB training. The AC group was 1 point higher than both the left and right. This is not entirely unexpected because this group had higher pretesting scores. In psychometric testing, there is the consideration of practice effect and test–retest reliability. For the WAIS–III, the test–retest gains and losses for the age group 16 to 29 are reported as Coding $(+1.2)$, $p < .001$; Arithmetic $(+0.6)$, $p < .001$; Digit Span $(+0.5)$, $p < .05$; Symbol Search $(+1.0)$, $p < .001$; Letter-Number Sequencing $(+0.1)$, $p > .05$; Working Memory Index $(+2.9)$, $p < .01$; Processing Speed Index
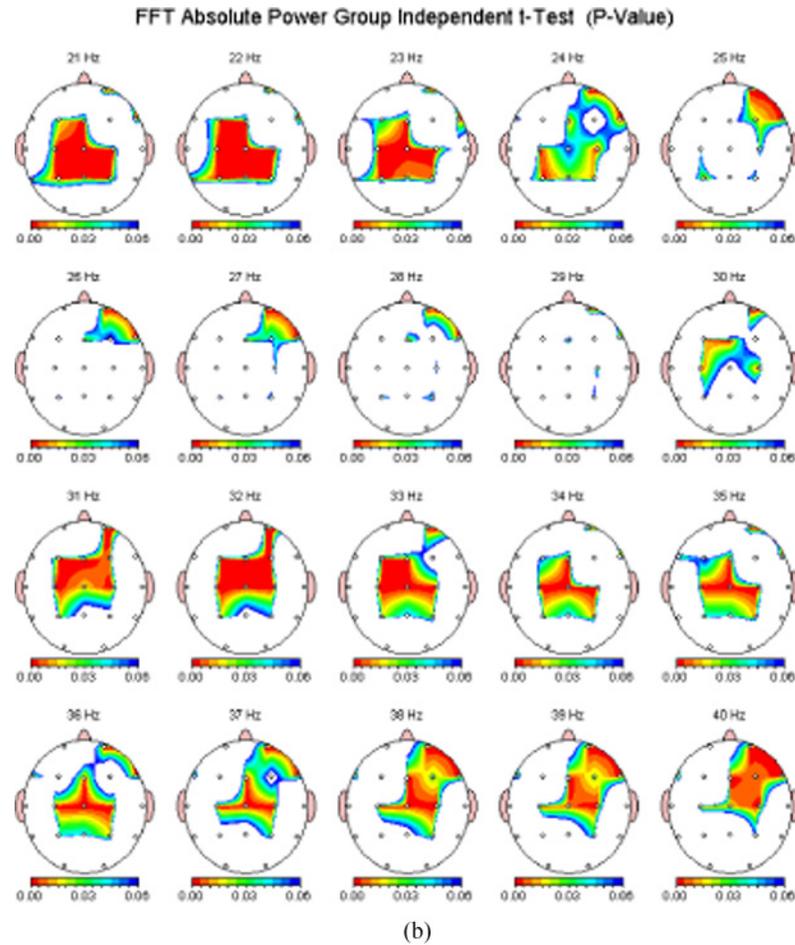
FIGURE 3. Comparison between LNFB training 14–18 Hz in AC and RPFC: A = 1–20 Hz; B = 21–40 Hz.

(a)

(+6.0), $p < .001$ (Sattler, 2001). The average gains in test–retest are measured for a 6-month period. The highest test increase for this practice effect occurs in Perceptual Organization (2.7 to 7.4) and the smallest increase occurs in Working Memory (1.3 to 3.1) in the Full Scale test–retest administration (Sattler, 2001). The Spearman rank-order correlation for our participant age group for test–retest gains at 6 months is .56, which suggests that practice effects are likely to be smaller for the most reliable subtests (Sattler, 2001). For all groups our test–retest period was approximately 4 months, allowing the possibility that the practice effect would increase to some degree; however, we consider the magnitude of change in the WMI and PSI scores considerably higher than might be accounted for by this effect alone. The differences between the pre- and postmeasure scores are significantly higher in our group than in the test–retest group. Except in the Arithmetic subtest, there was no change in the mean score. The Letter-Number sequencing scores for our group were higher than the test–retest group and changed in the desired direction but not at significant levels. Figure 6b shows the individual postsubtest scores for each ROT group. This graph shows the AC influenced higher subtest scores, except in the SS and CD subtests, whereas the LPFC and RPFC show higher influence on SS. These scores and their correlations with the regions of interest are the topic of further analysis for a future work.

