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Increasing Individual Upper Alpha Power by Neurofeedback Improves Cognitive Performance in Human Subjects[1]

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The hypothesis was tested of whether neurofeedback training (NFT)—applied in order to increase upper alpha but decrease theta power—is capable of increasing cognitive performance. A mental rotation task was performed before and after upper alpha and theta NFT. Only those subjects who were able to increase their upper alpha power (responders) performed better on mental rotations after NFT. Training success (extent of NFT-induced increase in upper alpha power) was positively correlated with the improvement in cognitive performance. Furthermore, the EEG of NFT responders showed a significant increase in reference upper alpha power (i.e. in a time interval preceding mental rotation). This is in line with studies showing that increased upper alpha power in a prestimulus (reference) interval is related to good cognitive performance.

KEY WORDS: alpha; theta; oscillations; neurofeedback; cognitive performance.

INTRODUCTION

Several studies indicate that EEG alpha activity is associated with cognitive performance (Anokhin & Vogel, 1996; Klimesch, Doppelmayr, Pachinger, & Ripper, 1997; Neubauer, Fink, & Schrausser, 2002; Neubauer, Freudenthaler, & Pfurtscheller, 1995; Vogt, Klimesch, & Doppelmayr, 1998). Different parameters of alpha, however, are related to different aspects of cognitive performance in different ways. As reviewed in Klimesch (1999) there is a double dissociation between cognitive performance, EEG frequency (in the theta and upper alpha frequency range), and type of EEG response. Whereas for alpha, good cognitive performance is related to large resting power but small "test" power during task performance (i.e., a large extent of alpha suppression), for theta the opposite

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relationship holds true. Small resting theta power but a large increase in theta during performance reflect good performance. As an example, it was demonstrated that resting alpha power is increased under conditions that are associated with enhanced cognitive processing capacity or situations where subjects try to increase their capacity (e.g., during states of increased attention or in young healthy as compared to elderly subjects), but is decreased under conditions that are associated with reduced capacity (in neurological diseases, during drowsiness and sleep onset).

This double dissociation was also documented by studies using the event-related desynchronization (ERD) method, developed by Pfurtscheller & Aranibar, 1977). It was shown that the extent of upper alpha suppression and thus small test power is indicative of good memory performance. Resting alpha power, however, is positively associated with memory performance (Doppelmayr, Klimesch, Stadler, Pöllhuber, & Heine, 2002; Klimesch, Vogt, & Doppelmayr, 2000; Vogt et al., 1998). For theta it was found that small resting power is associated with good performance (Klimesch et al., 1997) whereas during task performance large theta power is associated with good memory (Doppelmayr, Klimesch, Schweiger, Stadler, & Röhm, 2000).

One interesting question is, whether the observed relationship between alpha and cognitive performance is of correlative or causal nature. In using repetitive transcranial magnetic stimulation (TMS), Klimesch, Sauseng, and Gerloff (2003) have tested this question. The idea was to induce rhythmic activity into the cortex by a brief series of TMS pulses with a frequency at individual alpha frequency (IAF) in an attempt to increase cognitive performance. Because it is well known that TMS and rTMS has disruptive effects when applied during task performance, rTMS was applied during a brief period before a (mental rotation) task had to be performed. The rationale of the experimental procedure is based on the above described finding that the magnitude of alpha desynchronization depends on the amplitude of alpha oscillations during a resting or reference period that precedes task performance and that inducing alpha activity via rTMS enhances alpha power in the reference period. The findings indicated that only rTMS delivered at IAF (and not at control frequencies below or above IAF) leads to a significant improvement in performance (i.e. the accuracy but not speed of mental rotation) when compared with sham. Furthermore, the influence of rTMS at IAF on EEG parameters mimicked exactly that situation, which we know, is typical for good performance: increased reference power, decreased test power, and, consequently, a large ERD. The interesting conclusion, thus, is that rTMS at IAF improves performance by way of those factors which are known to be of importance under normal conditions. Thus, in the present study we tested the question whether by means of neurofeedback training (NFT)—aiming to increase individual upper alpha power—a similar enhancing effect on cognitive performance can be observed.

