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EEG NEUROFEEDBACK: A BRIEF OVERVIEW AND AN EXAMPLE OF PEAK ALPHA FREQUENCY TRAINING FOR COGNITIVE ENHANCEMENT IN THE ELDERLY

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Neurofeedback (NF) is an electroencephalographic (EEG) biofeedback technique for training individuals to alter their brain activity via operant conditioning. Research has shown that NF helps reduce symptoms of several neurological and psychiatric disorders, with ongoing research currently investigating applications to other disorders and to the enhancement of non-disordered cognition. The present article briefly reviews the fundamentals and current status of NF therapy and research and illustrates the basic approach with an interim report on a pilot study aimed at developing a new NF protocol for improving cognitive function in the elderly. EEG peak alpha frequency (PAF) has been shown to correlate positively with cognitive performance and to correlate negatively with age after childhood. The present pilot study used a double-blind controlled design to investigate whether training older individuals to increase PAF would result in improved cognitive performance. The results suggested that PAF NF improved cognitive processing speed and executive function, but that it had no clear effect on memory. In sum, the results suggest that the PAF NF protocol is a promising technique for improving selected cognitive functions.

Keywords: Biofeedback; Cognitive aging; Cognitive enhancement; EEG; Neurofeedback; Neuroplasticity; Peak alpha frequency

INTRODUCTION

Neurofeedback (NF, also called *EEG biofeedback*) is an electroencephalographic (EEG) operant-conditioning training technique that helps individuals learn to control or change their brain activity. It is used to treat a variety of neurological and psychological conditions and to increase cognitive performance in nonclinical individuals. Routine conditions treated with NF include Attention Deficit Hyperactivity Disorder (ADHD), anxiety, epilepsy, and addictive disorders. Traumatic brain

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injury (TBI), learning disabilities, depression, and schizophrenia are currently being investigated as potential candidates (Monastra, 2003).

The present article consists of two parts. The first part briefly reviews the history and current state of NF in the treatment of psychological or neurological disorders and discusses its future promise. This review is a selective overview of NF research; for detailed or specialized reviews, see Lubar, 1991, 1997, 2003; Monastra, 2003; Moore, 2000; Nash, 2000; Sterman, 1996, 2000; Thatcher, 2000; Trudeau, 2000. The second part of this article presents an example in the form of a preliminary report on work toward a new NF protocol intended to enhance cognitive function, particularly in elderly participants.

HISTORICAL OVERVIEW

The electroencephalogram is produced by synchronous postsynaptic potentials from thousands to millions of neurons, and is usually recorded at the scalp, although intracranial EEG is sometimes recorded. When amplified, digitized, and plotted, the raw EEG signal appears as a complex oscillatory pattern. This complex signal can be filtered to isolate narrow frequency bands (defined in Hz) that reflect specific brain sources and functions (Duffy, Iyer, & Surwillo, 1989).

NF was discovered and developed concurrently by independent researchers for the treatment of different pathological conditions. In the late 1960s, Sterman and his colleagues accidentally discovered that cats trained to produce 12–15 Hz activity over their rolandic cortex were more resistant to substance-induced epileptic seizures than non-trained cats, and in the early 1970s these researchers demonstrated this phenomenon in humans as well (for a review, see Sterman, 2000). This training has been termed SMR NF, for *sensorimotor rhythm*, since the 12–15 Hz EEG activity trained is recorded over, and is typical of, primary sensorimotor cortex. In the 1970s, Twemlow and Bowen (1976) first reported on the potential of NF to increase alpha (8–13 Hz) and theta (4–7 Hz) magnitude as a treatment for alcoholism, though the first controlled study to support these findings was published 13 years later (Peniston & Kulkosky, 1989). Posterior alpha activity is associated with relaxed consciousness; alpha "blocking" (i.e., reduction) is associated with alertness and active processing (Berger, 1929; Penfield & Jasper, 1954; Pilgreen, 1995). Central-posterior theta is associated with drowsiness (Duffy et al., 1989, p. 111). In the late 1970s, Hardt and Kamiya (1978) reported on the efficacy of alpha neurofeedback to reduce or increase anxiety, depending on the direction of the training (i.e., alpha magnitude inversely proportional to anxiety). Around the same time, similar work by Garrett and Silver (1976) found alpha enhancement to reduce test anxiety. Both alpha and alpha/theta NF is administered at the vertex of the head (electrode CZ according to the International 10/20 System; Homan, 1998). Although these anxiolytic effects were found in one study to be related to perceived success at the training but independent of direction of training (Plotkin & Rice, 1981), later research supported the directional effects of alpha training in generalized anxiety, showing decreased versus increased heart-rate reactivity to stress for alpha enhancers and supressors respectively (Rice, Blanchard, & Purcell, 1993).

In the mid 1970s, based on the observation that 12–14 Hz (SMR) enhancement with 4–7 Hz inhibition (often seizures are 4–7 Hz) NF over rolandic cortex reduced convulsions and related motor activity in epileptics, (Lubar & Shouse, 1976; Shouse & Lubar, 1979) successfully applied this treatment to reduce hyperactivity in a hyperkinetic child, which showed a reversal effect when SMR was suppressed in an ABA crossover design. Since then, subsequent studies have shown the utility and success of theta/SMR NF for the treatment of ADHD, and have added beta (16–20 Hz) enhancement for improvement of attention (Linden, Habib, & Radijevic, 1996; Lubar, 1991; Lubar & Lubar, 1984; Lubar, Swartwood, Swartwood, & O'Donnell, 1995). The rationale for this treatment is based on studies that showed abnormally lower beta and greater theta activity in children with ADHD as compared to controls (Bresnahan, Anderson, & Barry, 1999; Chabot, di Michele, Prichep, & John, 2001; Chabot & Serfontein, 1996; Mann, Lubar, Zimmerman, Miller, & Muenchen, 1992; Monastra, Lubar, & Linden, 2001).

