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Brain and Cognition 59 (2005) 314–321

Brain and Cognition

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Effect of neurofeedback on hemispheric word recognition

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Accepted 17 May 2004

Abstract

We applied SMR/θ neurofeedback (NF) training at central sites of 20 Israeli children aged 10–12 years, half boys and half girls. Half of the subjects received C3 training and the other half C4 training, consisting of 20 half-hour sessions. We assessed the effects of training on lateralized lexical decision in Hebrew. The lateralized lexical decision test reveals an independent contribution of each hemisphere to word recognition (Barnea, Mooshagian, & Zaidel, 2003). Training increased accuracy and sensitivity. It increased left hemisphere (LH) specialization under some conditions but it did not affect interhemispheric transfer. Training did affect psycholinguistic processing in the two hemispheres, differentially at C3 and C4. Training also increased hemispheric independence. There were surprising sex differences in the effects of training. In boys, C4 training improved LH accuracy, whereas in girls C3 training improved LH accuracy. The results suggest that the lateralized NF protocol activates asymmetric hemispheric control circuits which modify distant hemispheric networks and are organized differently in boys and girls.

Keywords: Neurofeedback; Hemispheres; Lexical decision; Hemispheric specialization; Interhemispheric transfer; Neural plasticity

1. Introduction

The goal of this paper is to assess rigorously whether a common protocol of operant conditioning of the ongoing EEG can modify cerebral activity and cognitive processes. Specifically, we aim to determine whether rewarding enhancement of the SMR amplitude (12–15 Hz) and reduction of the θ amplitude (4–8 Hz) recorded from lateralized anterior central leads, C3 or C4, can selectively affect hemispheric dynamics, assessed by lateralized visual word recognition.

1.1. Neurofeedback

(For a more detailed coverage, please see Barnea, Rassis, Raz, Othmer, & Zaidel, in press.) 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. Operant learning of electroencephalographic (EEG) parameters has been demonstrated in animals and humans (Birbaumer, 1977, 1984; Birbaumer, Elbert, Prockstron, & Lutzenberger, 1981; Kamiya, 1969; Plotkin, 1976; Sterman, 1977). When demonstrating the effectiveness of NF, it is necessary to exclude simple repetition or incidental context/attention effects of the training protocol. Showing differential effects of different protocols with the same context provides an "existence proof" of the effect of NF but it is necessary to include a baseline condition in order to measure the size of the effect of NF. Further, it is important to assess the long-term persistence of the effects of training. This experiment addresses the "existence proof": it seeks to establish the existence of effective lateralized NF training that can modulate hemispheric function. In particular,

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0278-2626/$ - see front matter
doi:10.1016/j.bandc.2004.05.008

we ask whether a lateralized training site has a selective effect on the hemisphere "underneath."

In general, it is believed that θ activity (~4–8 Hz) is related to encoding and retrieval during working memory, that upper α (~10–12 Hz) is related to sensory processes in long-term semantic memory, that lower α (~8–10 Hz) is related to attention, and that sensory motor rhythm (SMR, 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 improved perceptual sensitivity, attention, and semantic memory. These authors also reported that a NF training protocol that rewards an increase in β □, results in improved vigilance. In turn, Egner and Gruzelier (2003) found that NF training for increasing the α/θ 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.

