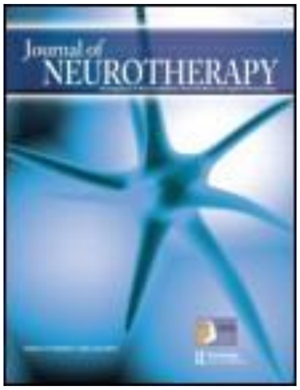

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Effects of SMR and Theta/Beta Neurofeedback on Reaction Times, Spatial Abilities, and Creativity

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EFFECTS OF SMR AND THETA/BETA NEUROFEEDBACK ON REACTION TIMES, SPATIAL ABILITIES, AND CREATIVITY

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Neurofeedback training (NFT) has been demonstrated to be a useful, inexpensive, nonpharmacological tool in the treatment of attention deficit hyperactivity disorder and epilepsy in humans. Different neurofeedback training protocols have been associated with positive effects on performance in sports, creativity, memory, and simple reaction time tasks. During NFT, individuals receive visual or acoustic feedback of their brain oscillations, which are recorded by electroencephalogram (EEG). Through operant conditioning that employs this feedback, the individuals subsequently may be able to modulate the respective oscillations. The most widely used training protocols focus on either the enhancement of the sensorimotor rhythm (SMR; 12–15 Hz) or modulation of the theta/beta ratio (TBR; theta: 4.5–7.5 Hz, beta: 17–21 Hz). We investigated whether healthy individuals are able to learn, within 30 NFT sessions, how to modulate either the SMR ($n = 13$) or the TBR ($n = 14$), and whether such modulation can lead to an enhancement in different cognitive or creative tasks. A control group ($n = 14$) that received NFT with daily changing frequency bands and instructions was included for comparison. Although neither the TBR group nor the control group was able to modulate the EEG in the trained frequency bands, the SMR group was successful in doing so. In addition, only the SMR group was able to attain significantly better results in simple and choice reaction time tasks and a spatial rotation task after training as compared to the two other groups. No effects of NFT were found for the other attention-related tasks or for creative tasks. A series of 30 SMR training sessions can increase the ability to increase SMR amplitudes and therefore may have a future application in settings where the cultivation of fast reactions and good visuospatial abilities are relevant (e.g., in sports).

Neurofeedback training (NFT) or electroencephalogram (EEG) biofeedback training refers to a specific type of biofeedback procedure used in the treatment of disorders such as attention deficit hyperactivity disorder (ADHD; Arns, de Ridder, Strehl, Breteler, & Coenen, 2009; Gevensleben et al., 2010; Gevensleben, Holl, Albrecht, Schlamp, et al., 2009; Holtmann et al., 2004; Leins et al., 2007; Thompson & Thompson, 1998) and epilepsy (Monderer, Harrison, & Haut, 2002; Sterman & Egner, 2006; Strehl, Kotchoubey, Trevorrow, & Birbaumer, 2005; Tan et al., 2009; Walker & Kozlowski, 2005), as well as in some brain–computer interfaces (Birbaumer et al., 1999; Pfurtscheller et al., 2006). The basic idea is that, using operant conditioning, individuals learn how to self-regulate bioelectrical brain processes, as assessed by the EEG. Electrodes are attached to the scalp and specific parameters such as slow cortical potentials, alpha rhythm, sensorimotor rhythm (SMR), or theta/beta ratio (TBR) are extracted in real time from the signal. Easily understandable displays, using

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simple shapes or video games, are presented to the participant, who is instructed to alter the feedback display (e.g., to increase or decrease parameters of a bar or circle) and thus alter the associated brain activity.