Neurofeedback training (NFT) has mainly been used as a therapeutic tool to treat different types of disorders e.g., attention-deficit-hyperactivity-disorders (Fuchs, Birbaumer, Lutzenberger, Gruzelier, & Kaiser, 2003; Lubar, Swartwood, Swartwood, & O'Donnel, 1995) and epilepsy (Lantz & Sterman, 1988; Sterman, 1996). Neurofeedback studies use acoustic or visual feedback to provide a subject with the necessary (feedback) information to increase or decrease the power of a specific frequency band in relation to other frequency bands (Lubar, 1997). In recent studies (Egner & Gruzelier, 2001, 2004; Vernon et al., 2003) neurofeedback has been successfully used to enhance attentional and memory performance in healthy subjects, who were instructed to increase their EEG band power in a frequency range of 12–15 Hz, termed "sensorimotor rhythm" (SMR) by Sterman (1996). Lantz and

Sterman (1988) reported improved performance in memory tasks in epileptic patients who were able to increase their EEG power in the 12–15 Hz frequency range by NFT. It is important to note that this frequency range overlaps with the upper alpha band (of about 10–13 Hz). In these studies, unlike in those of Klimesch and colleagues (cf. Klimesch, 1999 for a review), frequency bands were not adjusted to IAF. Thus, it may very well be the case that particularly those subjects with high IAF were actually modifying their power in the upper alpha range. Considering the importance of upper alpha for cognitive performance one might assume that at least part of the effects found for NFT in the SMR frequency range are due to the influence of upper alpha activity.

The aim of the present study was to apply NFT in order to increase cognitive performance by increasing upper alpha power or decreasing theta power. For a better comparison with the findings from Klimesch et al. (2003) we used a cube rotation task to test changes in cognitive performance. Because it has been repeatedly reported that some people, usually called nonresponders, are not able to change their EEG (Fuchs et al., 2003; Lubar et al., 1995), we analyzed responders and nonresponders separately.

METHODS

Participants

After giving their written, informed consent, subjects participated in the following study, which was carried out according to the Declaration of Helsinki. The sample consisted of 18 healthy students (9 males with a mean age of 25.4 years and $SD = 3.8$, and 9 females, mean age =24.3 and $SD = 3.3$). All subjects were right-handed and had normal or corrected-to-normal vision.

Mental Rotation Task

Cognitive performance was assessed by a modified version the IST-70 a standard German intelligence test; Amthauer, 1970) cube rotation task consisting of 90 trials. In each trial one item consisting of two dice, a target and test dice, arranged one above the other, was presented (Fig. 1). The target stimulus was always the upper dice and was surrounded by a gray frame. For half of the items the lower dice was the same as the upper dice but rotated [Fig. 1(a)]; for the other half it was a different dice [Fig. 1(b)].

Stimuli were presented in three blocks, each block comprising 30 different items. As determined in a pilot study, task difficulty did not differ between blocks. The first block was preceded by eight training trials. Every trial started with the presentation of a fixation cross for 3 s. Then an item was presented which remained on the screen for 6 s. Subjects had to indicate—by pressing a corresponding button—whether the test cube was a rotated target or not. They were told to respond before the item disappeared. One second before, a warning signal was presented to remind subjects to respond. Only responses given before that warning signal were included for statistical analyses.

Procedure

The experiment consisted of eight sessions: (i, ii) two resting sessions (one with open, the other with closed eyes for 2 min each); (iii) mental rotation task (first block,

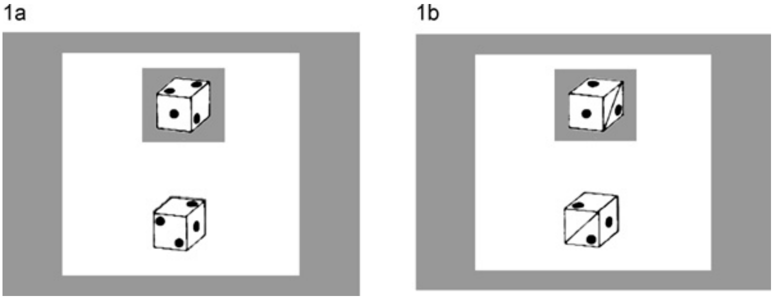

Fig. 1. Example for two stimuli used in the mental rotation task. The lower dice in 1a is the same as the upper but rotated in space, the lower dice in 1b is a different one than the upper dice.

