Effects of neurofeedback on hemispheric attention networks

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Abstract

Neurofeedback (NF) is an operant conditioning protocol for self-regulating patterns of brain activation. The “SMR/Theta” protocol rewards increasing power in the 12–15 Hz range while reducing or arresting power in 4–8 Hz range, and it has been used to ameliorate Attention Deficit Hyperactivity Disorder. We examined whether SMR/Theta at frontal sites, F3 and F4, affected attention in the two cerebral hemispheres of normal children, and whether training had differential effects on three attentional networks, Conflict, Orienting, and Alerting. These networks were measured using the Attention Network Test (ANT) and a lateralized version of it, the LANT. Ten Israeli girls (ages 11 ± 1.2 years) performed both the ANT and the LANT, before and after 20 half-hour NF sessions. We found that NF sped up performance. In the ANT, training decreased Conflict and increased Orienting and Alerting. There was an effect of training side, showing that NF was consequential. In the LANT, Conflict was unaffected, but NF improved A and it increased Orienting, especially in the left visual field. Training at F3 resulted in a greater change than at F4. We concluded that: (1) NF was effective, (2) the protocol improved all three attention networks indexed by the ANT, but (3) it did not affect C in the LANT, and (4) the effects of NF were not restricted to the hemisphere under the training electrode.

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1. Introduction

The goal of this paper is to determine the efficacy of neurofeedback (NF) training for modulating hemispheric control of attention in children. We used a standard clinical NF protocol, increasing the power in the 12–15 Hz band and decreasing it in the 4–8 Hz band, and a new battery for assessing the 3 networks of attention: executive, spatial orienting, and alerting.

1.1. Attention

Attention enables basic psychological functions, has a distinct anatomy, and can be influenced by specific brain injuries and states. This leads to the notion that attention is an organ system (Posner & Fan, 2004). Attention selects aspects of the environment (e.g., objects) or ideas stored in our memory for conscious processing at any given time. Investigators have been studying attentional operations for about a century. In 1892 William James argued that attending is the same as being aware, but we now know that certain aspects of attention can be involuntary and can occur unconsciously. Since the 1980s, human neuroimaging studies have allowed examination of the whole brain during
tasks involving attention and consequently provided us with much information on how the brain houses these attentional processes (Posner & Fan, 2004; Posner & Petersen, 1990). The ability to trace changes in attention over time has provided methods for validating and improving pharmacological and other forms of therapy.

1.2. Attentional networks

Attention can be viewed as a system of anatomical areas carrying out the functions of alerting, orienting, and executive control (Posner, 2004b). Recently, Posner and associates (Posner, 2004a; Posner & Rothbart, 1998, 2000, in press; Raz, Fan, & Posner, in press; Raz, Fossella, McGuiness, Zephrani, & Posner, in press), devised a simple Attention Network Test (ANT) that can be performed by adults, children, patients, and even non-human animals (Fan, McCandliss, Sommer, Raz, & Posner, 2002). The ANT takes about half an hour to administer and provides three numbers that indicate the efficiency of the networks that perform the alert, orient, and conflict resolution functions, respectively. Previous work with this test has provided evidence of its reliability, its heritability, and the independence of the three different attentional functions (Fan, McCandliss, Flombaum, & Posner, 2001; Fan, Wu, Fossella, & Posner, 2001).

Although previous studies have examined the areas involved in the components of the ANT (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Hopfinger, Buonocore, & Mangun, 2000), recent research reported data concerning the brain areas involved in carrying out the ANT as a whole (Fan, McCandliss, et al., 2001; Raz, in press). These fMRI data suggest this test activates three largely orthogonal networks related to components of attention. Pharmacological studies (e.g., Maroccoc & Davidson, 1998) have related each of the networks to specific chemical neuromodulators: cholinergic systems arising in the basal forebrain play an important role in orienting; the norepinephrine system arising in the locus coeruleus of the midbrain is involved in alerting; and the anterior cingulate cortex (ACC) and lateral prefrontal cortex are target areas of the mesocortical dopamine system—involved in executive attention. A cross-sectional view of the fMRI activations of the alerting network shows thalamic activation (i.e., alerting effect). The cross-sectional view of the orienting network shows parietal activation. And the cross-sectional view of the conflict network shows ACC activation (Fan, McCandliss, et al., 2001; Raz, in press).