There are few behavioral studies of the effects of NF training on hemispheric specialization and interaction in the normal brain, and most rely on the slow potential shift method rather than on the frequency band approach. Hardman et al. (1997) showed individual (personality) differences in the ability to change the asymmetry of the negative shift, and the individual differences were allegedly associated with hemispheric differences in arousal asymmetries. There is evidence for the control of lateralized slow cortical potential shifts across both central (Kotchoubey et al., 1996) and frontal (Hardman et al., 1997) sites. Such shifts can have lateralized consequences, both sensory-motor (Rockstroh et al., 1993) and cognitive (Pulvermuller et al., 2000). The experiment of Pulvermuller et al. (2000) is particularly relevant to our study. Normal subjects were trained to create a positive or a negative shift in their slow cortical potential with feedback to C5 or C6 recordings. The data showed 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. The authors do not report whether C6 training had no effect on target words in the LVF. If so, then C5 training appears to modulate selectively the LH, presumably because the lexical decision task was "callosal relay," exclusively specialized in the LH, so that targets in both visual fields are affected equally (Zaidel, Clarke, & Suyenobu, 1990). To confirm this interpretation, it would be necessary to assess the effect of training at C6 on an independently verified direct access lexical decision task. That would be similar to the approach taken in this experiment. The Pulvermuller et al. experiment did show 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, and the data on the effects of NF training on left visual field (LVF) (RH) targets are not reported. Our experimental design is intended to remedy these difficulties. Thus, our proposed experiment differs from that of Pulvermuller et al. (2000) in NF protocol (frequency band vs. slow cortical potential), as well as in task (direct access vs. presumed callosal relay).

1.2. Lateralized lexical decision with lateralized distractors

Consider a lexical decision task with lateralized word or orthographically legal nonword targets in one visual hemifield (VF), and word or nonword distractors in the opposite VF, with responses consisting of manual 2-choice button presses. The targets and distractors are matched in length. This paradigm consistently exhibits the following effects: (1) There is a right visual field (RVF) advantage (RVFA), signaling LH specialization for the task, larger than shown by unilateral targets with no distractors (Iacoboni & Zaidel, 1996). (2) There is an interaction between target wordness and VF, with a larger RVFA for words than for nonwords, and a larger word advantage in the RVF than in the LVF, indicating different processing strategies in the two VFs and signaling independent hemispheric processing. (3) Decision is facilitated when the target and distractor are both words or both nonwords. This effect is called "lexicality priming" (LP) and it is larger for word than for nonword targets and larger for LVF than RVF targets (Iacoboni & Zaidel, 1996). Lexicality priming is inherently interhemispheric (Zaidel, Iacoboni, Laack, Crawford, & Rayman, 1998) and it illustrates automatic interhemispheric interaction even during independent hemispheric processing.

A RVFA alone in lateralized lexical decision is ambiguous about the role of the RH in processing LVF targets. It may be that the LH is exclusively specialized for this task and that LVF targets are first relayed through the posterior corpus callosum from the RH to the LH, prior to lexical processing in the LH ("callosal relay," Zaidel et al., 1990). Alternatively, the RH may be able to process the targets it receives directly, albeit not as efficiently and using a different strategy than the LH ("direct access," Zaidel et al., 1990). Lateralized lexical decision in English commonly exhibits the direct access pattern (Zaidel et al., 1990).

1.3. Hebrew morphology

Hebrew words are morphologically complex. Most Hebrew words are derived from abstract 3-consonant roots embedded in one of several abstract word patterns.

The root and word pattern may be independent morphological structures. The root is not a word but an abstract cluster of consonants that may not be contiguous and may not have an independent lexical entry. This suggests that Hebrew may be more dependent than English on specialized morphological analyzers in the (anterior) LH.

Several early studies found a reduced or reversed RVFA for Hebrew or Yiddish words (Mishkin & Forgays, 1952; Orbach, 1953, 1967), but subsequent studies found a consistent RVFA for Hebrew, similar to English (Carmon, Nachshon, & Starinsky, 1976; Faust, Kravetz, & Babkoff, 1993; Koriat, 1985; Shannon, 1982). However, none of the studies allowed for the possibility that the RVFA in Hebrew is different in degree than in English.

In a recent experiment, Barnea, Mooshagian, and Zaidel (2003) studied 28 young adult right-handed native Hebrew readers. They found a robust RVF advantage, larger than that observed in English. There was no overall lexicality priming effect, but there was one for LVF targets, significant only for nonword targets.

Weems, Zaidel, Berman, and Mandelkern (submitted-a, submitted-b, 2004) analyzed the EEG correlates of lateralized lexical decision and found significant effects in θ (this time defined as 3.9–7.8 Hz), α (7.8–11.7 Hz), low β (11.7–18.5 Hz), and γ (35–43 Hz). What guidelines do those data provide for effective modulation of behavior in the lateralized lexical decision task via NF at different locations using different frequency bands? Given that a specific behavioral effect is associated with a specific EEG effect, suppose that recreating that EEG correlate will facilitate recreation of the corresponding behavioral effect. Suppose also that if a specific EEG correlate occurs at a particular electrode site then NF at that same site is most likely to recreate the associated behavioral change.