In the last few years, NFT has gained much interest and has proven to be effective in treating both ADHD (Arns et al., 2009; Fuchs, Birbaumer, Lutzenberger, Gruzelier, & Kaiser, 2003; Kropotov, Ponomarev, & Grin'-Yatsenko, 2001; Lévesque, Beauregard, & Mensour, 2006) and epilepsy (Kotchoubey et al., 1999; Kotchoubey et al., 2001; Monderer et al., 2002; Sterman & Egner, 2006; Sterman & MacDonald, 1978). The therapeutic effectiveness of NFT in autism also has been investigated in detail recently (Kouijzer, de Moor, Gerrits, Buitelaar, & van Schie, 2009; Kouijzer, de Moor, Gerrits, Congedo, & van Schie, 2009). Besides the already widely accepted interventions just mentioned, other applications of NFT include the regulation of emotional disturbances (Raymond, Varney, Parkinson, & Gruzelier, 2005); the rehabilitation of stroke patients (Doppelmayr, Nosko, Pecherstorfer, & Fink, 2007); the alleviation of tinnitus (Dohrmann, Weisz, Schlee, Hartmann, & Elbert, 2007; Schenk, Lamm, & Ladwig, 2003); and the enhancement of cognitive, physical, and sports performance in healthy individuals (Hanslmayr, Sauseng, Doppelmayr, Schabus, & Klimesch, 2005).

It is the aspect of performance improvement in healthy participants that is addressed in this study. Although academic performance increases after NFT in patients with ADHD because they have been trained to focus their attention, we are interested in understanding how performance improvement may occur in healthy individuals, that is, those without measurable cognitive deficits. Improving individuals' peak performance is a highly relevant topic for a broad range of activities that call for either fast reactions (e.g., many sports disciplines) or long periods of intense concentration (e.g., surgeons, air traffic controllers).

In the ADHD-related NFT literature (Arns et al., 2009), several different aspects of attention or attention-related deficits in persons with ADHD are reported. We were particularly interested in continuous focused attention, which TBR NFT has been shown to improve (Leins et al., 2007) and in attentional failures such as errors of omission or commission.

Hanslmayr and colleagues (Hanslmayr et al., 2005) have reported superior performance in a cube rotation task after upper alpha NFT. Participants who were able to increase upper alpha (10–12 Hz) amplitude by means of NFT showed better results in this task as compared to participants who were unable to do so. Similarly, Vernon et al. (2003) reported that healthy participants were able to increase SMR activity already after only eight NFT sessions and that this increase was related to improvements in a cued recall task. Finally, Egner and Gruzelier (2004) trained participants to increase either SMR (12–15 Hz) or low beta rhythm (15–18 Hz). Although the SMR training resulted in increased perceptual sensitivity, the low beta rhythm training yielded faster reaction times. On the basis of these results, it is of interest to investigate whether SMR and TBR training will exert differential effects on reaction times or visuospatial abilities.

Additional positive associations of NFT with performance in healthy participants have been reported in the areas of musical creativity (Egner & Gruzelier, 2003) and dance (Raymond et al., 2005), as well as in cognitive areas such as feature binding and intelligence (Keizer, Verschoor, Verment, & Hommel, 2010). For a more detailed review, see Vernon (2005) or Gruzelier (Gruzelier & Egner, 2005).

Taken together, these studies suggest that different NFT protocols exert positive effects on several aspects of attention (Arns et al., 2009), reaction times (Egner & Gruzelier, 2004), higher cognitive processes (Hanslmayr et al., 2005; Vernon et al., 2003), and creativity (Vernon, 2005). As just outlined, the most commonly used types of NFT for improving performance (e.g., in ADHD) are the SMR and TBR training.

Although the reported studies strongly suggest positive effects of NFT in several domains, there is still a lack of controlled studies, for example, using sham NFT (Logemann, Lansbergen, Van Os, Bocker, & Kenemans, 2010). In addition, it is still unresolved whether NFT will work in a similar manner in healthy adults, as it does with patients suffering from ADHD. The goal of this study, conducted with healthy adult volunteers, is threefold. Using real SMR or TBR training and comparing with a sham neurofeedback control group we investigate (a) whether the training protocols exert intended effects on the EEG in the trained frequency band, (b) whether the training leads to changes in the feedback thresholds of the trained frequency band (or the TBR), and (c) whether the performance in the aforementioned cognitive parameters is modulated selectively by either the SMR or the TBR training.