1.3. Lateralized Attention Network Test

We developed a lateralized version of the battery, the Lateralized Attention Network Test (LANT), to assess the hemispheric status of each network. We found that the three networks are similarly and independently represented in each hemisphere. There were sex differences, showing that Conflict was larger in adult females than in males. However, there was little difference in attention between young adults and 11-year-old children. There was evidence that girls have a larger Conflict in the LH, and that adults have a larger Orienting in the RH (Zaidel, Barnea, Rassis, & Raz, 2004). These results are consistent with the view that each normal hemisphere has a complete cognitive repertoire for interacting with the environment, including its own attentional/control system.

1.4. Neurofeedback

Neurofeedback (NF) is an operant conditioning procedure whereby an individual modifies the amplitude, frequency or coherence of the electrical activity of his/her own brain. Many authors have demonstrated operant learning of various electroencephalographic (EEG) parameters in animals and humans (Birbaumer, 1977, 1984; Birbaumer, Elbert, Rockstroh, & Lutzengerer, 1981; Kamiya, 1969; Plotkin, 1976; Sterman, 1977), but some methodological issues persist (Loo, 2003). We propose to assess rigorously a popular method for modulating cerebral activity using NF training. The approach provides feedback on the slow (Theta) and fast (SMR) EEG frequency ranges. The former is inhibited, whereas the latter is reinforced.

The main methodological difficulties in assessing the effect of NF training on cognition are the following. First, there is the ubiquitous problem of a proper control group. It is not enough to demonstrate an effect of NF, but critical to exclude simple repetition or incidental context/attention effects of the training protocol. It is possible to demonstrate that NF works, by showing differential effect of different protocols, but that does not allow a determination of the degree of change, namely, relative to a neutral or a baseline condition. A double blind sham control, where the subject engages in the same kind of feedback condition as with NF but without veridical feedback, is expensive and sometimes detectable by the subject. Second, even though the subject learns to change his/her EEG profile, that change often does not seem to last past the training session. Third, there is little or no controlled experimental data on the long-term persistence of the effects of training. This experiment seeks to address primarily the first problem: establish the existence of effects of lateralized NF training on hemispheric function. In particular, we ask whether a lateralized training site has a selective effect on the hemisphere underneath.

There are few controlled experiments on the effects of NF training on cognition in normal individuals. In general, it is believed that Theta activity (~4–8 Hz) is related to encoding and retrieval during working
memory, that upper Alpha (~10–12 Hz) is related to sensory processes in long-term semantic memory, that lower Alpha (~8–10 Hz) is related to attention, and that SMR (Sensory Motor Rhythm, 12–15 HZ) is related to attention as well (Vernon et al., 2003). More specifically, Egner and Gruzelier (2001) found that a NF training protocol that rewards increasing the SMR amplitude: (1) improved perceptual sensitivity, (2) reduced commission errors and improved speed in a sustained attention task, (3) improved cued recall in semantic memory, and (4) improved accuracy in a focused attention task. These authors also reported that a NF training protocol that rewards an increase in Beta 1, results in improved speed in vigilance, presumably due to increased arousal obtained by modulating the noradrenergic system. In turn, Egner and Gruzelier (2003) found that NF training for increasing the Alpha/Theta ratio improved musical performance under stress. Finally, Pulvermuller, Mohr, Schleichert, and Veit (2000) found that NF training of an increase in the negative shift of the slow cortical potential over the left hemisphere (LH) improved word recognition in lexical decision. In most previous studies, the control condition was an alternative NF protocol. Thus, Pulvermuller et al. (2000) found an opposite effect, a decrease in word recognition during lexical decision, when rewarding an increase in the positive shift of the slow cortical potential.