Then the data of Weems et al. suggest that lateralized lexical decision will be facilitated by (1) increasing θ power in frontal and central sites over the LH, relative to the RH, (2) Increasing low β power in frontal sites over the LH, relative to the RH, and increasing low β power in central sites over the RH, relative to the LH. Thus, C3-(SMR/$\theta\uparrow$), should impair performance in the lateralized lexical decision tasks, whereas C4-(SMR/$\theta\uparrow$) should improve it.

2. Methods

Twenty 10- to 12-year-old Israeli children, 10 boys and 10 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 child was evaluated by the Intergrated Visual and Auditory (IVA) Continuous Performance Test (CPT) (Sandford, 2002) and those falling more than 1 standard deviation below age norm were excluded.

2.1. 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 10 3-min game periods. Training was administered using the Neurocybernetics (Encino, CA) EEG Biofeedback system and the ProComp (Thought Technology; Montreal, Quebec) differential amplifier, or the TruScan 32 System from Deymed Diagnostics. Signal was acquired at 256 Hz, A/D converted and band-filtered to extract the θ (4–8 Hz) and SMR (12–15 Hz) components, among others. The SMR frequency component was fed back using an audio-visual online feedback loop in the form of a video game. The amplitude of the SMR band was represented by the size, speed or brightness of the object in the game. The participants' task was to increase the size or the brightness, or accelerate the speed of that object. When the θ amplitude exceeded some predetermined level (80% of baseline), reward feedback was suppressed. 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 C3 or C4, according to the standard 10–20 system, with the reference electrode placed on ipsilateral, and the ground electrode 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.

Five boys and five girls were trained at C3 and five boys and five girls were trained at C4.

2.2. Lateralized lexical decision

2.2.1. Apparatus

Subjects were seated at a distance of 57.3 cm from the monitor of a 12 in. MacIntosh iBook computer, with their chins in a chin rest, and their eyes aligned with a fixation cross at the center of the monitor. Subjects' hands were placed on the keyboard with their index and middle finger of the left hand (Lh) resting on the 'C' and 'D' keys, respectively, and their index and middle finger of the right hand (Rh) resting on the 'M' and 'K' keys, respectively. The software package MacProbe (Hunt, 1994) for the MacIntosh was used to present stimuli and to collect responses.

2.2.2. Procedure

The fixation cross was displayed during the entire experiment. A warning tone sounded 750 ms before the presentation of each stimulus. Upper case Hebrew letter strings were presented for 183 ms in a black font on a white background. Subjects had 1500 ms to respond. There was an inter-trial interval of 1500 ms. Two letter strings of the same length were presented on each trial, one to each visual field. The target stimulus was indicated by an underline while the other stimulus served as a distractor. In half of the trials, the LVF stimulus was nominated as target, and in half of the trials, the RVF stimulus was nominated as target. The subjects' task was to indicate whether the underlined letter string was a word or a nonword by pressing the appropriate key on the keyboard.

Subjects made responses with both hands simultaneously. Each subject participated in a practice session before the test condition began. Each subject received 190 trials, such that half of the trials had word targets, and half had nonword targets.