A number of studies have shown the potential of NF to improve cognitive performance in healthy individuals as well. Beatty, Greenberg, Deibler, and O'Hanlon (1974) trained healthy young adults to either augment or suppress occipital theta (3–7 Hz) activity based on findings that occipital theta amplitude is negatively correlated with vigilance. After only two 1-hour NF sessions, they found improved and worsened performance, respectively, in a monitoring task. Rasey, Lubar, McIntyre, Zoffuto, and Abbott (1996) trained four college students to increase beta (16–22 Hz) while suppressing theta-alpha (6–10 Hz) amplitude at the vertex (CZ). After 20 sessions, two of the participants learned to control their EEG according to the requirements, whereas the other two failed. Learners, but not non-learners, showed improvement in attention as measured by a continuous performance Go/No-Go test.

Recently, several studies have focused on the specificity of the EEG frequency to be trained and its effects on cognition. Vernon and colleagues (2003) trained 32 medical students to either augment SMR (12–15 Hz) activity or augment theta (4–7 Hz) activity, while suppressing neighboring frequencies. Only the SMR group managed to change their EEG and improve semantic working memory and focused attention, whereas the theta group neither changed their EEG nor improved cognitive performance. In a similar recent study, researchers from the same group (Egner & Gruzelier, 2004) found frequency-specific cognitive effects of NF. They showed that training college students to increase SMR amplitude improved their perceptual sensitivity (d') and reduced omission errors and reaction time variability, whereas training others to increase beta (15–18 Hz) amplitude increased their reaction time speed and the amplitude of the P300 event-related potential (ERP). Both of the latter studies included control waiting-list groups that showed no effects. Finally, slow cortical potential (SCP) (<1 Hz) NF over the left hemisphere has been shown to speed up or slow down lexical decisions when individuals are trained to produce negative and positive SCP shifts, respectively (Pulvermueller, Mohr, Schleicert, & Veit, 2000). As in Rasey et al. (1996) and Vernon et al. (2003), individuals who failed to change their SCP showed no cognitive changes.

NF sessions typically last for 1 hour or less, including participant preparation time plus 20–40 minutes of NF, and are usually administered twice per week. The number of sessions needed for treatment varies substantially from individual to individual, depending, among other things, on the condition being treated, the individual's learning success, and the severity of the condition. Sterman (2000) reports using 25 sessions to treat epileptic seizures. Lubar (1991) suggests that 40–80 sessions are needed to treat ADHD. In contrast, improvement in patients with anxiety disorders has been reported with only eight NF sessions (see Moore, 2000, for a review). However, in our experience with epilepsy and ADHD, some clients may need many more sessions, for at least a year or more, to show learning and significant improvement. Moreover, since NF is an operant conditioning technique, it may well follow the laws of schedules of reinforcement in its patterns of acquisition and extinction. Therefore, occasional post-treatment "boosting" sessions are recommended (Lubar, 2003).

The rationale for the development of NF protocols has been based on EEG and neuroimaging research on correlates of brain pathology (e.g., ADHD, depression, TBI), accidental discovery (e.g., epilepsy); or neurophysiological correlates of cognitive states (e.g., anxiety, substance abuse). Sometimes more than one NF protocol is found to be effective for the same syndrome. For example, in addition to SMR training, SCP-NF is found to reduce seizure activity in epileptic patients (Kotchoubey, Strehl, Holzapfel, Schneider, Blankenhorn, & Birbaumer, 1999). Some propose the comparison of clients' EEG to normative EEG databases in order to individualize NF according to each client's abnormalities (Thatcher, 1999). This is partly based on the rationale that identical symptoms may be due to different underlying pathologies. A good example is that attentional problems may be due to a variety of conditions, including ADHD and depression. Even single diagnoses such as ADHD have been shown to have subtypes of quite distinct EEG patterns (Chabot et al., 2001). However, EEG abnormality does not necessarily signify pathology, just as normal EEG does not guarantee healthy brain function. Therefore, caution and experience must be applied in such decisions, just as with any other medical or psychological treatment. A combination of standardized protocol, EEG normative database comparison, experience, and expert consultation will maximize the probability of treatment success.

Clinical efficacy of NF varies across studies. Treatment protocols for epilepsy and ADHD seem to have the strongest empirical support, followed by those developed to treat anxiety and substance abuse. Treatments for depression, schizophrenia, traumatic brain injury, learning disabilities, Tourette's and chronic fatigue syndromes, and autism are all under investigation (Jarusiewicz, 2002; Monastra, 2003). Long-term effects of NF have been reported after 6 months and up to 10 years post-treatment (Lubar, 2003; Monastra, 2003; Trudeau, 2000). The existing research therefore suggests that NF is a promising technique for treating a number of disorders. And though most of the important studies establishing the effectiveness of NF for treatment have not combined it with other forms of therapy, NF should not be considered a panacea or sole treatment for all symptoms of the conditions treated. Other concurrent forms of care are recommended, including psychotherapy, family therapy, group support, and medication, whenever needed (Lubar, 2003). Furthermore, there is a need for more research to investigate the specificity of NF versus placebo, as well as the specificity of EEG frequency and scalp location for obtaining and maximizing therapeutic results.