5 min); (iv) threshold determination; (v) first NFT (theta or upper alpha) session; (vi) mental rotation task (second block, 5 min); (vii) second NFT (upper alpha or theta) sessions; (viii) mental rotation task (third block, 5 min). Each NFT session contained four blocks with each block lasting 5 min. Alpha and theta NFT sessions were counterbalanced between subjects, as were the second and third block of the mental rotation task.

EEG signals were amplified by a Neuroscan 32-channel system (Neuroscan, El Paso, TX, USA), with a sampling frequency of 250 Hz and upper and lower frequency limits of 30 Hz and 0.15 Hz, respectively. A common linked earlobe reference was used and impedances were kept below 10 kΩ. A set of 30 Ag–AgCl electrodes, positioned according to the international 10–20 system, were used for data acquisition. The EOG was recorded from two additional bipolar channels.

Neurofeedback

Neurofeedback was given by means of colored squares, presented on a computer screen. Subjects viewed an arrangement of $2 \times 3 = 6$ colored squares. This arrangement corresponded to the electrode sites F3, Fz, F4, P3, Pz, and P4. Because it is well known that alpha power is typically highest at parietal sites and theta power at frontal sites we decided to use three parietal and three frontal leads for neurofeedbacktraining. Powerspectra were calculated for every second at each electrode, and were presented color-coded for each square. The color scheme ranged from a highly saturated red to a highly saturated blue and the presented colors corresponded to the current values of alpha or theta power, respectively. For example, for upper alpha NFT, the feedback color was closer to the fully saturated red the closer the measured power was to the threshold value. For theta NFT, the color was closer to the fully saturated blue the farther away the power was from the threshold. Subjects were informed that the squares change their color according to the subject's brain activity. For upper alpha NFT (upper alpha enhancement) subjects were instructed to make the squares as red as possible. For theta NFT (theta decrement) subjects were told to make the squares as blue as possible. Threshold values for NFT were adjusted individually by using the following procedure. The difference in the magnitude of individual upper alpha power during eyes-open and eyes-closed was divided by two to obtain three possible threshold values, one at the value for eyes-open (level 1), a second at the mean value between eyes–open and closed (level 2), and a third at the value for eyes-closed (level 3). Subjects started with level 1. This level was accepted if subjects could not increase their individual upper alpha power during more than 10% of training time in the threshold session. If they exceeded that criterion, training was continued using level 2. If they still exceeded the 10% criterion, the threshold was set at level 3.

Frequency bands were adjusted individually according to IAF (determined as the frequency of peak alpha power during the eyes-closed condition). For upper alpha, frequency boundaries were IAF to IAF + 2 Hz. For theta, NFT boundaries were IAF−6 to IAF−4 Hz.

Statistical Analysis

The impact of NFT on the EEG was assessed by calculating difference values in upper alpha and theta power for NFT with respect to the resting session with eyes open (NFT minus eyes-open). Power was calculated by averaging artifact free epochs using an FFT algorithm with a time window of 1 s and a frequency resolution of 1 Hz. On the basis of these difference values reflecting training success—defined by a positive difference for upper alpha NFT, but by a negative difference for theta NFT—subjects were divided into upper alpha and theta responders (9 subjects with positive and 10 subjects with negative values, respectively). A subsample (4 subjects) of upper alpha responders was also theta responders.

The impact of NFT on cognitive performance was assessed by one-way ANOVAs with factor PREPOST (levels: preNFT, postαNFT, postθNFT), calculated separately for responders and nonresponders (in upper alpha or theta NFT). To control for training effects, a one-way ANOVA was carried out separately for responders and nonresponders with factor BLOCKNUMBER (first Block, second Block, third Block). The dependent measure for these ANOVAs was percent accurate responses in the cube rotation task. To test for differences in baseline performance, *t* tests between responders and nonresponders (in upper alpha and theta NFT) were carried out. In addition, correlations were calculated between training success in upper alpha or theta NFT on the one hand and the change in cognitive performance before and after upper alpha or theta NFT, on the other hand.