FIGURE 3 (continued)

FFT Absolute Power Group Independent t-Test (P-Value)
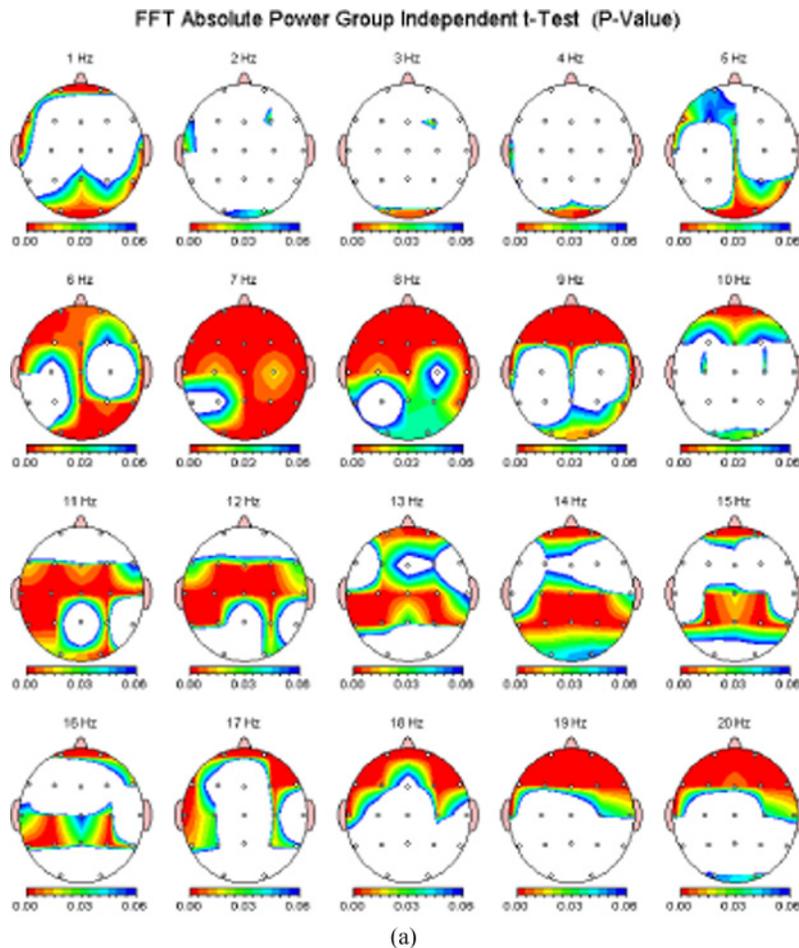

(b)

Subjective Reports

Figure 7 (a, b, and c) shows the results of the subjective reports provided by the participants at the end of each session. The reports are scaled according to the mental processes and strategies employed to obtain points during the training. The mental activities are as follows:

- WM = working memory: We consider this as using any type of mnemonic process to elicit activity in the specific region of interest, including mathematics, use of foreign language, declarative memory, and STM relating to memory of prior sessions in which they were successful.

- A = attentional processes: We consider this involving any attentive processing to internal and external stimuli.
- DAS = daily stressors: We consider this any report of thoughts to grades, tests, finances, or such outside stressors.
- V = visualization: We consider this visualization techniques, mental rotation, spatial organization, or imagery techniques.
- Ap = Appetitive thoughts: We consider this any focus given to sexual imagery, food, hunger, and thirst.
- DS = dissatisfaction with performance: We consider this thought processes directed toward dissatisfaction with the game, with their points, and with the inhibitory factors.