Success of NF can be assessed with various objective and subjective measures, including standardized tests and inventories, self-reports, and reports from family, educators, or employers. Post-NF EEG "normalization" is another measure to assess learning success and validate NF as a specific treatment. However, although post-NF EEG changes often correspond to the training protocol, some times they do not, even if clinical improvement is achieved (Sterman, 2000). It is important to remember that the adjustment of brain function is not always easy or simple with NF, just as it is not always easy or simple with medication. For example, in an NF experiment involving children with learning disabilities, Fernandez and colleagues (2003) found EEG changes not only in the frequencies trained (4–13 Hz) but also in slower and faster frequencies (ranging from 3–19 Hz) and at electrode sites other than the ones trained, suggesting a large-scale reorganization of EEG activity.

Lubar (2003) reports more than 1200 organizations worldwide (including private clinics and research centers/laboratories) utilizing NF for treating ADHD alone, based on information from NF equipment manufacturers. There are several professional organizations that promote education and research on NF, including the International Society for Neuronal Regulation and its chapters worldwide (www.isnr.org), the Association for Applied Psychophysiology and Biofeedback (www.aapb.org), the Electroencephalography and Clinical Neuroscience Society (www.ecns.com), and the Biofeedback Society of California (www.biofeedbackcalifornia.org) based in the United States. In addition, the Biofeedback Certification Institute of America (www.bcia.org) tests and certifies clinicians who provide NF services to the public.

EEG Neurofeedback certification from the Biofeedback Certification Institute of America (BCIA) is considered the standard in the field by the Association for Applied Psychophysiology and Biofeedback. Certification is available to professionals that meet the degree and licensing requirements in BCIA approved health care fields. Additional requirements include a 36-hour didactic EEG biofeedback education, covering areas from neuroanatomy to treatment planning and professional conduct, 25 contact hours with a BCIA-approved mentor to review 10 personal and 100 patient sessions, and a 3-hour written examination. Recertification is necessary at 4-year intervals to ensure that providers continue to uphold BCIA ethical practices and monitor new developments in the field.

PAF NF: A PROPOSED PROTOCOL FOR COGNITIVE ENHANCEMENT

One of the most prominent EEG phenomena is the *alpha* rhythm, an oscillation in the range of 8–13 Hz with an average peak of 10–11 Hz in healthy adults. *Peak alpha frequency* (PAF) corresponds to the discrete frequency with the highest magnitude within the alpha range, and is known to be slower in children and the elderly, although it also varies across individuals (Klimesch, 1997; Posthuma, Neale, Boomsma, & de Geus, 2001). While the amplitude of alpha rhythm oscillations is associated with relaxation, anxiety, and internal focus (discussed above), the frequency of this oscillation has been positively correlated with mental performance at all ages, both in healthy individuals and in individuals with neurological conditions (for reviews, see Angelakis, Lubar, Stathopoulou, & Kounios, 2004b; Klimesch, 1997). Among other correlates, PAF is inversely correlated with age after the age of 20 (Kopruner, Pfurtscheller, & Auer, 1984), and is lower in individuals with Alzheimer's disease compared to healthy matched controls (Klimesch, 1997).

Although previous studies have shown the effectiveness of neurofeedback in the treatment of various neurological and psychiatric disorders such as epilepsy

(Sterman, 2000) and ADHD (Lubar & Lubar, 1999), by altering EEG amplitude in the alpha, beta, or theta frequencies, to our knowledge no published study to date has investigated the effects of training individuals to change the peak frequency of their alpha rhythm. The present pilot study investigated whether training elderly individuals to restore (i.e., increase) their PAF to the levels of younger people would result in improved cognitive performance. As a control for this experimental treatment, two other neurofeedback conditions were employed, one to train an increase in alpha amplitude, and one pseudo-neurofeedback placebo condition in which the participant was told she was having real neurofeedback but was actually viewing playback of another participant's session. It was expected that, out of the three treatments, PAF NF would result in the largest improvements in cognitive performance, whereas alpha amplitude NF and pseudo-NF would result in either no improvement or small improvements in cognitive performance due to placebo effects. In total, six healthy senior citizens have participated to date. Therefore, the present study serves as a pilot for further research, and preliminary results were interpreted in terms of common patterns within subgroups.

METHOD

Participants

Four healthy elderly women and two healthy elderly men were recruited from the greater Philadelphia area. Participants were pseudo-randomly assigned to the two groups, one experimental (EF1, EM, EF2) and one control (CF1, CM, CF2), matched for sex and education (E: experimental, C: control, F: female, C: male; e.g., EF1 = first experimental female). The age of the participants ranged from 70 to 78 years (EF1: 74, EM: 73, EF2: 75, CF1: 70, CM: 78, CF2: 74). Participants were paid a base wage of \$10/hour, plus an extra \$2.5/hour for each training session in which they showed improvement. In addition, participants received a bonus of \$2.5 for each hour of participation upon completion of all training sessions (40 maximum) and final assessment. Informed written consent was obtained from all participants. The study was approved by the Internal Review Board of the University of Pennsylvania.

Equipment and Instrumentation

For pre- and post-training EEG measurement, a 128-channel electrode cap designed according to the extended International 10–20 System of electrode placement was used in conjunction with MANSCAN RECORDER, an amplifier and recording software system from SAM Technology (http://www.manscaneeg.com/DataAcquisition_page.htm). EEG was recorded at 250 samples per second (frequency bandpass: 0.05–100 Hz), referenced to digitally linked mastoids.

Neurofeedback administration requires a similar amplifier and recording software system to amplify and digitize the signal from the electrodes and to specify the protocol of neurofeedback training, respectively. Protocols can be designed utilizing the various training screens and scripts, which provide visual feedback to participants and designate the training parameters. Although neurofeedback is typically administered at one electrode site, many biofeedback hardware/software packages provide the versatility to monitor psychophysiological activity with as many as 40 electrodes in several modalities. In this study, neurofeedback was administered at parietal-occipital midline electrode POz with a BioGraph/ProComp + biofeedback system (Thought Technology Ltd.).