NFT-related changes in alpha and theta band power were tested by performing three-way ANOVAs with factor PREPOST (levels: pre, postαNFT, postθNFT), HEMISPHERE (levels: left, right) and LOCATION (levels: frontal, central, parietal, and occipital). These ANOVAs were calculated separately for NFT responders, nonresponders. The four different dependent measures for these analysis were: upper alpha and theta band power in a reference interval (from −1400 ms to −100 ms preceding the presentation of an item) and a test interval (from 500 ms to 2000 ms after presentation of an item). Because our hypotheses focus on NFT related changes, we will report only those significant findings that are due to PREPOST or to any interaction with this factor. In addition to ANOVAs, correlations were calculated between NFT-related changes in the reference interval (defined as difference scores: reference interval in mental rotation test after NFT minus reference interval in pretest) and training success.

RESULTS

Mental Rotation Task

As depicted in Fig. 2, an increase in cognitive performance could be observed only for upper alpha responders ($n = 9$) after upper alpha training. The respective ANOVA reveals a significant effect for factor PREPOST ($F_{2,16} = 4.36$, $p < 0.05$). No significant effects were obtained for upper alpha nonresponders, theta responders, and theta nonresponders as for the factor BLOCKNUMBER. The results of *t* tests indicated that cognitive performance in the baseline test did not differ between responders and nonresponders. Training success in upper alpha NFT and improvement in cognitive performance after upper alpha NFT correlated significantly ($r = 0.5$; $p < 0.05$; depicted in Fig. 3).

EEG Measures

During the performance of the mental rotation task an increase in reference upper alpha power was found only for upper alpha responders after upper alpha and theta NFT (Fig. 4). In addition, significant correlations between training success in NFT and increased reference power were found at right parietooccipital electrode sites (Fig. 5).

The three-way ANOVA for upper alpha responders revealed a significant effect for Factor PREPOST ($F_{2,16} = 6.28$, $p < 0.05$), which indicated, increased upper alpha reference power after NFT. None of the interactions including factor PREPOST reached significance. No significant effects were obtained for upper alpha nonresponders, theta responders, and theta nonresponders.

For theta responders (and reference power as dependent measure), no significant effects of PREPOST or interactions with this factor were found. Furthermore, no significant effects were obtained for the poststimulus interval.

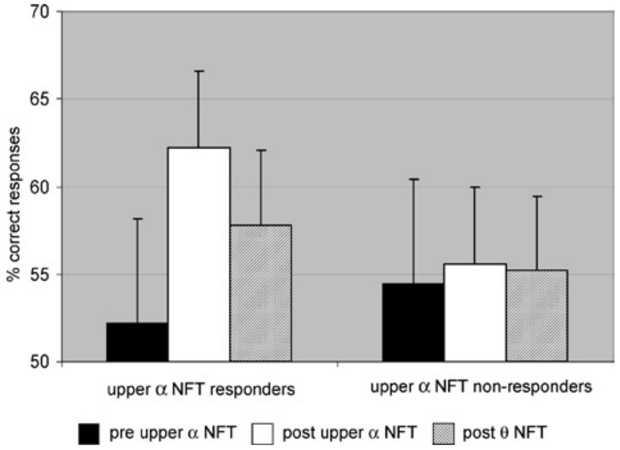

Fig. 2. The percentage of correct responses in cube rotations increases significantly after upper alpha NFT only for upper alpha NFT responders (the error bars indicate 95% confidence intervals). Responders and nonresponders do not differ before upper alpha NFT.