METHOD

Participants

Forty-two healthy participants (28 female, 14 male) with an age range of 17 to 32 years ($M = 24.9$) were recruited. All participants signed an informed consent after having been instructed carefully and in depth about all details of the study. The experiment was conducted in accordance with the declaration of Helsinki. At the end of the training, each participant received 250. As described next, each participant was assigned to one of three groups. Unfortunately, one member of the SMR group had to be excluded from analysis due to the loss of a great portion of this participant's data.

Training Protocols and Control Group

Each participant completed 30 training sessions. Each session comprised five 5-min blocks of training, interrupted by short breaks. Training took place every day for 6 weeks except on the weekends. Any training sessions that were missed were made up by participants after Week 6. Each training session was preceded and followed by two 2-min resting conditions with eyes closed and eyes open.

Participants were, matched for age and gender (nine female, five male), assigned to three groups. The control and TBR groups consisted of 14 participants; due to the aforementioned exclusion of one male participant the SMR group had only 13. All participants were right handed except for two members of the TBR group.

Materials and Procedure

Feedback Display and Reward Schedule. Participants were seated in front of a computer monitor that displayed a gray background, a white counter that indicated the number of earned reward points at the top of the screen, and the primary feedback related to the increase or decrease of the amplitude or ratio in the center, as well as three bars on the right side of the screen representing the inhibit bands (see Figure 1). The main feedback in the center consisted of an orange circle, indicating the reward threshold, and a smaller white disc within the orange circle, which represented the actual activity in the respective frequency band. Increases in SMR or decreases

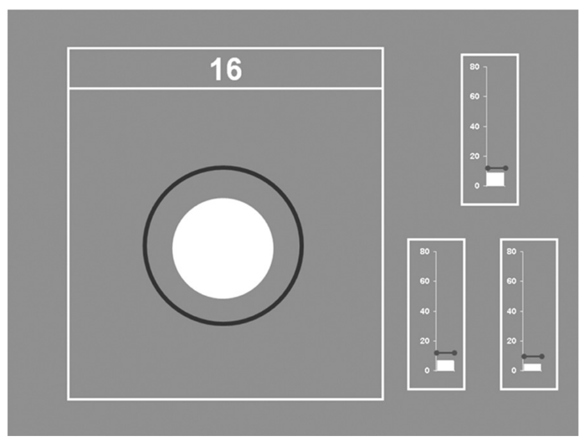


FIGURE 1. The amplitude of the relevant EEG frequency was represented by the white disc within the threshold circle. This white disc increased or decreased in size in response to successful or unsuccessful (respectively) amplitude or ratio changes of the selected frequency bands. The three bars on the right side represent the activity of three other frequency bands (''inhibit bands'': 3–5 Hz, 22–30 Hz, and 45–60 Hz) that participants also had to maintain below threshold to gain reward points. The counter at the top indicated the number of reward points accumulated within each block. The number increased every time the reward threshold, represented by the white disc's expansion to fill the orange circle, was exceeded for more than 250 ms.

in TBR led to an expansion of the inner white disc. If the reward threshold was reached (i.e., the white disc grew to fill the orange circle) for more than 250 ms, 1 reward point was added on the counter. This short interval was used to give feedback at a fast rate and immediately, as necessary for operant conditioning. After each reward, a 3-s no-reward interval followed. The reason to give no further reward within 3 s was to prevent a rapid increase in reward points for longer lasting increases; if, for example, a subject remained over threshold for 5 s, he or she would have received 20 reward points (4 per second); after three 5-s cycles the subject would have had received 60 points and, thus, the threshold would have to be increased (although only 3 points resulted in our method). On the right side of the monitor, three bars represented the different inhibit bands. These bands are used to prevent participants from manipulating EEG amplitude by blinking their eyes or by voluntarily contracting muscles (e.g., of m. masseter or temporalis). It is important to note that participants were not instructed to decrease these inhibit bands. This was simply a way to withhold reward points if the EEG was manipulated voluntarily by eye blinks or muscle artifacts. The frequencies for the inhibit bands were set at 3–5 Hz (for eye blinks) and 22–30 Hz and 45–60 Hz (for muscle artifacts) in the SMR group. In the TBR group, the inhibit band for eye blinks was set at 2–3.5 Hz; the other two bands retained the same settings as in the SMR group.