2.2.3. Stimulus materials

Stimuli were 380 letter strings combined into 190 fixed pairs. Using these 190 pairs, four possible lists were constructed, with each stimulus appearing once in each VF as a distractor and as a target across the four lists. Half of the stimuli were words and half were nonwords, formed from words by changing one or two letters and following the morphological constraints of Hebrew. All of the Hebrew letter strings were unpointed. Each list consisted of 48 nonword distractor–nonword target pairs, 47 nonword distractor–word target pairs, 47 word distractor–nonword target pairs, and 48 word distractor–word target pairs. The distractor and target of each pair were the same length, and the stimuli varied in length from 3 to 5 letters. Of the 48 word–word pairs, 16 were unrelated, 16 were semantically related, and 16 were morphologically related. Semantic relatedness was determined by ratings by native Israeli adults. Morphologically related pairs shared a root. The stimuli were selected from a pool developed by Frost (1997). Each subject received two of the four lists such that stimuli seen as distractors in one list were seen as targets in the opposite VF in the second list. Block (list) assignment was randomized across subjects. The order of trial presentation was randomized for each subject so that subjects receiving the same lists were not exposed to the stimuli in the same order. The experiment was preceded by a pilot study on 20 normal native Israeli young adults. Targets that showed chance mean accuracy were replaced in the final stimulus list.

2.2.4. Data analysis

Analyses of variance ANOVA with repeated measures were performed for percentage of correct trials and medians of reaction time (RTs) of correct responses as dependent variables. Those were supplemented by ANOVAs with signal detection sensitivity (d') and bias ($\ln \beta$) as dependent variables, where words were considered signal and nonwords were considered noise.

3. Results

We analyzed the results of the lateralized lexical decision by considering the effect of NF (pre, post) and side of electrode (left, right), without regards to sex, in order to maintain sufficiently large cell sizes. These analyses were then supplemented by analyses that include sex, whose results must be interpreted with caution, due to relatively small cell sizes.

3.1. Lateralized lexical decision (LD)

We carried out $2 \times 2 \times 2 \times 2 \times 2 \times 2$ repeated measures ANOVAs, including NF (pre, post) $\times$ Side (C3, C4) $\times$ Distractor Wordness (DW) (word, nonword) $\times$ Target Wordness (TW) (word, nonword) $\times$ VF (left, right) $\times$ Sex (boys, girls), with mean accuracy and latency of correct responses as dependent variables. We also ran $2 \times 2 \times 2 \times 2 \times 2$ ANOVAs including NF $\times$ Side $\times$ DW $\times$ VF $\times$ Sex, with signal detection sensitivity (d') and bias ($\ln \beta$) as dependent variables. The findings for all four dependent variables are summarized in Table 1.

3.1.1. Accuracy

There was the expected significant main effect of VF, showing a RVFA (RVF = 74.4%, LVF = 66.3%). The effect of TW was not significant ($F(1,18) = 1.284$, $p = .2721$). Neither was the interaction TW $\times$ VF significant ($F(1,18) = 3.183$, $p = .0912$). The interaction DW $\times$ TW did not quite reach significance ($F(1,18) = 3.183$, $p = .0913$). However, the 3-way interaction DW $\times$ TW $\times$ VF was significant, showing an asymmetric lexicality priming, significant only in the LVF. There was a main effect of DW, suggesting some form of interhemispheric interaction. Thus, accuracy revealed hemispheric specialization and lexicality priming but not direct access.

We will next focus on significant effects involving NF. The main effect of NF was significant, showing an improvement in performance (pre = 68.4%, post = 72.2%). The interaction NF $\times$ TW was significant, showing that NF improved nonword recognition but not word recognition. This was sharpened by a 3-way interaction NF $\times$ Side $\times$ TW, showing a greater improvement for nonword recognition following C4 than C3 feedback. There was a significant 3-way interaction NF $\times$ TW $\times$ VF, showing significant interactions TW $\times$ VF both pre- and post-training and thus supporting direct access. However, before training the RVFA

Table 1
Lateralized lexical decision in Hebrew

Interaction	*df*	*F* value	*p* value
Accuracy: NF × Side × DW × TW × VF			
NF	1	13.227	.0019
DW	1	11.286	.0035
VF	1	10.163	.0051
NF × TW	1	18.995	.0004
NF × Side × TW	1	7.541	.0133
DW × TW × VF	1	9.574	.0063
Latency: NF × Side × DW × TW × VF			
DW	1	6.126	.0236
TW	1	9.002	.0077
VF	1	6.053	.0242
NF × TW	1	5.324	.0331
NF × Side × TW	1	4.190	.0556
DW × TW	1	27.144	.0001
TW × VF	1	9.753	.0059
NF × TW × VF	1	4.692	.0440
Sensitivity: NF × Side × DW × VF			
NF	1	16.293	.0008
DW	1	10.126	.0052
VF	1	8.928	.0079
Bias: NF × Side × DW × VF			
NF	1	10.069	.0053
NF × Side	1	5.386	.0322

Significant ANOVA effects. NF, neurofeedback; DW, distractor wordness; TW, target wordness; and VF, visual hemifield (of the target).