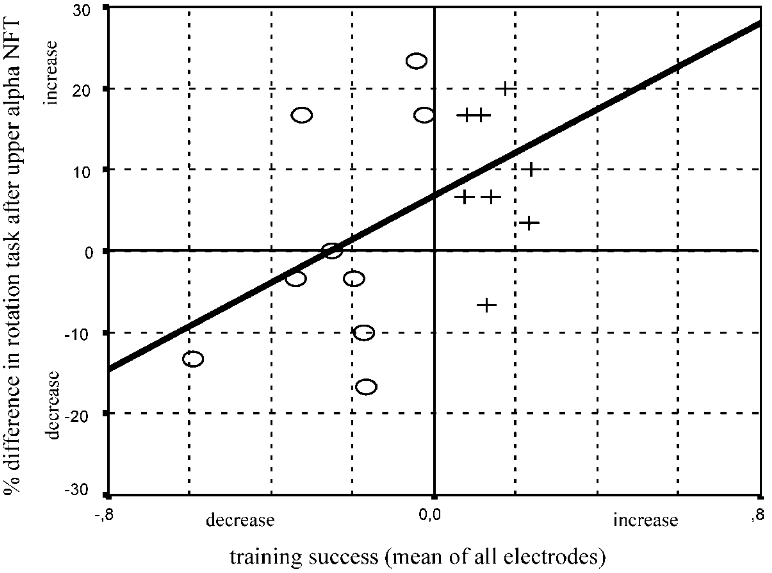

Fig. 3. The scatter plot shows the significant correlation between training success in upper alpha NFT (difference in band power: NFT – rest, *x*-axis) and improved cognitive performance in cube rotations pre– and post–upper alpha NFT (*y*-axis). Crosses represent upper alpha responders, whereas circles represent nonresponders. Due to an overlap of two responders only eight crosses appear in the plot.

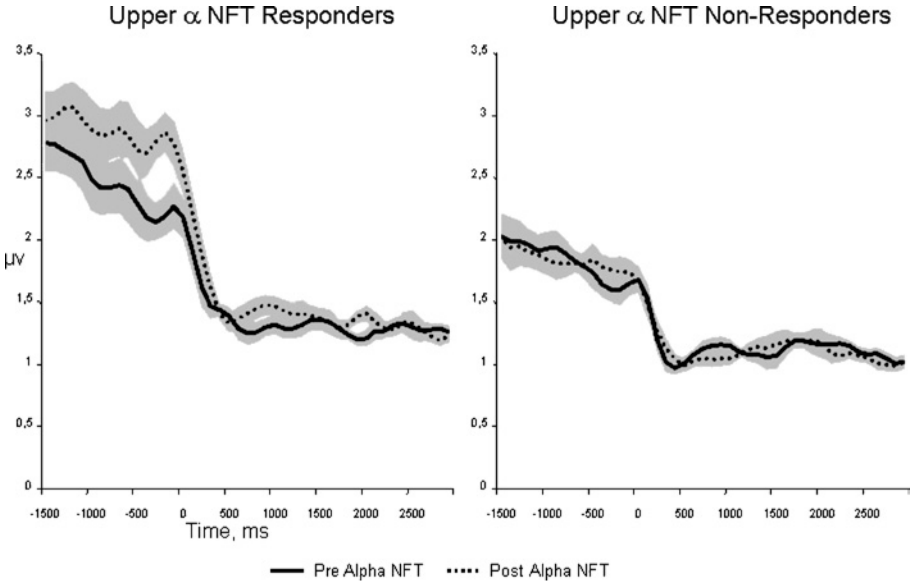

Fig. 4. A significant increase in absolute upper alpha power during the prestimulus interval can only be observed for upper alpha responders after upper alpha NFT. The solid line indicates power before upper alpha NFT, the dotted line after upper alpha NFT. The grey areas around the lines represent standard error. Stimulus for cube rotation is presented at time 0.