FIGURE 4. Coherence comparisons between ROT for LNFB training 14 to 18 Hz. A = AC compared to LPFC; B = AC compared to RPFC; C = RPFC compared to LPFC.

FFT Absolute Power Group Independent t-Test (P-Value)

(a)

- MV = mental verbalization: We consider this mental conversation with self, with the game, singing songs or swearing at the game.
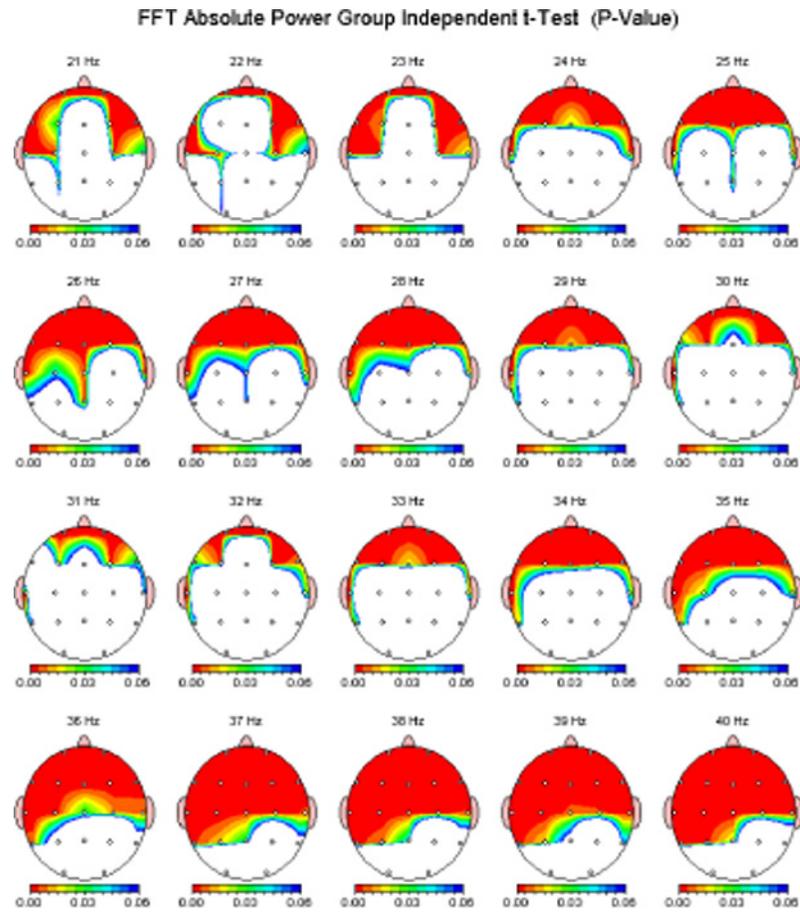
The AC participants reported a tendency toward working memory and attentional processes, with an emphasis with working memory. The LPFC participants report a tendency similar to the AC except the tendency is toward attentional processes. The RPFC participants report a tendency toward working memory processes, with an apparent increase in MV and V as opposed to the AC and LPFC. The subjective reports provided by the participants in this study provide a number of insights into the differences between hemispheric processing of the DLPFC and AC.

DISCUSSION

This is the first study to evaluate changes as a result of LNFB training between three discrete brain regions—namely, the dorsal anterior cingulate gyrus (BA 32), and the right and left dorsolateral prefrontal cortex (BA 8) and part of an ongoing effort to describe a network of executive attention. The regions of training in this study have shown to be active in fMRI and PET studies during working memory and cognitive tasks

FIGURE 4 (continued)

FFT Absolute Power Group Independent t-Test (P-Value)

(b)

(see Introduction) without clarity of the interactions between the AC and DLPFC. We discuss the coherence and absolute power differences in the following subsections.