Assessment Instruments and Tasks

Neuropsychological and personality assessment. A short questionnaire was used to assess neurological and psychological state and current self-rating of cognitive function. Participants were administered the State-Trait Personality Inventory (STPI) (Spielberger et al., 1979), and a number of standard psychometric tests, including the Digit Span (Wechsler, 1995), the Word List Memory Task (Welsh, Butters, Hughes, Mohs, & Heyman, 1991), the Stroop test (Stroop, 1935), the Passage Comprehension test (Woodcock & Johnson, 1977), Raven's Standard Progressive Matrices (Raven, 1960), and the Logical Memory, Faces, Verbal Paired Associates, Family Pictures, and Visual Reproduction subtests of the Wechsler Memory Scale-III (Wechsler, 1997).

Cognitive tasks during pre- and post-training EEG. Two tasks were employed during pre- and post-NF EEG assessment, the "n-back" task and a "Go/No-Go" oddball task. The n-back task had three separate blocks of 5 minutes each and 1-minute practice before each block. Single letters were presented on a computer monitor for 250 milliseconds at a rate of 2.5 seconds and were preceded by a warning tone by 500 ms. During the first block ($n-1$), participants were asked to respond (by pressing a mouse button with their right index finger) whenever the current letter matched the one before it. During the second block ($n-2$), they were asked to respond when the current letter matched the one two positions before it; the third block ($n-3$) required matching with the letter three positions before. Matching targets were pseudo-randomly presented 14% of the time.

The Go/No-Go oddball task had three separate identical blocks of 5 minutes each and 1 minute of practice before the first block. It presented three different tones through loudspeakers at a random rate of 1.0–1.3 seconds. A high-pitched tone (target) was presented 20% of the time, a lower-pitched (standard) tone was presented 65% of the time, and a complex, novel sound was presented 15% of the time. Participants were required to respond with a mouse button-press only to the high-pitched target tones.

Procedure

Neuropsychological and personality assessment. EEG, personality, and cognitive assessment were performed twice: before and after the completion of NF training. Personality and cognitive evaluation was administered by two independent psychometricians, one for all of the pre-training and the other for all of the post-training evaluations. Both administrators were blind to the participants' training condition. After a brief orientation, participants were administered the short questionnaire, the STAI, and the psychometric tests. Personality and cognitive assessment lasted for approximately 1.5 hours and was split into two sessions on different days before NF, whereas it was administered in one session with an intermediate break after NF.

EEG acquisition. Participants were fitted with the electrode cap and impedances at all channels were reduced to below 20,000 Ohms. EEG assessment involved six recordings in the following order: a 3-minute eyes-closed resting baseline (ECB) block, a 3-minute eyes-open resting baseline (EOB) block; three 5-minute *n*-back task blocks (1back, 2back, 3back); three 5-minute Go/No-Go oddball-task blocks (OB1, OB2, OB3); a 3-minute eyes-open post-task rest (PTRO) block; and a 3-minute eyes-closed post-task rest (PTRC) block.

Neurofeedback training. NF training was administered once or twice per week for a total of 31–36 sessions. Among the experimental participants, EF1 participated in 35 sessions, EM in 31, and EF2 in 36. Among the controls, CF1 participated in 35 sessions, CM in 36, and CF2 in 32. Experimental participants were trained to increase their PAF, whereas two controls were trained to increase their alpha amplitude. In both cases (frequency and amplitude measures), alpha was defined as 8–13 Hz. The third control (CF2) was shown playback of one of the other experimental participant's (EF1) sessions. None of the participants knew which condition they were in, nor did they know there were experimental and control conditions. They were all told that different training protocols were tested to see which one, if any, might provide cognitive improvement. After training, all participants reported the belief that they had been in an experimental group, except for the pseudoneurofeedback participant CF2, who reported finding the feedback confusing and ineffective.

Sessions lasted approximately 1 hour and included 10 minutes of preparation, 2 minutes of EOB EEG recording, 8 minutes of NF, a 3-minute break watching a documentary video (or reading after the tenth session), 8 minutes of NF, a 3-minute break as before, and 8 final minutes of NF. A reference electrode was attached to, and the training electrode was attached to a posterior midline site (POz). The NF system provided auditory and visual feedback for increasing the EEG training measure (PAF or alpha amplitude) while keeping the other (alpha amplitude or PAF) from rising above baseline levels. Participants were instructed to try to note and utilize the particular strategy that yielded the desired effect, and were verbally encouraged when they performed well. All participants received approximately equal amounts of encouragement by the experimenter. At the end of each session, participants were asked to describe their subjective experience.

Data Analysis

EEG data were analyzed by a "non-blind" experimenter. Fast Fourier Transform (FFT) was computed using a bandpass pre-filter of 5–15 Hz. Eye-blink artifacts were eliminated using an adaptive filter constructed with EMSE 5.0 (www.source-signal.com) separately for each participant, and additional artifacts were excised by visual inspection. For resting conditions, all 128 channels were analyzed, but for task conditions only limited midline channels were analyzed due to excessive artifacts at lateral and frontal sites. At the time this article was prepared, only the EOB, PTRO, and 1-back conditions had been analyzed. All results discussed are descriptions of the data pattern and are not statistically derived conclusions, due to the small number of participants.

Figure 1 Changes in peak alpha frequency across sessions for three PAF-NF participants. Normalized trendlines (smoothed with a 6-point running mean) show changes in estimated PAF (computed using percent time above training threshold).