In the control group, the 3–5 Hz and 45–60 Hz inhibit bands were used similarly to the SMR group. However, the other inhibit band (22–30 Hz in the SMR group) was set respective to the varying training frequencies (which changed from day to day in the randomized broadband feedback [RBF] group): the inhibit band was selected so that it did not interact with the frequency that was being trained. If, for example, the training frequency was 24–25 Hz, the inhibit band was set higher—in this case, 28–30 Hz. If the amplitude in one of these bands was above threshold, no reward was provided. The thresholds of all inhibit bands were fixed at twice the amplitude of a relaxed state.

The reward threshold was set individually and manually for each participant within each training block. The idea was to provide appropriate levels of reward within a 5-min period to keep the participants motivated. Although it is common to set the reward with respect to the time a participant exceeds a given threshold, we had to choose another strategy due to technical limitations. Thus, we decided to change the reward threshold if fewer than 45 or more than 55 reward points were given within a 5-min block. If a participant exceeded the individual threshold more than 55 times during a 5-min block, the threshold was increased (for the next block); if the threshold was exceeded fewer than 45 times, it was reduced. Threshold adjustment for the first training block within a training session was performed with respect to the last threshold value (from Block 5) of the previous training session. The first threshold (Session 1, Block 1) was adjusted according to a pretest and instruction phase: The threshold was modulated until 10 rewards per minute were achieved. The reward threshold for the control group was set in a similar way, so that these participants received approximately the same amount of positive feedback from the targeted frequency band.

Training Instructions and Groups. The SMR group's instruction was aimed at increasing the amplitude of their SMR (12–15 Hz). The TBR group's instruction sought to decrease their theta/beta ratio (theta = 4.5–7.5 Hz; beta = 15–21 Hz). The control group received a so-called RBF training. These participants were instructed to either increase or decrease the amplitude of EEG frequencies in a variety of different 1-Hz broadbands selected from the range of 6 to 35 Hz. The selected frequency changed each day, and during half of the training sessions participants were instructed to increase the amplitude of a given band, and in the other half of the sessions they were told to decrease the amplitude of either the same or a different band. The purpose of varying feedback bands and directions was to provide the participants with individual feedback while minimizing the chances that any real neurofeedback-related training effects would occur (Doppelmayr, Weber, Hoedlmoser, & Klimesch, 2009).

During the training, participants in the SMR and TBR groups were instructed to try to increase the size of the visual stimulus, as often as possible and for as long as possible. This increase is equivalent to an increase in the SMR amplitude or a decrease in the TBR. Control participants, on the other hand, were asked to increase or to decrease the size of the stimulus (increase vs. decrease instruction changed by session). Participants in all groups were told that they would earn reward points for correct performance and that they should try to maximize their points.

EEG Setup, Recording, and Analysis. Data were recorded by the BioGraph ProComp Infinity (Thought Technology®), using a sampling rate of 256 Hz. For all participants, electrodes were placed at C3 and C4 with reference on the left earlobe. A ground electrode was placed on the right earlobe. For the feedback, the ongoing EEG at the electrode sites C3 and C4 was band-pass filtered (IIR Butterworth Filter), and peak-to-peak amplitudes were calculated within the respective frequency bands. The average peak-to-peak amplitudes recorded from electrodes at C3 and C4 were used to create the visual feedback. This setup was used in all groups. EEG data were exported from ProComp Infinity to Neuroscan® Edit. All data were inspected carefully for muscle artifacts and eye movements. One-s artifact-free EEG segments were used for spectral analysis and were averaged. The amplitude values of the SMR, theta, and beta bands were exported for further analysis.