Coherence

LNFB training of 14 to 18 Hz produces effects in delta frequency for each ROT, which is possibly related to the encoding of information relative to task; higher cognitive functioning is reported to involve slow synchronization of the delta or theta frequency over longer distances (Lubar, 1997), whereas faster frequency bands are reported to involve local neuronal populations (von Stein, Rappelsberger, Sarnthein, & Petsche, 1999). The comparison between the AC

and RPFC show the greatest difference in absolute power increase in the delta frequency. The AC shows patterns of increased activation in the delta frequency domain as a result of training the cluster of neurons within the AC. Of particular interest is the apparent concentration of delta to the anterior regions regardless of region trained except for contralateral communication between the ROT in lateral PFC and the posterior parietal regions.

The theta frequency shows differential effects as a result of training in each ROT for the AC and RPFC as compared to LPFC. The AC as compared to the RPFC shows specific increase patterns and expounds a lesser degree of difference for all regions; however, this activity may be more specific to functional encoding of

FIGURE 5. Coherence comparisons between ROT for LNFB training 14–18 Hz. A = AC compared to LPFC; B = AC compared to RPFC; C = RPFC compared to LPFC.
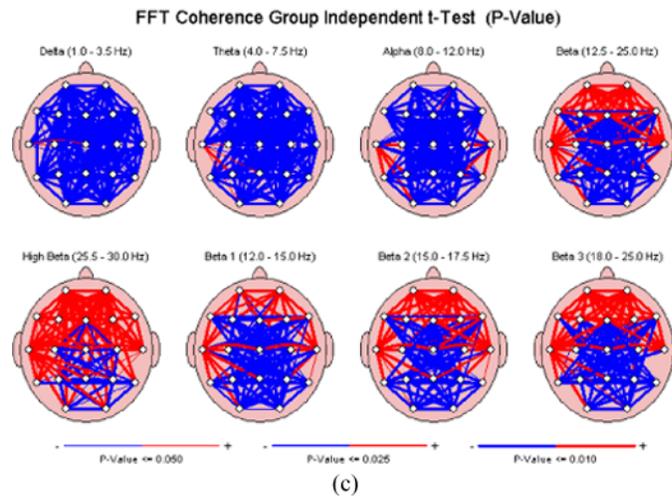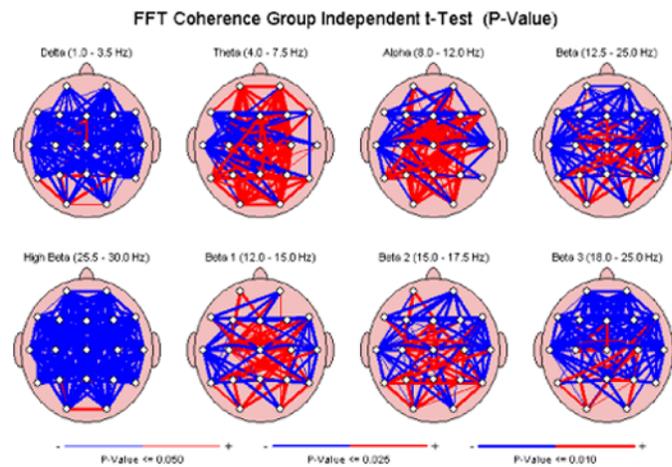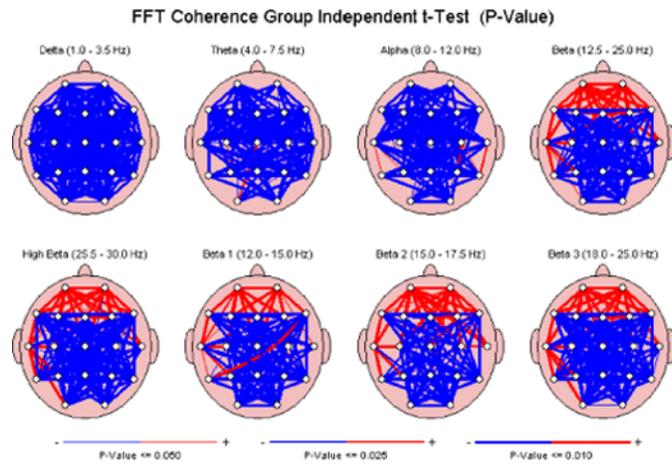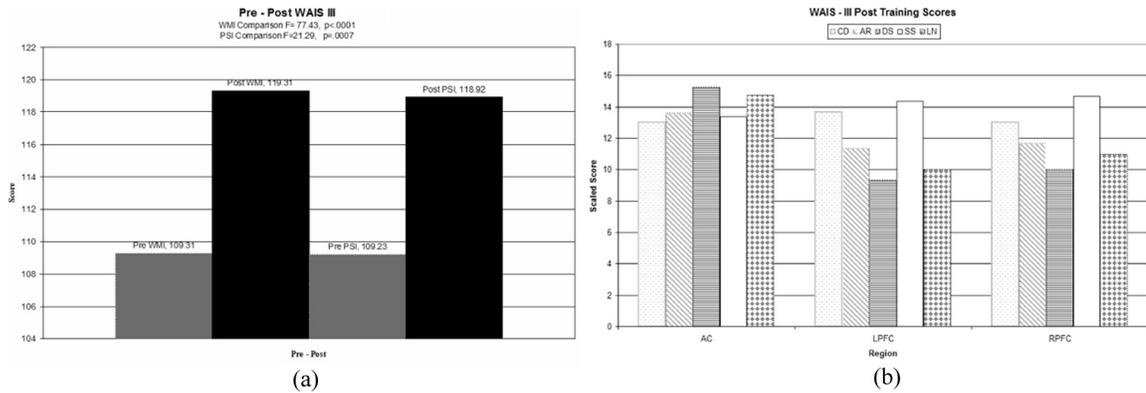
FIGURE 6. Post-psychometric results. A = mean increase for WMI and PSI scores resulting from LNFB training in each of the ROT for all groups. B = scaled scores for the individual subtests per region of training. Legend: CD = coding; AR = arithmetic; DS = digit span; SS = symbol search; LN = letter-number sequencing.
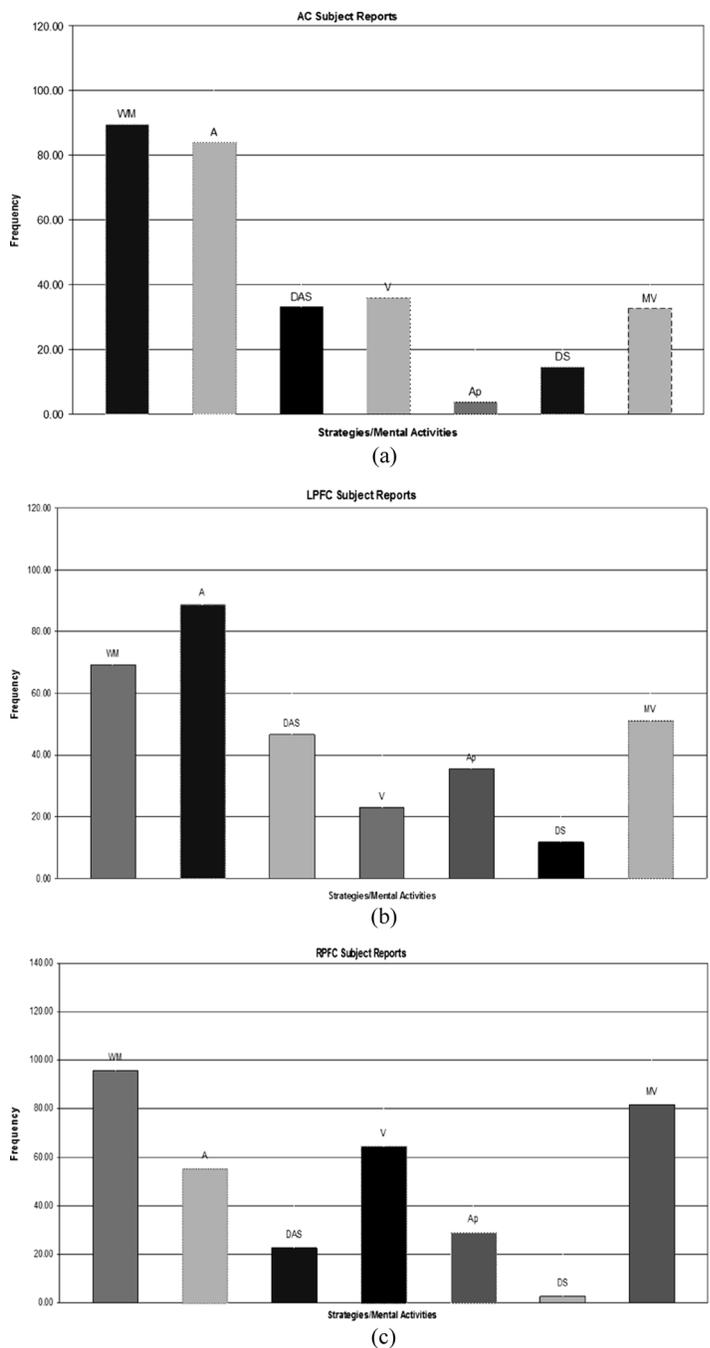