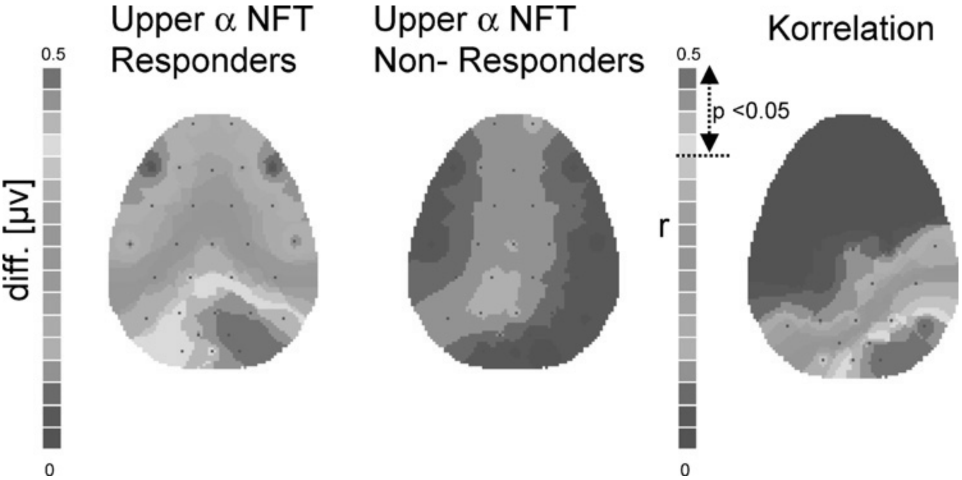

Fig. 5. NFT-related upper alpha power changes during cube rotation. Differences in reference upper alpha power before and after upper alpha NFT is more pronounced at right parietooccipital areas for responders. Significant correlations between training success and difference in reference power were obtained for electrode sites P6, O1, PO2, Oz, and O2 (yellow and red colors).

Significant correlations between training success and NFT-induced increases in upper alpha reference power were found for electrode sites P6, Po2, O1, Oz, and O2 ($r = 0.5$; $r = 0.46$; $r = 0.41$; $r = 0.44$; $r = 0.55$, respectively), depicted in Fig. 5.

DISCUSSION

As expected, those subjects who were able to enhance their upper alpha power performed better on the cube rotations after upper alpha NFT (cf. Fig. 1). The better subjects were able to increase their upper alpha power the larger was the improvement in cognitive performance after NFT (cf. Fig. 2). Although, a similar relationship between NFT success and cognitive performance has been shown previously by Egner and Gruzelier (2001, 2004), our study differs considerably from these and other Neurofeedback studies because we used only one training session. Therefore, our findings reflect only short-term effects measured directly after NFT.

The influence of upper alpha NFT on the EEG is characterized by increased reference power (as depicted in Fig. 4), which was found for responders but not for nonresponders. The finding that upper alpha power was also slightly increased after theta NFT can be explained by a carryover effect because half of the subjects received theta NFT after upper alpha NFT. Another possible explanation could be that there is some interaction between these two frequency bands and changes in one band can induce changes in the other band. For the poststimulus interval, no significant influence of NFT could be observed. Thus, with respect to reference power, the rTMS study by Klimesch et al. (2003) shows the same relationship between cognitive performance and upper alpha activity. The topography of the NFT-related power-changes is clearly centered at right parietooccipital recording sites (cf. Fig. 5), which agrees well with the fact that these areas play an important role for mental rotation, e.g. the fMRI study by Thomson et al. (2000) or the rTMS study by Klimesch et al. (2003). An interesting fact is that those electrode sites showing a NFT-related increase in reference power were not actually used for feedback. Thus, larger enhancing effects may have been obtained if only right parietooccipital sites were used for NFT.

The specific pattern of our results and the fact that performance did not increase across the number of blocks in mental rotation demonstrates that general training effects can be excluded as a possible trivial explanation of our findings. However, it could be argued that upper alpha responders are subjects with better cognitive performance in general, and, thus, also better in improving their performance from baseline to test (after NFT). Such an interpretation is unlikely because responders and nonresponders do not show performance-related differences in the baseline condition.

Finally, we want to draw attention to the fact that, unlike in Klimesch et al. (2003), NFT was not effective in changing poststimulus power during actual task performance. One possible interpretation of this finding is that NFT is more effective in changing tonic than phasic alpha power. In contrast to phasic (or event-related) changes in the EEG (typically measured by changes in poststimulus power), which are more or less under volitional control and occur at a rapid rate, tonic changes (typically measured by changes in resting or reference power) are not (or less) under volitional control and occur at a slower rate. Thus, we may conclude that—in contrast to rTMS, which is capable of inducing tonic as well as phasic changes—NFT is more effective in inducing tonic changes in alpha power.

To our surprise, and in contrast to upper alpha, theta NFT did not show any significant effects, neither on cognitive performance in the mental rotation task nor on the EEG pattern during task performance. The reasons for this negative finding are not yet obvious, but may indicate that subjects are more effective in changing their alpha than theta activity. Another reason may lie in the fact that we didn't adjust the threshold value for theta as we did for upper alpha. This is an important question that should be addressed in future research.

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