There are even fewer behavioral studies of the effects of NF training on hemispheric specialization and inter-hemispheric interaction in the normal brain. Hardman et al. (1997) successfully used a bipolar NF training protocol requiring subjects to change the asymmetry of the negative shift of the slow cortical potential across F3 and F4. Individuals high on “withdrawal” (a putative personality variable related to hemispheric arousal asymmetries: active → LH, withdrawn → right hemisphere (RH)) exhibited greater right shifts. However, there was no independent behavioral evidence for concomitant changes in hemispheric processing. Kotchoubey et al. (1996) in turn demonstrated a similar ability to control the asymmetry of the slow cortical potential across C3 and C4. Thus, there is evidence for the control of lateralized slow cortical potential shifts across both central and frontal sites. Such shifts can have lateralized consequences, both sensory-motor (Rockstroh et al., 1993) and cognitive (Pulvermuller et al., 2000). Rockstroh et al. (1993) showed that changes in asymmetry of the slow cortical potential between C3 and C4 affected the laterality of a sensory-motor task and of a forced-choice handedness task in the expected directions. Unfortunately, the experiment confounded response hand with task, and the hemisphericity of the task was assumed rather than assessed directly. In an important recent experiment, Pulvermuller et al. (2000) trained normal subjects to create a positive or a negative shift in their slow cortical potential with feedback to C5 or C6 recordings. The authors observed improved lexical decision of word targets in “responders” following C5 but not following C6 training when central lexical probes were presented following discriminative stimuli (those used for training). The same pattern was observed for probes lateralized to either visual field. However, if indeed C6 training had no effect on target words in the LVF, then the effect of C5 training suggests: (1) that it modulates selectively the LH, and (2) that the lexical decision task was exclusively specialized in the LH (callosal relay, cf. Zaidel, Clarke, & Suyenobu, 1990), so that targets in both visual fields are affected equally. A more critical test would involve training at C6 and testing with a lexical decision task that is independently verified to be direct access, i.e., where each hemisphere applies its own strategies to targets in the opposite visual field (Zaidel et al., 1990). That would be similar to the approach described in Barnea, Rassis, and Zaidel (in press). Further, the Pulvermuller et al. experiment showed an effect of side (left, right) of training electrode (C5 training was effective, C6 training was not), and of experimental group (responders, nonresponders), thus demonstrating the efficacy of the NF protocol. But the control group (nonresponders) is problematic.

To summarize, two main questions are addressed by the experiments described here. First, does NF work? Second, if it does, what kind of change can it produce in attention? In particular, does the location of the training electrode matter? Does training affect the two hemispheres differentially? We operationalize these questions by studying the effects of lateralized NF, using a common protocol, on hemispheric control of attention. Two patterns of results are important. First, does the experiment reveal simply a main effect of NF (before, after training), or does it exhibit a NF × Side (left, right electrode) × · · · interaction? Only the latter is evidence that NF is truly effective in bringing about cognitive change, since all non-essential experimental context effects are the same in F3 and in F4 training. Second, does the NF protocol affect the two hemispheres differently, namely, is there a significant NF × Side × VF (left, right) × · · · interaction?

2. Methods

2.1. Attention Network Test (ANT)

The following description is adapted from Fan et al. (2002). Stimuli were presented via E-Prime, a computer application for running online psychological experiments, on an IBM-compatible Pentium III personal computer, with a 733 MHz CPU, running Windows 98. Stimuli were presented on a 15 in. MAG X3770 monitor with a refresh rate of 85 Hz and a resolution of 1024 × 768 pixels. Participants viewed the screen from a distance of 57 cm, and responses were collected unima-
nually, using the right hand, from a computer mouse placed in front of the subject. Targets consisted of a leftward or a rightward arrow centered 1.06° of visual angle above or below the fixation. This target was flanked on either side by two arrows in the same direction (congruent condition), or in the opposite direction (incongruent condition), or else by lines (neutral condition). The participants’ task was to identify the direction of the centrally presented arrow by pressing the left key for the left direction and the right key for the right direction. A single arrow or line consisted of 0.55° of visual angle and the contours of adjacent arrows or lines were separated by 0.06° of visual angle. The stimuli (one central arrow plus four flankers) subtended a total 3.08° of visual angle. Performance in the congruent condition minus performance in the incongruent condition defines the Conflict or executive component of attention.