(a)

(b)

information from regions involved in spatial orientation, which is possibly attributed to the posterior regions being involved in the evaluation of visual and sensory information and encoding into memory, as the encoding of episodic (short-term) and working memory processes seem to be reflected by oscillations within the theta frequency band (4–8 Hz; Klimesch, Doppelmayr, Pachinger, & Ripper, 1997; Klimesch, Doppelmayr, Pachinger, & Russegger, 1997) within a thalamo-hippocampal-cortical system (Burgess & Gruzelier, 1997; Fell, Fernandez, Klaver, Elger, & Fries, 2003; Klimesch, Doppelmyr, Schimke, & Ripper, 1996). During encoding, the increase in theta is significantly larger for items that can later be remembered (Klimesch, Doppelmayr, Russegger, & Pachinger, 1996; Klimesch et al., 2001).

The alpha 1 frequency shows substantial differential effects as a result of LNFB training in each ROT. The training in the AC appears to increase communication between anterior and posterior regions of cingulate cortex and encoding processes with LPFC. The LPFC, on the other hand, may be more involved in the strengthening of encoding and mnemonic processes relative language, attention to physical state, and other sensory information. The RPFC shows similar patterns as the AC when compared to training in LPFC; however, the AC appears to initiate activity increase in more of the anterior regions than does the RPFC or LPFC. This offers evidence against the idea that the left and right PFC work in conjunction in memory processing. It may infer that the RPFC (at least this cluster of neurons) is directly associated to attentional monitoring along with the AC and parietal regions and is possibly an effect for visual and spatial encoding in conjunction with AC of attentional processes relating to the game and evaluation of thought processes needed to achieve the desired result. The alpha 2 frequency shows effects for positive associations in similar regions as alpha 1. This result is the possibly attributable to interactions between attention and working memory processes that is to say that the processing of external and internal stimuli requires an equal portion of attention from the right hemisphere. The alpha rhythm (8–12 Hz) is generated mainly by corticocortical and thalamocortical networks (Klimesch et al., 1997; Klimesch, Schimke, & Schwaiger, 1994; Steriade, Gloor, Llinas, Lopes da Silva, & Mesulam, 1990), and research suggests distinct roles for lower (8–10 Hz) and upper (10–12 Hz) alpha band activity in cognition. The lower band relates primarily to response readiness and attentional demands (Klimesch, Pfurtscheller, & Schimke, 1992) and plays only an indirect role in memory. By contrast, oscillations in the upper alpha band have been consistently observed during

FIGURE 7. Subjective reports of strategies and mental processes used during the LNFB training in each ROT. Contained in the figure from top to bottom are A = AC, B = LPFC and C = RPFC. Legend: WM = working memory; A = attention to self, relaxation, game or score on screen; DAS = daily stressors; V = visualization techniques; Ap = appetitive thoughts, i.e., hunger or sexual imagery; DS = dissatisfaction with performance; MV = mental verbalization, talking to the game, self, or singing songs. The AC group reports activities utilizing working memory and attentive processes most frequently. The reports of LPFC strategies and mental processes consist of utilizing working memory and attentive processes most frequently, with an emphasis on attention. The RPFC group reports of strategies and mental processes consist of activities utilizing working memory and mental verbalization processes most frequently, with visualization also increased as opposed to the AC or LPFC.