Table 2
Significant ANOVA effects including Sex

Interaction	*df*	*F* value	*p* value
Accuracy: NF × Side × DW × TW × VF × Sex			
Sex	1	7.531	.0144
NF × Side × VF × Sex	1	5.581	.0312
Latency: NF × Side × DW × TW × VF × Sex			
NF × Side × VF × Sex	1	4.904	.0417
Bias: NF × Side × DW × VF × Sex			
NF × Side × DW × Sex	1	4.207	.0570

for nonwords was greater than the RVFA for words, whereas after training there was the standard pattern of a greater RVFA for words than for nonwords. Thus, training may be said to "normalize" psycholinguistic processing in the two hemispheres.

3.1.2. Latency

The findings are summarized in Table 2. There was a RVFA (LVF = 970 ms, RVF = 935 ms), an advantage to words (931 ms) compared to nonwords (974 ms), and faster decision of targets with nonword than word distractors. The TW × VF interaction was significant and showed the standard direct access pattern for latency in this task in English. The significant DW × TW interaction showed an asymmetric lexicality priming. Thus, the task demonstrates all the classic effects of hemispheric specialization, hemispheric independence (direct access), and interhemispheric interaction.

We will focus now on effects involving NF. There was no main effect of feedback. The NF × TW interaction showed that NF speeded up nonword recognition but not word recognition. The NF × Side × TW interaction showed that C3 feedback improved both word and nonword recognition, whereas C4 improved nonword recognition ($p = .0445$) but tended to impair word recognition ($p = .1955$). Finally, the NF × TW × VF interactions showed no TW × VF interaction before training ($p = .7211$), but a significant and classic TW × VF interaction following training ($p = .0007$). The change was due to a speeding up of nonword recognition, more in the LVF ($p = .0001$) than in the RVF ($p = .077$).

Thus, C3 and C4 feedback has different effects and NF "normalized" the TW × VF interaction by changing it from a pattern consistent with callosal relay to one showing "direct access."

3.1.3. Sensitivity

There was the expected significant RVFA (LVF = .944, RVF = 1.43), and an effect of DW, showing better decision of targets with nonword than word distractors.

There was a significant overall effect of NF (pre = 1.036, post = 1.33), but no significant interactions with NF. Thus, the overall change with training could be simply due to test repetition or training context effect.

3.1.4. Bias

Training increased nonword bias (pre, $\ln\beta = .035$; post, $\ln\beta = .231$). The NF × Side interaction shows that the change in bias is due to C4 feedback.

Thus, the improvement in performance with C3 feedback is not due simply to a strategic change in bias.

3.2. Sex differences

To assess the effects of Sex, we added the variable Sex (boys, girls) to the previous analyses. We will consider only significant effects involving Sex and NF and we will focus on effects also including Side. Effects that include NF × Side show that NF training is effective and side-specific. However, the results must be interpreted with caution since there are only five subjects per NF × Side × Sex.

We used 2 × 2 × 2 × 2 × 2 × 2 repeated measures ANOVAs: NF × Side × DW × TW × VF × Sex with accuracy and latency as dependent variables or NF × Side × DW × VF × Sex with sensitivity and bias as dependent variables. The findings for all dependent variables are summarized in Table 2.

3.2.1. Accuracy

The main effect of Sex showed that the boys were more accurate (73%) than the girls (67%). Critically, the 4-way interaction NF × Side × VF × Sex showed that improvement with feedback in a given VF depends on the side of feedback and the sex of the child. Thus, boys showed improvement in the RVF with C4 feedback ($p = .0483$), whereas girls showed improvement in the RVF with C3 feedback ($p = .0038$) (Fig. 1).