RESULTS

NF Performance

All three experimental participants learned to increase their PAF, as shown by the trend lines (smoothed with a 6-point running-mean filter) in Figure 1, and both alpha controls learned to increase their alpha amplitude, as shown in Figure 2. Both figures show normalized percent-time above training threshold.

Self-Reports

During experimental training (PAF NF), two participants (EF1, EM) showed higher PAF when they concentrated, relaxed, "thought everything is going well in life," had pleasant thoughts, thought of food, traveling, funny stories, or "crazy things their children had done," said the alphabet backwards to themselves, or thought of foods that start with the letter Z. A third experimental participant (EF2) increased both alpha amplitude and PAF when she thought of people who cared for her, had pleasant thoughts, emptied her mind, relaxed, sang simple songs to herself, imagined calling friends to help her, or thought about "an appointment today." These experimental participants had lower PAF when they thought of problems, were frustrated, had not participated for some time, or were drowsy.

During control training (alpha amplitude), participants (CF1, CM) showed more alpha amplitude when they reported that they were relaxed or sleepy, thought

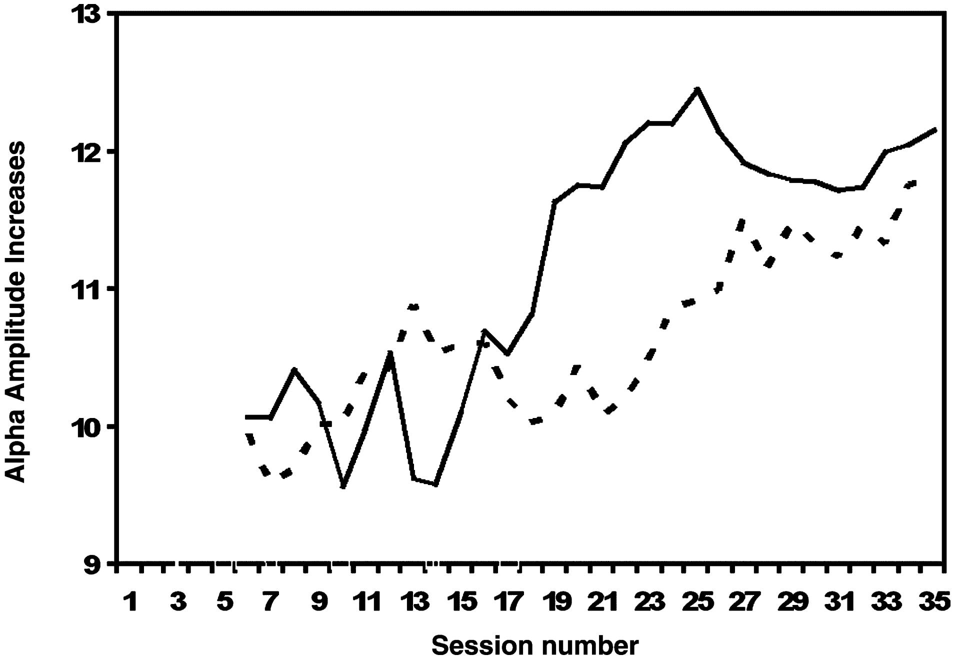

Figure 2 Changes in alpha magnitude across sessions for two alpha-magnitude NF participants. Normalized trendlines (smoothed with a 6-point running mean) showing changes in estimated alpha magnitude (computed using percent time above training threshold).

of what had to be done for the week, Christmas presents, cooking, upcoming vacations, actors, singers, jazz music, or their adolescence, concentrated on the "smiley face" feedback screen, thought of nothing particular, or had a blank mind. These participants showed less alpha amplitude when they reported that they had worries, problems, or unpleasant memories, thought about war or injustice, thought about his wife at the hospital, tried hard, focused on something, let their mind wander, or had not participated recently. Finally, the pseudo-NF control participant (CF2) reported not being able to understand what thoughts yield positive feedback on the screen.

All PAF participants rated themselves as thinking faster, averaging a 1-point (19%) improvement (EF1: 1.0; EM: 1.5; EF2: 0.5) after NF training. Two control participants rated themselves as thinking slightly faster (CF1: 0.5; CF2: 0.5), and one as thinking more slowly (CM: –1.5), averaging a 0.16-point slowing (–8%). Moreover, no PAF participant reported a change in concentration level, whereas two controls rated themselves lower in concentration; CF1 by 1.5 points (–27%), and CF2 by 1.0 point (–14%).

STPI

After training, two PAF and one active control participants scored higher in Trait Depression. EF1 scored higher by 7 points (70%), EM by 2 points (11%), and CF1 by 9 points (90%). Moreover, two controls scored lower in Trait Curiosity

(CF1 −6, 21%; CF2 −4, 12.5%), and the pseudo-NF control (KCF2) scored 5 points higher in Trait Anger (28%).

Memory

Verbal memory tests with consistent pre/post training patterns within groups showed no change for experimental participants, and mixed results for controls. In the word memory list, CF1 scored higher by 2 points (29%), CM scored higher by 4 points (80%), and CF2 scored higher by 2 points (25%), whereas in the recall stories task (first part), CF1 scored lower by 8 points (75%), CM scored lower by 1 point (8%), and CF2 scored lower by 4 points (31%).

Visual memory tests showed worsening for the experimental participants, and improvement for the active controls after training. Specifically, in the Visual Reproduction task, CF1 scored higher by 4 points (9.3%), and CM scored higher by 11 points (12.7%), whereas EF1 scored lower by 18 points (20%), EM scored lower by 24 points (36%), and EF2 scored lower by 15 points (18%).