EEG recordings over a period of 30 days, including five training blocks and four resting recordings per person per day, resulted in 270 data sets per person, channel, and frequency band. To reduce the data for statistical analysis, first the amplitude values of C3 and C4 were averaged. Next, the five training blocks within each day were averaged (Day 1–Day 30), and finally, days were grouped on a 5-day basis, resulting in one data set each for T1 (Sessions 1–5), T2, (Sessions 6–10), T3 (Sessions 11–15), T4 (Sessions 16–20), T5 (Sessions 21–25), and T6 (Sessions 26–30). In most cases, these groupings corresponded exactly to Weeks 1 through 6. Due to the high individual variability of amplitude values, the percentage of amplitude increases, similar to the ERS computations of Pfurtscheller (2005) were calculated, resulting in a percentage increase, abbreviated AmpInc for T1 to T2 (AmpInc T1–T2), T1 to T3 (AmpInc T1–T3), T1 to T4 (AmpInc T1–T4), etc.

The threshold values for the SMR threshold (in the SMR group) and the theta/beta threshold (in the TBR group) were noted for each training session. For analysis of changes in thresholds the average of the thresholds for each training block was computed and averaged for 5 consecutive days (T1 = Day 1–Day 5, T2, =Day 6–Day 10, etc.). Again the increase of threshold (ThrInc) values with respect to T1 was computed; however, a difference (rather than a percentage increase) was calculated. These increases are abbreviated ThrInc T1–T2, ThrInc T1–T3, ThrInc T1–T4, and so on.

Performance Tests. Several tasks were performed by the participants before the first and after the last session of training in order to investigate the effects of NFT on cognitive and creative performance. These tasks were presented either in a paper-and-pencil format or on a computer using Presentation (version 6.0) for stimulus presentation.

Simple Reaction Time Paradigm. After a dark gray fixation cross (1 cm × 1 cm) had appeared in the center of the screen on a light gray background, the cross was replaced by a dot (4.5 cm in diameter) for 100 msec, followed again by the fixation cross. Participants had to react as quickly as possible to the dot by pressing the left mouse button (using that hand they usually use for mouse operation—in this and the following tasks all participants used the right hand independent of the original handedness). The interstimulus interval varied randomly from 1 to 4 s. Fifty trials per participant were performed.

Choice Reaction Time Paradigm. After a dark gray fixation cross (1 cm × 1 cm) had appeared in the center of the screen on a light gray background, the cross was replaced by either a distractor stimulus (XXX) or a target stimulus (OOO). The target and distractor displays measured 1.5 cm high by 4.5 cm wide. Participants were instructed to press the left mouse button when the target appeared and to do nothing when the distractor appeared. Targets and distractors were presented in pseudorandom order, with the constraint that no more than four identical items be presented consecutively. The interstimulus interval was 1,400 ms, and the ratio of targets to distractors was 1:5.34 (50 targets and 267 distractors).

Spatial Rotation Task. This task employed the same fixation cross that was described for the previous two tasks. The cross appeared for 1 s, then it was replaced by two three-dimensional shapes (Shepard figures; Shepard & Metzler, 1971), arranged side by side. The two shapes were actually the same, but the right shape was either mirrored and rotated along the vertical axis or just rotated. Participants had to indicate whether the two figures were identical (but rotated) or mirrored (and rotated), by pressing the left or right mouse button, respectively. The angular difference ranged from 20° to 180°, in 20° steps. Forty object pairs were presented, with 20 simply rotated and 20 mirrored and rotated. Pretests revealed a very high variability in individuals' abilities to perform this task; therefore, the presentation time was individually adjusted on the basis of each participant's pretest results. In the pretest, 40 stimulus pairs were shown with a presentation duration of 4, 5, or 6 s each. For the actual test, the presentation duration that had resulted in pretest accuracy in the range of 65% to 75% was chosen.

D2 Test of Attention. The D2 (Brickenkamp, 2002), an attention and concentration test in paper-and-pencil format, uses a single page that displays 14 rows, each with 47 letters, either *p* or *d*. Some letters are accompanied by one, two, or three small marks, similar to apostrophes or quotation marks (e.g., p'' or 'd' or 'p). All instances of the letter *d* that were accompanied by exactly two lines (e.g., ''d or d'' or, d,) served as targets and were to be marked, whereas all other letter–line combinations were distractors and were to remain unmarked. The participants had 20 s to complete each row. To reduce the total test time, we used only the first 10 rows. The items processed (IP; i.e., overall number of items that have been processed), items correct (IC, i.e., IP minus omissions and commission errors), and omission and commission errors were entered for analysis.