We see that feedback often affects the performance of the hemisphere opposite the electrode site. This suggests that the training involved changes in control and that hemispheric specialization for control may be complementary to hemispheric processing (cf. Zaidel, 1987).

3.2.2. Latency

There was no sex difference in latency ($p = .8579$). The critical 4-way interaction NF × Side × VF × Sex showed that improvements in latency following feedback are restricted to the RVF in boys and occur with both C3 and C4 feedback. There was a dissociation between the effects of NF training on speed and on accuracy. Thus, both C3 and C4 feedback improved RVF accuracy in girls, but neither improved RVF speed.

3.2.3. Sensitivity

The main effect of Sex showed that boys were more sensitive ($d' = 1.37$) than girls ($d' = 1.0$). There were no

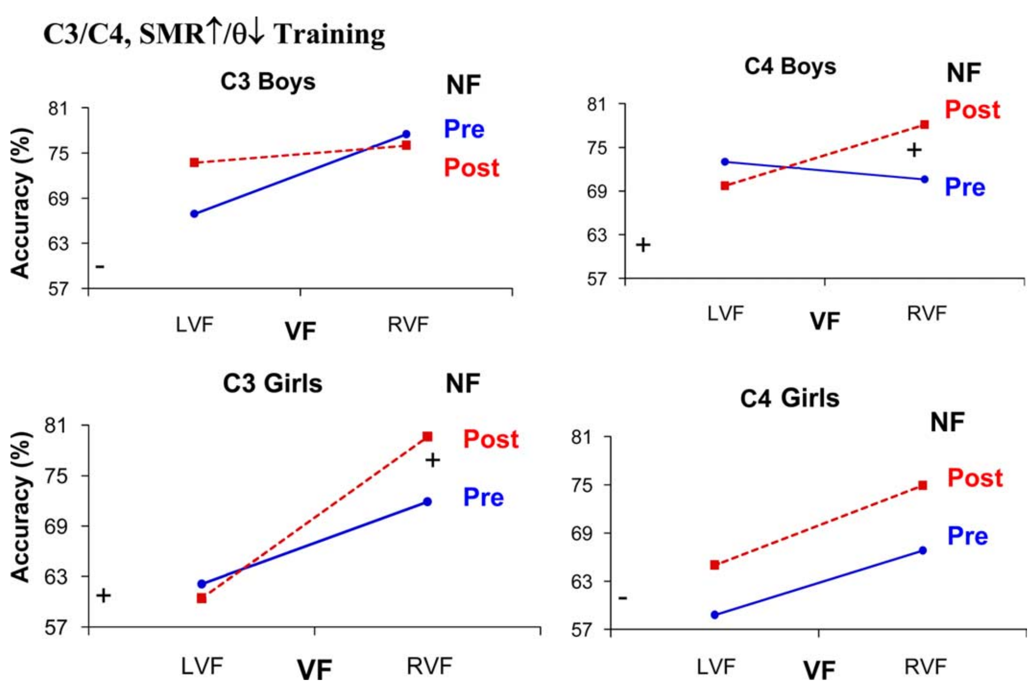

Fig. 1. The interaction of NF (pre, post) × Side (C3, C4) × VF (left, right) × Sex (boys, girls) in Accuracy ($p = .0312$). VF, visual hemifield of the target; LVF, left VF; and RVF, right VF; t, significant interaction; –, non-significant interaction.

significant interactions involving NF, Side, and Sex, suggesting that the effects in accuracy were due to strategic changes in bias.

3.2.4. Bias

There was no sex difference in bias ($p = .8428$). The borderline significant interaction NF × Side × DW × Sex shows that, in general, NF training increased "nonword' bias but that the extent differed with target wordness, training side and sex.

4. Discussion

The data are summarized in Table 3 and its implications are summarized in Table 4.