Stroop

After training, two out of the three PAF participants increased their response speed and accuracy, whereas the two active controls decreased their speed. Of the PAF participants, EF1 scored 17 seconds faster (12%) with 7 more hits (7%), and EM scored 25 seconds faster (16%) with 5 more hits (7%). From the active controls, CF1 scored 12 seconds slower (8%), and CM 12 seconds slower (11%), whereas the pseudo-NF control (CF2) did not change her speed. However, EF2 (a PAF participant) did not fit this pattern. In contrast to the other two PAF participants, she decreased her speed by 49 seconds (−43%), and her hits by 6 (−8%).

N-back Task

There was no overall improvement in the total number of correct responses or false alarms for either group. However, during the third, and most demanding block (3-back), all PAF participants showed decreased performance (–17% average), and all controls showed increased performance (+16.6% average). Across blocks, while PAF participants increased their average reaction time (RT) by 14%, all PAF participants improved their RT stability (coefficient of variation: −53%). In contrast, controls increased their average RT by 4% and demonstrated worsened RT stability (coefficient of variation: +18%).

Go/NoGo Task

After NF training, all PAF participants and one active control decreased their RT, whereas the two other controls increased it. On average, PAF participants decreased their RT by 6%, whereas controls (on average) kept it unchanged. However, PAF participants increased their errors by 186% whereas controls increased them by only 50%.

Table 1 Average change per group (experimental vs. control) in different cognitive domains after neurofeedback training

	Experimental	Control
Speed of processing		
Self-reported speed of thinking	+	–
Speed in Stroop	+	–
Reaction time in Go/No-Go	+	
Reaction time in *n*-back	–	
Executive function		
Self-reported concentration	–	
Performance in Go/No-Go	–	–
Performance in Stroop	+	
Reaction time stability in *n*-back	+	–
Memory		
Performance in 3-back	–	+
Visual Memory	–	+
Memory for words	+	
Story recall	–	

"+": improvement, "–": worsening.

Table 1 summarizes some general trends from the results on cognitive performance. In sum, after NF training, experimental (PAF) participants reported thinking faster, whereas controls reported slight worsening in concentration. Psychometric testing comparing pre- to post-NF performance suggested that PAF training worsened performance in visual reproduction, improved speed and accuracy in the Stroop test (only two of the three participants), worsened performance in the 3-back task, improved reaction-time consistency in the *n*-back task, and increased errors in the oddball task more than for the control participants. Control participants were found to improve in word recall, worsen in story recall, improve in visual reproduction, become slower in the Stroop test, score better in the 3-back task, lose reaction-time consistency in the *n*-back task, and increase their oddball-task errors, although much less than the experimental participants.

EEG Results

Overall, across electrodes, two experimental and two control participants increased their alpha magnitude after the completion of NF training, whereas one control participant (CF1) reduced her alpha magnitude and one experimental participant (EF1) did not change her alpha magnitude after NF training.

Figure 3 reveals an interesting pattern of PAF results. For both the EOB resting EEG (top row) and for EEG during the 1-back task (bottom row), PAF training for the experimental group was associated with an increase in PAF at frontal sites, but not at posterior sites, with little or no observable PAF changes for the control group. An increase in PAF was not unexpected for the experimental group. However, it was not expected to occur at frontal sites rather than the posterior site used for PAF training. These results suggest that the increase in PAF resulting from training was not occurring in posterior brain areas but was instead occurring in frontal

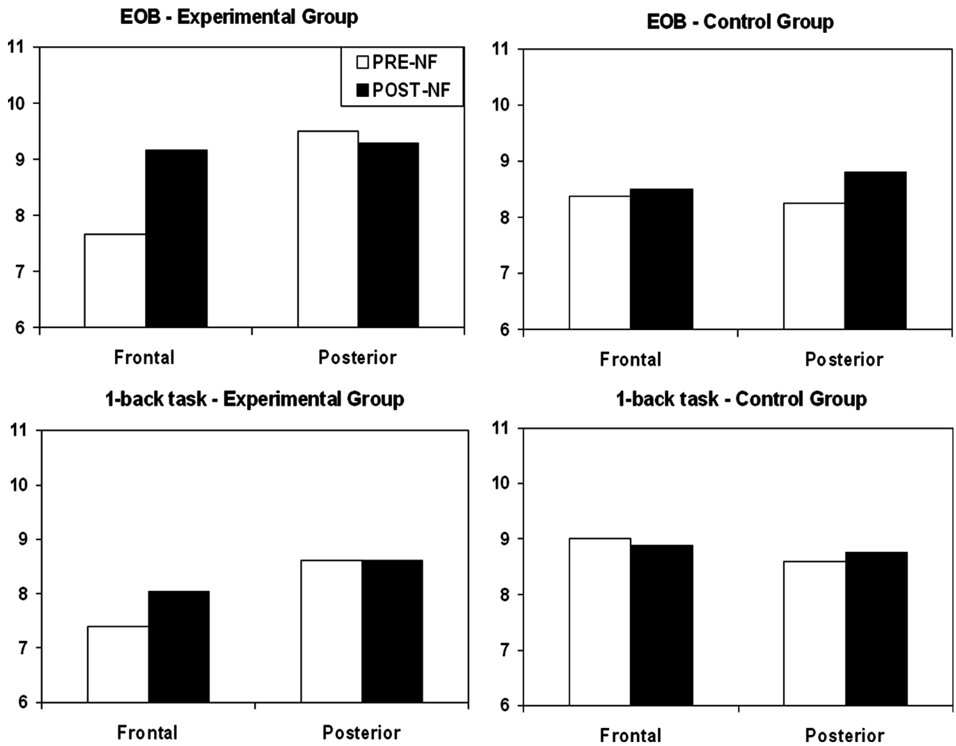

Figure 3 Peak alpha frequency (PAF) for the experimental and the control group, before and after neurofeedback (NF) training, for frontal (Fz and FCz) and posterior (Pz and POz) midline sites. Top left: eyes-open baseline, experimental group. Top right: eyes-open baseline, control group. Bottom left: 1-back task, experimental group. Bottom right: 1-back task, control group.

areas. The lone posterior electrode site used during training was apparently detecting (via electrical volume conduction) an increase in frontal PAF. This suggests that posterior PAF is not as malleable as frontal PAF.