Creativity Test. The Verbal Creativity Test (Schoppe, 1979) comprises nine subtests. The first six subtests are related to verbal creativity tasks, such as inventing new names. The other three subtests are titled Unusual Applications, Utopic Situations, and Inventing Nicknames. Based on the raw scores, an Index of Creativity (CI) is calculated, which results in a label of high or low creativity. Two equivalent versions of the test are available. The first test session used Version A; the second session used Version B.

Feedback Display and Reward Schedule

To analyze the effects of NFT on cognitive performance, we performed three steps of analysis. First, we analyzed whether the participants were able to alter their EEG according to the instructions. Second, we investigated the changes in threshold values in more detail, and third, we computed the effects of NFT on cognitive performance.

To determine whether the participants were able to increase SMR amplitudes or theta/beta ratios, four two-way analyses of variance (ANOVAs) were run. These ANOVAs comprised the factors Time (AmpInc T1–T2 to AmpInc T1–T6) as the repeated measure, Group (SMR, TBR, and RBF) as the between-participants measure, and AmpInc as the dependent variable. Separate analyses were performed for the SMR, theta, and beta frequency bands as well as for the theta/beta ratio. To further investigate training effects, we performed separate regressions for each training group in the SMR frequency as well as for the TBR using the amplitude (Day 1–Day 30, i.e., the five-block average of the respective amplitude or ratio of each day) as dependent variable.

Beside changes in amplitude values we also investigated changes in threshold settings. Two two-way ANOVAs were run, with the factor Time (ThrInc T1–T2 to ThrInc T1–T6) as the repeated measure, Group (SMR, TBR) as the between-participants measure, and ThrInc as the dependent variable. (Changes in threshold values were not run for the control group because this group's training protocol presented different frequency bands and different instructions every day.) Again, linear regressions were calculated for the threshold values of the SMR band in the SMR group as well as for the theta/beta threshold in the TBR group, using the respective values for all 30 days (Day 1–Day 30).

Finally, to evaluate the effects of NFT on cognitive performance, we ran one-way ANOVAs with Group (SMR, TBR, and RBF) as the between-participants factor and the pre/post difference scores from the cognitive and creativity tests as the dependent variable. Separate ANOVAs were run for: simple reaction time, choice reaction time, number of correct responses in the spatial rotation task, reaction time for correct responses in the spatial rotation task, IP, IC, omission and commission errors in the D2 test of attention, and the summed scores (CI) from the creativity subtests. For those parameters that showed significant group differences, additional pre/post analyses were performed using repeated measures *t* tests. For analysis of the simple reaction time task, the data set from one participant (SMR group) was missing. For the choice reaction time, task three data sets (two sets of participants of the control group and one set from a participant of the TBR group) were missing.

RESULTS

In this section, Greenhouse-Geisser corrected *p* values are reported where appropriate. To analyze changes in amplitude and TBR, two-way ANOVAs including Time as repeated measure and Group as between-participants measure were performed. The first ANOVA was performed to analyze whether a potential SMR increase is detectible within or across groups. The ANOVA (Time $\times$ Group), run for the SMR frequency band, yielded no significant main effects. However, of interest, the interaction reached significance: $F(8, 152) = 2.71$, $p = .024$. As depicted in Figure 2, only the SMR group showed significant increases in amplitude. One-sample *t* tests performed with the amplitude increases from AmpInc T1–T2 to AmpInc T1–T6 indicated that only