(a)

(b)

(c)

(semantic) long-term memory processes (Klimesch et al., 1996; Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998; Klimesch et al., 1994). In contrast to the theta band, higher alpha amplitude at rest, and lower alpha amplitude during task performance (reflecting a large alpha suppression during task), is correlated with efficient memory performance in healthy adult participants (Klimesch et al., 1997; Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999; Stipacek, Grabner, Neuper, Fink, & Neubauer, 2003; Vogt, Klimesch, & Doppelmayr, 1998).

The beta frequency shows effects for all ROT as a result of LNFB training. The AC appears to be interactive with more regions in this frequency. This effect is plausibly related to a learning effect, response conflict and resolution, motivation and goal direction—namely, that the AC directs the other regions in both lower and higher frequencies necessary for completion of task and directs the RPFC to follow suit and coordinate the load for attention. The LPFC shares a significant relationship with the cuneus and left supramarginal gyrus in this frequency, which is a possible encoding effect in conjunction with the AC. The RPFC shows only effects for the AC and right post central gyrus for the overall beta frequency.

Absolute Power

The absolute power comparisons show differing activation patterns for each ROT as a result of LNFB training. Training 14 to 18 Hz activity in the AC produces widespread differences in absolute power increase in most frequency domains, especially in anterior regions in the higher beta frequencies, suggesting that the AC facilitates activation of regions specific to task in these regions. Of particular note is the degree of difference when AC is compared to RPFC and LPFC. The AC appears to initiate regions different from the LPFC as compared to RPFC for this training task. The DLPFC has been implicated as a key substrate mediating a variety of executive functions, including representation of task

demand (Perlstein, Elbert, & Stenger, 2002), working memory (Levy & Goldman-Rakic, 2000), response selection (Rowe, Toni, Frakowiak, & Passingham, 2000), and response switching (Garavan, Ross, Murphy, Roche, & Stein, 2002), whereas the AC is suggested to be activated by competing information streams (Hester, Fassbender, & Garavan, 2004). The comparisons in all frequency domains suggest that each of the ROT have a particular role in executive attention and working memory processes; however, it is plausible that the AC performs primary orchestration of this activity through thalamo-cortical loops and the patterns presented in the data add evidence to the idea that the AC is a gating mechanism between subcortical regions and the cortex (Pizzagalli et al., 2003). Studies have identified greater bilateral activation of AC, left middle frontal gyrus, right posterior cingulate, the left parietal lobe, and bilateral caudate and left parahippocampal gyrus in encoding experiments during correct expected outcomes (Kosson et al., 2006). Similarly, Levesque et al. (2006) demonstrated that neurofeedback techniques initiate blood oxygenated level dependent changes in the AC, caudate, and substantia nigra in children with ADHD. It is plausible that the effects produced by training in the AC reflect a network of executive attention. The encoding of episodic (short-term) and working memory processes is suggested to be reflected as oscillations within the theta frequency band (4–8 Hz; Klimesch, Doppelmayr, Schimke, & Ripper, 1997; Klimesch et al., 1999) within a hippocampal-cortical loop system (Burgess & Gruzelier, 1997; Fell et al., 2003; Klimesch et al., 1996). During encoding the increase in theta is significantly larger for items that can later be remembered (Klimesch et al., 1996; Klimesch et al., 2001). Theta amplitude shows the greatest increase in the comparison between AC and LPFC and perhaps is a defining characteristic of the role of the AC in encoding processes. Theta synchronization is suggested to be maximal during retrieval processes and the amplitude of Theta synchronization during retrieval predicts retrieval success (Fingelkurts, Fingelkurts, Krause, & Sams, 2002; Jensen & Tesche,