Targets were preceded by one of five types of cues, used to define Orienting and Alerting: no cue, center cue, double cue, and a valid spatial cue. For the no-cue trials, participants saw only a spatial fixation for 100 ms. Under this condition, there were neither alerting nor spatial cues. For the center-cue trials, participants were shown an asterisk at the location of the fixation cross for 100 ms. Therefore, alerting was involved. For the double-cue trials, the time course was the same as in the center-cue trials except that there were two simultaneous warning cues corresponding to the two possible target positions—up and down. It was expected that Alerting was involved, but the attentional field was larger under the double-cue condition than under the central-cue condition. For the valid-cue trials, the cue was at the target position and the time course was the same as in the center-cue and double-cue trials. The valid cues were always displayed at the locations of the targets. Alerting was defined as performance in the double-cue condition minus performance in the no-cue condition. Orienting was defined as performance in the valid-cue condition minus performance in the center-cue condition. It was expected that both Alerting and Orienting were involved under the valid cue condition. A variable duration of the first fixation was used to produce additional uncertainty about cue onset.

Each trial consisted of five events. First, there was a fixation period for a random variable duration (400–1600 ms). Then, a warning cue was presented for 100 ms. There was a short fixation period for 400 ms after the warning cue and then the target and flankers appeared simultaneously. The target and flankers were presented until the participant responded, but for no longer than 1700 ms. After participants made a response, the target and flankers disappeared immediately and there was a post target fixation period for a variable duration which was based on the duration of the first fixation and RT (3500 ms minus duration of the first fixation minus RT). After this interval the next trial began. Each trial lasted for 4000 ms. The fixation cross appeared at the center of the screen during the whole trial. Target location was always uncertain except when a valid spatial cue was presented.

2.2. Lateralized ANT (LANT)

This simple variation of the ANT rotated each stimulus display 90° clockwise to present lateralized targets. The conditions are all the same, except that targets are flashed for 170 ms each. Responses are made unimanually using the right hand on a computer mouse placed on end, at midline, facing the right. “Up” responses are made with the index finger, and “down” responses are made with the middle finger.

2.3. Participants

Ten 10- to 12-year-old Israeli girls volunteered to participate in the study. All were screened for neurological or psychiatric histories and for learning disabilities or attention deficits. Screening was done by interviewing the parents, teachers, and a special education professional familiar with their school progress. In addition, each girl was evaluated by the Integrated Visual and Auditory (IVA) Continuous Performance Test (CPT) (Sanford, 2002) and those falling more than 1 standard deviation below age norm were excluded.

2.4. Neurofeedback

Neurofeedback (NF) training was conducted over a period of 4 weeks, with each participant receiving 20 training sessions, and each session lasting 30 min and consisting of ten 3-min game rounds. Training was administered using the Neurocybernetics (Canoga Park, CA) EEG Biofeedback system and the ProComp differential amplifier (Thought Technology; Montreal, Quebec), or the TruScan 32 System from Deymed Diagnostics. Signal was acquired at 256 Hz, A/D converted and band-filtered to extract the Theta (4–8 Hz) and SMR (12–15 Hz) components, among others. The Theta and SMR frequency components were fed back using an audio–visual online feedback loop in the form of a video game. The amplitude of the SMR/Theta frequency ratio was represented by the size or speed of the object in that game. The participants’ task was to increase the size or accelerate the speed of that object. When all reward conditions were satisfied for a minimum of 0.5 s, an auditory beep and visual incentive (e.g., highway stripe, star in the sky) was provided as reinforcement. The participants were instructed to try maximizing their point scores.