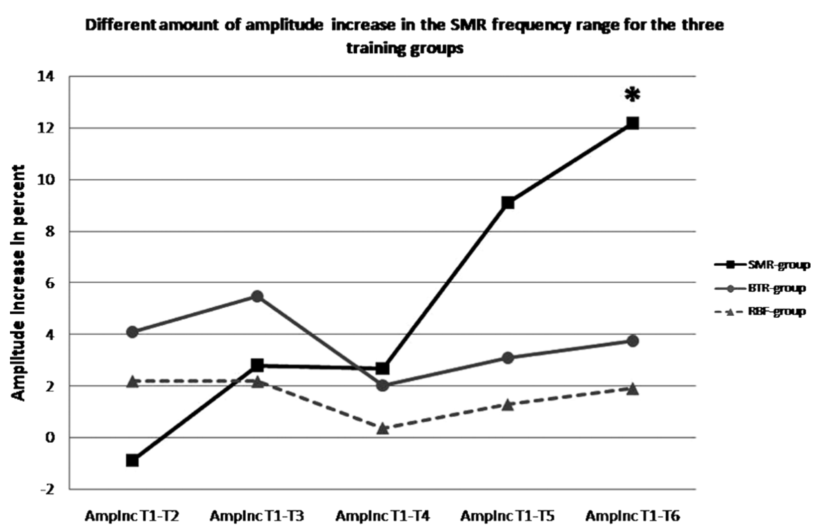


FIGURE 2. The significant interaction between Amplitude Increase and Group in the sensomotoric rhythm (SMR) frequency band, indicating that the expected SMR amplitude increase occurred in the SMR group only. *Note.* Neither the theta/beta ratio (TBR) group nor the randomized broadband feedback (RBF; control) group showed an increase in SMR amplitude.

for the increase AmpInc T1–T6 in the SMR group a significant result emerged, $t(12) = 2.268$, $p = .043$. As expected, the SMR-amplitude increase of the TBR group and the control group did not reach significance.

Similar analyses for the theta and beta frequency bands as well as for the theta/beta ratio revealed no significant main effects or interactions.

To further analyse amplitude changes in the SMR band for the three groups, linear regressions were calculated, again separately for the three training groups. A significant result was obtained only for the amplitude increase of the SMR rhythm in the SMR group ($\beta = 0.78$; $p < .001$). (Similar results were observed using nonlinear regression models.) The regressions calculated for SMR amplitude increase for the TBR group and the control group did not reach significance.

The same type of regression was calculated for the TBR for all three groups, but none of the regressions yielded a significant result.

To analyse whether there were significant changes in threshold in the course of the training, separate one-way ANOVAs were calculated for the changes in SMR threshold in the SMR group as well as for the TBR threshold in the TBR group. These ANOVAs included Time as within-participants factor and the respective threshold increase (ThrInc) as dependent variable. The first ANOVA, calculated for increases of the SMR thresholds, revealed a significant result, $F(4, 52) = 3.45$, $p = .041$. Post hoc one-sample t tests comparing the increase of each time point with the baseline indicated a significant increase for the SMR threshold in the SMR group for ThrInc T1–T5, $t(12) = 2.52$, $p = .027$, and ThrInc T1–T6, $t(12) = 2.24$, $p = .045$, as depicted in Figure 3. The ANOVA performed to analyze changes in the TBR threshold did not reach significance.

To analyse the effect of neurofeedback on behavioral changes, separate one-way ANOVAs with Group (SMR, TBR, and RBF) as between-participants factor and the pre/post difference values as dependent variables were calculated. Separate analyses were run for the pre/post differences of the following parameters: simple and choice reaction times, IP, IC, the number of omission and commission errors of the D2, reaction times, number of correct answers in the spatial rotation task, and CI for the creativity test. Only three of these eight repeated measures ANOVAs revealed significant group effects: simple reaction times, $F(2, 39) = 6.34$, $p = .004$; choice reaction times, $F(2, 37) = 4.33$, $p = .021$; and number of correct responses in the spatial rotation task,