2002; Klimesch et al., 1999). Thus an explicit role for theta has been identified in encoding, retention, and retrieval of a memory trace (Klimesch, Doppelmayr, Rohm, Pollhuber, & Stadler, 2000). Lower theta amplitude at rest, and higher amplitude during learning performance (reflecting a large increase in theta power during task), has been demonstrated to predict good memory performance (Klimesch et al., 1997; Klimesch et al., 1999; Klimesch et al., 1992).

The alpha power increases are significant in comparing the AC to both regions in DLPFC, with a greater global effect as compared to LPFC in anterior regions and the comparison with RPFC shows a more specific pattern. This result offers insight into the central role of the AC in executive processes and the degree to which each of the ROTs influence the other ROIs in this executive attention network. Engle and Kane (2004) and Kane and Engle (2003) characterized executive attention as comprising those domain-general processes that keep stimulus and goal representations accessible outside of conscious focus, which are most useful and detectable under conditions of interference, distraction, and response competition. This concept appears valid with the increases in the trained frequency in the AC and RPFC as compared to the LPFC. The AC and RPFC appear to initiate activity in anterior regions as compared to LPFC, whereas the AC compared to RPFC shows activation increase in posterior central and parietal regions, possibly illustrating its role in memory and evaluative processes involving self and motivational content, as several working domains are involved in the maintenance of executive attention; more important, numerous regions are implicated in this network at any given point, elaborating on network specific functions within the frequency domain. The ROT in this study are found to show peak activations during target detection experiments (McKiernan, D'Angelo, Kaufman, & Binder, 2006) and are suggested to be involved in self-initiated thoughts (Gusnard, Akbudak, Shulman, & Raichle, 2001). Duncan and Owen (2000) explored the role of PFC in response conflict, task novelty, and number of elements

in working memory, working-memory delay, and perceptual difficulty, and they found plausible joint recruitment of three PFC regions: mid-dorsolateral PFC, mid-ventrolateral PFC, and the dorsal anterior cingulate cortex. These regions were posited to form a general network recruited by diverse challenges, such as response selection, working memory maintenance and stimulus recognition. The alpha 2 frequency is suggested to be a primary component for working memory.

The comparisons for the beta frequency show significant increase in anterior regions as a result of training in the RPFC and AC as compared to LPFC. Studies report an increase of local coherence in the beta 2 range in the left frontal regions extending to the central area and in the beta 3 band mainly in the right frontal regions extending to central and anterior-medial temporal areas during imagery and language thought processes (Petsche, Lacroix, Linder, Rappelsberger, & Schmidt-Henrich, 1992). The AC shows increased beta power in parietal and central regions as compared to the RPFC, illustrating its influence in a broader range of cortical regions; moreover, the similarities between the patterns of power and coherence increase in these two regions as compared to training in LPFC suggest an important role in executive attention and possibly implicates the LPFC in both working memory and perhaps most memory processes. Each ROT tends to influence anterior and posterior regions in a selective fashion relative to task and demand. The coherence results indicate the AC and RPFC produce similar integration and differentiation effects as compared to LPFC. The AC appears to influence more integration among frontal, central, and parietal regions as compared to RPFC in the theta, alpha, and low-beta bands as well as a more global differentiation effect in the beta frequency domain. Executive attention, memory, cognition, and the roles of the AC and DLPFC and associated frequency patterns are areas of interest for our lab and future works will attempt to define and describe the specificity with which regions and frequencies interact to regulate executive attention. Two

enhancements to this study would be (a) to have a larger sample size and (b) to conduct a larger number of sessions (> 30) as it may take a longer period of conditioning to bring a network to its full potential. Two possible conclusions can be drawn from this work:SSNOL utilizing LORETA neurofeedback produces significant positive changes in both working memory and processing speed tasks, and this training protocol affords the opportunity to influence and study neural networks within the brain.

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