An active scalp electrode was placed at F3 or F4, according to the standard 10–20 system, with the reference electrode placed on ipsilateral, and the ground elec-
trode on the contralateral, earlobe, respectively. Impedance was kept below 5 kΩ, and artifact-rejection thresholds were set individually for each participant so as to interrupt feedback during eye and body movements that caused gross EEG fluctuations.

3. Results

3.1. ANT

We carried out the following ANOVAs: NF (before, after) × Electrode Side (F3 = left, F4 = right) × Flanker Congruity (congruent, incongruent, neutral) × Cue (valid, center, double, none) × Target Position (up, down). The dependent variables were accuracy (proportion correct) and speed (median latency). Significant effects are listed in Table 1. We list but do not discuss effects involving Target Position.

3.1.1. Accuracy

It is noteworthy that there was no significant overall improvement with NF, nor a significant interaction involving both NF and Side, so that the efficacy of the training protocol was not demonstrated. This may be due to ceiling effects reflected in the high overall accuracy (97%).

The overall effect of Flanker Congruity was significant, showing a robust conflict effect, where neutral targets were the same as congruent targets. The interaction of Congruity with Side appears to reflect a chance bias due to ceiling effects reflected in the high overall accuracy (97%).

The effect of NF did not quite reach significance, but there was an overall improvement. There was the usual robust Conflict effect and, again, the neutral condition was the same as the congruent condition. The significant effect of Cue reflects a significant Orienting ($p = .0011$) and a significant Alerting ($p = .0011$). NF decreased Conflict, even when neutral trials were excluded ($p = .0011$). The interaction NF × Cue reflects a significant increase in Orienting ($p = .0487$), due to a selective speeding up of responses to valid cues. Similarly, NF increased Alerting ($p = .0037$), due to a selective speeding of responses to double cues.

The critical interaction NF × Side × Cue × Target Position shows that NF is effective. NF × Cue was significant for targets below fixation with F3 training ($p = .0040$), and this was due to a significant NF × Alerting interaction ($p = .0190$), reflecting an increase of Alerting with NF from a negative (−16 ms) to a significant ($p = .0161$) positive value (55 ms).

3.1.2. Latency

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3.2. LANT

We carried out the following ANOVAs: NF × Side × Congruity × Cue × Target Visual Hemifield (VF) (left, right). Again, the dependent variables were proportion correct and median latency. Significant effects are listed in Table 2.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>NF × Side × Flanker × Cue × Target Position in the ANT</th>
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<tbody>
<tr>
<td>Accuracy</td>
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<td>Flanker</td>
<td>2</td>
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<tr>
<td>Side × Flanker</td>
<td>2</td>
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<tr>
<td>Side × Flanker × Cue</td>
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<tr>
<td>NF × Flanker × Cue × Target</td>
<td>6</td>
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<tr>
<td>NF × Side × Flanker × Cue × Target</td>
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<tr>
<td>Latency</td>
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<tr>
<td>Flanker</td>
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<td>Cue</td>
<td>3</td>
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<tr>
<td>NF × Flanker</td>
<td>2</td>
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<tr>
<td>Flanker × Target</td>
<td>2</td>
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<tr>
<td>NF × Cue</td>
<td>3</td>
</tr>
<tr>
<td>NF × Side × Cue × Target</td>
<td>3</td>
</tr>
</tbody>
</table>

Significant ANOVA effects.
3.2.1. Accuracy

The critical interaction NF × Side approached significant, showing a trend towards a significant improvement following F3 training (p = .07), but (insignificantly) worse performance (p = .4) following F4 training. This demonstrated that NF is effective in modulating behavior.