DISCUSSION

Effectiveness of PAF NF

The present pilot study examined the effects of a new NF protocol on the cognitive performance of healthy elderly participants. In contrast to existing NF protocols that involve training changes in EEG amplitude, this new protocol focused on changing peak frequency. To control for non-specific effects, two alternative conditions were employed, one active NF and one pseudo-NF placebo.

Both experimental and active control participants showed progressive learning in their NF protocols, as shown in Figures 1 and 2. Even though the two training protocols targeted the same frequency band, the two protocols contrasted each other, as each protocol inhibited reward for increases in the dimension of the other. Specifically, the PAF NF protocol withheld reward if alpha magnitude increased, and the alpha magnitude NF protocol withheld reward if PAF increased.

Interestingly, preliminary results suggest that the cognitive effects of the two protocols also contrasted. The PAF protocol suggested general improvement in speed of processing and executive function, and the alpha magnitude protocol showed improvement in memory, whereas each protocol showed a general decrease in the cognitive dimensions for which the other protocol showed improvement (see Table 1). Moreover, the pseudo-NF protocol showed either similar cognitive changes to those of the active control protocol (i.e., alpha magnitude), or no changes.

The results described above suggest not only that PAF NF is feasible, but also that it has specific effects on cognitive performance. The latter point is supported by both the contrasting effects of the active control NF protocol and the fewer effects of the pseudo-NF condition. In other words, PAF NF showed apparent cognitive improvement in areas that alpha amplitude NF did not, and vice versa, whereas both of these NF protocols showed greater cognitive effects than did the pseudo-NF placebo condition. Although previous studies have repeatedly shown changes specific to the employed protocol (e.g., Hardt & Kamiya, 1978; Lubar, 1991; Sterman, 2000), the present study discriminated between frequency-specific EEG effects on cognition by controlling for all possible non-specific factors of NF training, such as training environment and procedure, electrode position, frequency band, verbal coaching, number of sessions, and individual differences. To some extent, the present study also controlled for experimenter bias, since cognitive performance before and after NF training was assessed by "blind" experimenters who were not aware of each participant's NF condition. In a recent study, Egner and Gruzelier (2004) have similarly showed the specificity of EEG NF frequency on behavioral changes by showing different cognitive effects for individuals trained to increase the amplitude of neighboring frequencies (12–15 Hz versus 15–18 Hz).

EEG Changes and their Relationship to Behavioral Changes

Overall, EEG changes after training did not fit all protocol-specific expectations. First, we were surprised to find post-NF alpha magnitude increases independent of NF condition. Specifically, two experimental and two control participants showed increased alpha magnitude during the post-training recording. The likely explanation for this is that participants were anxious during the initial EEG recording due to the unfamiliarity of the procedure, whereas they likely felt more relaxed during the post-training recording. While participants were shown a short video explaining the EEG procedure, future studies should consider including a more elaborative pre-training session to familiarize participants with the EEG and NF procedures and to minimize their anxiety.

Second, even though all training was applied posteriorly (electrode site POz), the experimental group showed post-training PAF increases frontally (but not posteriorly), whereas the control group showed little or no PAF changes at any electrode site. Specifically, post-NF PAF topography shifted more anteriorly for the experimental group only (see Figure 4). In previous studies, we (Angelakis et al., 2004b) have shown that frontal PAF topography correlates with cognitive preparedness, as well as strong correlations between PAF and response control (Angelakis, Lubar, & Stathopoulou, 2004a). Furthermore, the apparent increase in frontal PAF is consistent with improvement in measures of executive function. In sum, these results