The lexical decision experiment showed all three canonical effects of the task: (1) A RVFA signaling LH specialization, (2) a TW × VF interaction signaling independent hemispheric psycholinguistic strategies, and (3) a DW × TW (×VF) interaction signaling (anasymmetric) lexicality priming. NF training did not affect interhemispheric interaction, but it did affect hemispheric specialization in conjunction with sex, and it affected the independent hemispheric psycholinguistic strategies (TW and TW × VF). The effect of NF on the RVFA was a bona fide effect of training since it interacted with side (location) of electrode (NF × Side × VF × Sex). By contrast, the psycholinguistic effects may not have been due to NF per se because they did not interact with Side. Nonetheless, there was evidence that NF was effective due to the NF × Side interaction in bias and the NF × Side × TW interactions in accuracy and in latency. The latter showed that nonword recognition improved more after C4 than after C3 training. It follows that NF is effective in modulating behavior, but our data do not indicate the size of the effect, due to the lack of a non-NF control group.

The experiment also suggested that there are dramatic sex differences in the effects of NF on lateralized behavior by virtue of the significant NF × Side × VF × Sex interactions in both accuracy and latency. Thus, C4 training improved RVF accuracy in boys whereas C3 training improved RVF accuracy in girls. This shows an effect of NF on the RVFA: In both cases, LH specialization increased following an SMR↑/θ↓ protocol.

It is noteworthy that the side of the training electrode made a difference in the effect of the neurofeedback training protocol, but that the effect was not localized to the hemisphere underneath the electrode. This does not preclude the possibility that training on one side affects control circuits in the hemisphere underneath, and that those unilateral circuits have bilateral effects. We posit that the NF protocol indeed affected hemispheric control networks. Those networks appear to show dramatic sex differences and may underlie strategic sex differences in hemispheric processing.

We conclude that the SMR↑/θ↓ protocol at C3 and C4 is effective in changing hemispheric visual word recognition, namely reading. (1) The protocol affected independent hemispheric contributions to reading, and (2) it increased left hemisphere specialization for the task; (3) the increase was sex-dependent, but (4) neurofeedback did not affect interhemispheric interaction via callosal transfer. However, the overall observed change in hemispheric word recognition may be due to repetition or other context effects, rather than to neurofeedback per se. (5) The side of training electrode makes a difference, but (6) C3 training did not selectively affect the left hemisphere and C4 training did not selectively affect the right hemisphere. However, it should be recalled that the lateralized lexical decision task measures hemispheric contributions in specific modules and corpus callosum involvement in specific channels. For a more general picture, many more protocols in new sites need to be assessed with tests for hemispheric specialization for diverse materials and measures of transfer in diverse channels of the corpus callosum.

Table 3
Summary of the data

Accuracy	Latency	d'	β
NF × TW[a]	NF × TW[a]		
NF × Side × TW[b]	NF × Side × TW[b]		
NF × TW × VF[c]	NF × TW × VF[c]		
			NF × Side[b]
NF × Side × VF × Sex[b]	NF × Side × VF × Sex[b]		

[a] Higher order effect is due to feedback.
[b] Effect must be due to feedback.
[c] Effect may not be due to feedback.

Table 4
Implications of the data

	×VF (Hem Spec)	×TW (Psycholing)	×TW × VF (Hem Indep)	×DW × TW (Lex Priming)
NF	+ –	+	+	–
NF × Side	+ –	+	–	–
NF × Side × Sex	– +	–	–	–

+, Effect present; –, effect absent; Hem Spec, hemispheric specialization; Psycholing, psycholinguistic strategy; Hem Indep, hemispheric independence; and Lex Priming, lexicality priming.

Acknowledgments

Thanks to Neurocybernetics (Canoga Park, California) for making the neurofeedback equipment available. Thanks to Maital Neta for research assistance. Special thanks to Michal Yeshurun, Yoel Atadgi, Naomi Epstein, and Reuven Tenne from the Regional High School in Kibutz Yagur, Israel for providing a hospitable research environment. Thanks also to Rachela Ovadia for help in coordinating the testing and to Nurit

Zaidel for help in screening out participants with learning disabilities. Above all, thanks to the children and their parents for their dedicated participation in the experiment. This work was supported by USPHS, NIH N20187.

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