Conflicts were significant, again showing no difference between the neutral and congruent conditions. The effect of Cue showed that Orienting was not significant (p = .063) and Alerting approached significance (p = .063). The NF × Cue interaction reflected a selective improvement in the central and valid cue conditions, although neither pre- nor post-NF were there significant Orienting or Alerting.

The interaction NF × Side × VF showed a trend towards significance and is particularly instructive. F3 training improved accuracy in both VFs (p = .0001 in both cases), whereas F4 training tended to impair performance (LVF, p = .3776, RVF, p = .0349). This shows that it is not the case that training over a given hemisphere selectively affects that hemisphere.

The Flanker × Cue interaction shows that Conflict is not independent of Orienting and Alerting. Only incongruent trials showed an effect of Cue, reflecting a significant Orienting (p = .0425), but not Alerting (p = .3779).

The significant interaction NF × VF × Cue shows that only LVF Orienting increased with training (p = .0342) (Although neither NF × VF × Orienting (p = .1201), nor NF × VF × Alerting (p = .5969) were significant.)

Again, the significant interaction Flanker × Cue shows that the three components of attention are not independent of each other.

We failed to observe a critical interaction involving NF and Side, thus failing to prove that NF is effective and responsible for the observed changes in speed of responses.

4. Discussion

A methodological issue deserves mention. The ANT and LANT included no invalid cues. And yet infrequent invalid cues usually “define” the Orienting of spatial attention since targets with valid cues are normally processed faster and more accurately than targets with either neutral or invalid cues, whereas targets with neutral cues usually show no difference from targets with valid cues. The use of center cues as neutral does yield significant Orienting, but the resulting estimate may change dramatically with the addition of invalid cues. Their addition will also allow a separate measurement of the facilitatory and inhibitory components of Orienting.

The results are summarized in Table 3. The ANT data showed no main effect of NF. However, given the absence of a non-training control group, this could reflect a counteract to possible repetition effects or to other training context effects. The latency data showed an increase in Conflict, Orienting, and Alerting following training, but this may not be due to NF per se. Nonetheless, the significant interaction NF × Side × Cue × Target Position shows that NF is effective in modifying behavior.

The LANT accuracy data showed trends towards a significant NF × Side and NF × Side × VF interaction, reflecting the fact that F3 training improved accuracy in both VFs, whereas F4 training impaired it selectively in the RVF. This shows, first, that NF is effective in modulating behavior on the LANT. Second, it shows that training with an electrode on one side of the scalp does not simply affect behavior in the hemisphere underneath. Still, both hemispheres are affected by training on both sides, albeit differentially. There was also evidence that only LVF Orienting increased with training.

<table>
<thead>
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<th>Table 3</th>
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<td>Summary of the findings in the ANT and the LANT: NF, Neurofeedback; C, Conflict; O, Orienting; A, Alerting</td>
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<tr>
<td><strong>ANT</strong></td>
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(+†) Significant effect; (≈+†) .07 ≥p > .05; (−) effect not significant.
The near-significant interaction NF × Cue in latency in the ANT reflects that training enhanced both Orienting and Alerting. Again, those changes may, however, not be due to NF per se.

Surprisingly, there were no simple laterality effects in any of the components of attention, suggesting that both hemispheres have similar attentional networks for orchestrating behavior, independently of each other. Training did have some lateralized consequences, which, however, may not have been due to NF per se.

The fact that training at F3 frequently had the same effects on both hemispheres and that F4 has the same effects on both hemispheres, different from F3, does not mean that F3 training did not affect circuits in the LH and the F4 training did not affect circuits in the RH. It is possible, for example, that F3 training affected circuit in the LH which, however, control bilateral behavior.

Neurofeedback increased Orienting and Alerting in latency in both the ANT and the LANT. This is consistent with a simple horse race or an additive model of hemispheric contributions to central presentations. However, it is noteworthy that training had an effect on Conflict in central presentations (ANT) which was not mirrored in lateralized presentations (LANT). It thus appears that central targets engage interhemispheric interactions which do not occur with lateralized targets.

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