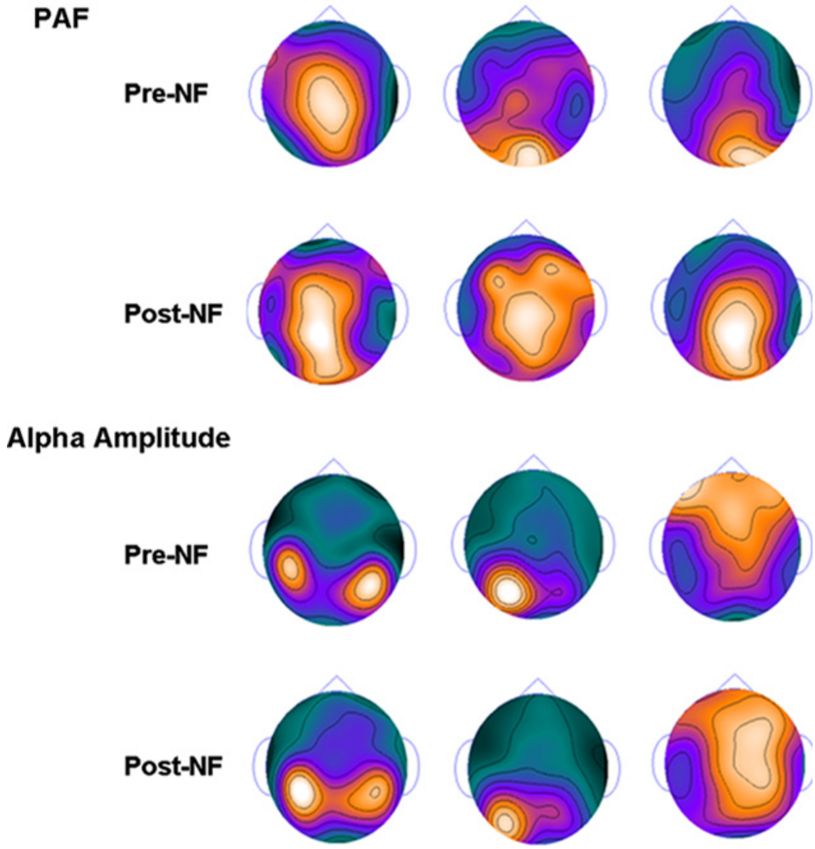

Figure 4 Topographic maps of resting EOB peak alpha frequency (PAF) before and after neurofeedback (NF) training. Top panel: experimental (PAF) participants; bottom panel: control (alpha magnitude) participants. Each map is a representation of a view of the top of the head, with the nose at the top of the map, and the left and right ears on the left and right sides of the map, respectively. Orange and white areas show the scalp regions exhibiting the greatest alpha EEG amplitude for that condition. Each map is individually scaled to the maximum and minimum values in that map in order to highlight the topographic distribution of PAF.

suggest that posterior PAF may not be as trainable as frontal PAF. Future studies can address this possibility by using multiple electrode sites during training. In this way, the training protocol can be modified to encourage posterior PAF increases while discouraging frontal PAF increases. In addition, future studies can directly encourage frontal (but not posterior) PAF increases.

The specific effects of PAF NF on processing speed support the idea that PAF reflects speed of information access (Klimesch, 1997). However, this increased speed did not appear to improve memory functions as would be predicted by the model suggested by Klimesch (1997), so this idea must be approached with caution until other studies measure the specific effects of PAF changes on different types of cognitive speed. In contrast, the present study suggested that memory improvement occurred in the alpha magnitude control group that was specifically trained to not increase PAF. This result came as a surprise, since we expected alpha magnitude NF to show lesser (if any) cognitive improvement compared to PAF NF. Some studies (e.g., Garrett & Silver, 1976) have reported decreases in test anxiety after alpha amplitude NF, which may have selectively affected memory functions in the present study.

As further research increases our understanding of subtle differences between the relationships between variant EEG frequencies and mental functions, we may be better able to address questions such as how theta/SMR NF and PAF NF might overlap. The present study extended previous findings (Angelakis et al., 2004a) that PAF is positively related to response control, by suggesting decreased reaction time variability after PAF training. However, similar effects have been reported in training younger individuals to reduce their theta/SMR ratio (Egner & Gruzelier, 2004). Moreover, response control is one of the symptoms of ADHD that respond to theta/SMR training (Lubar & Lubar, 1984). Since the theta (4–8 Hz) and SMR (12–15 Hz) frequency bands are immediately adjacent to the alpha band (8–13 Hz), it is worth considering whether there is some overlap between these two protocols, given that pushing PAF toward a higher frequency may actually increase upper alpha and decrease lower alpha magnitude (Klimesch, 1997).

Previous research has shown that frequency-specific NF training can be less than specific in its effects on the underlying EEG (Fernandez et al., 2003). This is not surprising, given that EEG frequencies are produced by different populations of neurons within the same system, and relevant parts of this system may well interact with and reorganize other parts, just as neurotransmitter-specific drugs may affect levels and functions of other neurotransmitters, such as selective serotonin reuptake inhibitors (SSRIs) that affect regulation of norepinephine as well (Sulser, 1989). Future studies may address these questions by directly comparing related NF protocols according to their effects on specific mental functions, and by examining potential overlap between such protocols. A logical goal, then, would be to compare the efficacy of these protocols in terms of the number of sessions required to produce a desired effect, as well as in terms of ancillary effects of each protocol.

Limitations of the Study

The present study has several limitations. First, due to the small sample size, these findings can serve only as pilot data suggesting further research. Second, the individuals who participated in the study were highly motivated and high-functioning seniors. This has both benefits and drawbacks: Less motivated and lower-functioning individuals may learn more slowly, but may have more room for improvement. Finally, even though the exploratory nature of this study did not allow for coaching specific to each participant (since conditions had to be identical for both groups), the present results suggest that some form of PAF training of healthy elderly individuals has promise. Furthermore, even with the limited sample size involved, the present data support the idea that EEG biofeedback is protocol-specific, resulting in quite different effects depending on the frequency and modality of training.

CONCLUSIONS

In general, NF has been shown to be a promising technique for a variety of psychological and neurological disorders, including epilepsy, anxiety, ADHD, and possibly TBI, depression, learning disabilities, and autistic disorders. Moreover, NF has been shown to help healthy individuals improve their cognitive performance.

According to the results reported here, PAF NF in healthy elderly individuals may improve cognitive processing speed and executive function, but have little or no effect on memory. In contrast, alpha amplitude NF may improve verbal, visual, and working memory, but worsen speed of processing and executive function.

The present study illustrated the process of developing a new NF protocol from theoretical conceptualization to protocol design, to EEG and behavioral results, and showed that NF is an EEG frequency-specific technique that can be controlled for non-specific placebo effects. As our understanding of the relationship between specific components of the EEG and mental function grows, new NF protocols may attempt to treat mental conditions not addressed previously. This will be the product of combining clinical observation, new knowledge of the EEG, and experimentation on NF.

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