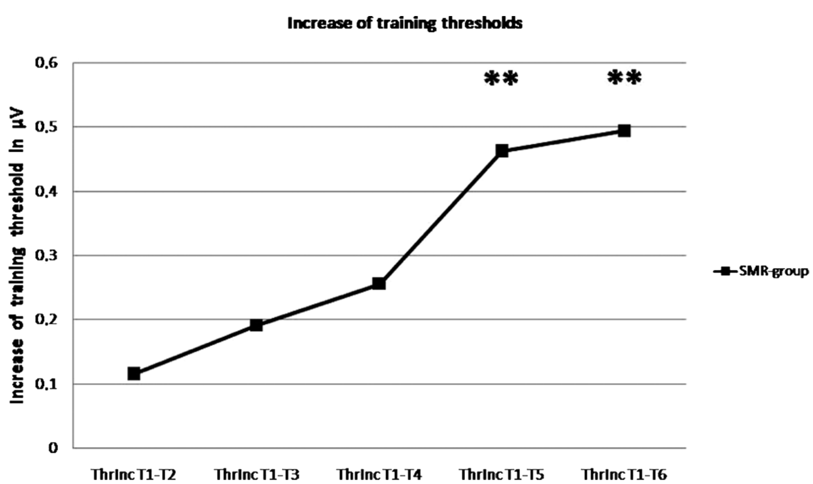


FIGURE 3. The significant results of the one-way analysis of variance clearly indicate the increase in threshold values of the sensomotoric rhythm (SMR) training. *Note.* The depicted values indicate the threshold increase, grouped as the average of each 5-day training session in comparison to the average of the first five-day session. Two asterisks indicate significant increases below 1% level, as compared to the baseline (T1 = 0; see text for details).

$F(2, 40) = 5.40$, $p = .011$. The respective results are displayed in Figure 4a to 4c.

LSD contrasts for the simple reaction time task yielded significant differences between the SMR and control group ($p = .001$) but not between the TBR and control group. Although the SMR group was about 17.4 ms faster after NFT, there was almost no speed difference for the TBR group, and a slowing of 21.5 ms in the control group. The TBR and control groups were not significantly different.

The choice reaction time task produced similar results: a significant difference between SMR and controls ($p = .011$), but no difference between TBR and controls. Again, the SMR group yielded faster reaction times after NFT.

With respect to the increase in the number of correct answers in the spatial rotation task, we can see a similar pattern: a significant difference ($p = .046$) between SMR and control, corresponding to an average increase of 6.7 correct answers after NFT for the SMR group. The difference between the control and TBR groups did not reach significance.

The ANOVAS performed for changes in the reaction times for correct answers in the rotation task, for the D2 changes, IP, IC, omission and commission errors, and the CI creativity scores revealed no significant group differences.

Table 1 provides a concise overview of those parameters that revealed significant group differences, the respective pre/post values, and additional pre/post *t*-test results.

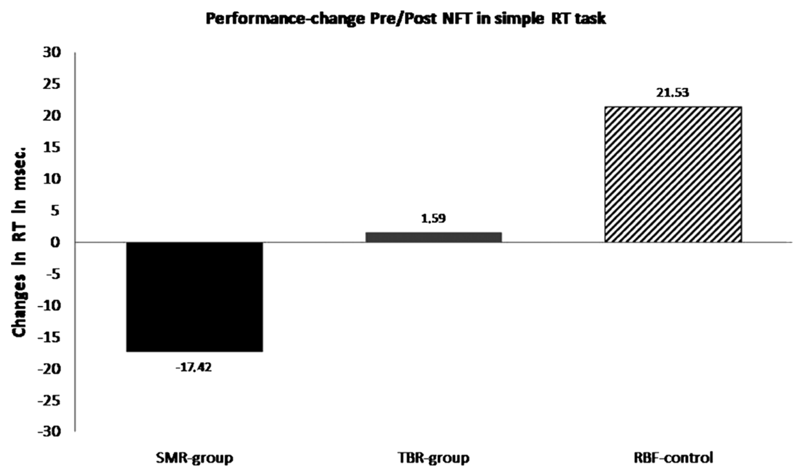
DISCUSSION

The results indicate that SMR NFT exerts positive effects in specific cognitive domains. As a first step, we analysed whether the participants were in fact able to increase the amplitude of either the SMR rhythm or the TBR. Although our results suggest that healthy individuals are well able to learn to increase the SMR amplitude, we could not find changes in the TBR. The fact that our participants were not able to alter the TBR warrants further investigation.

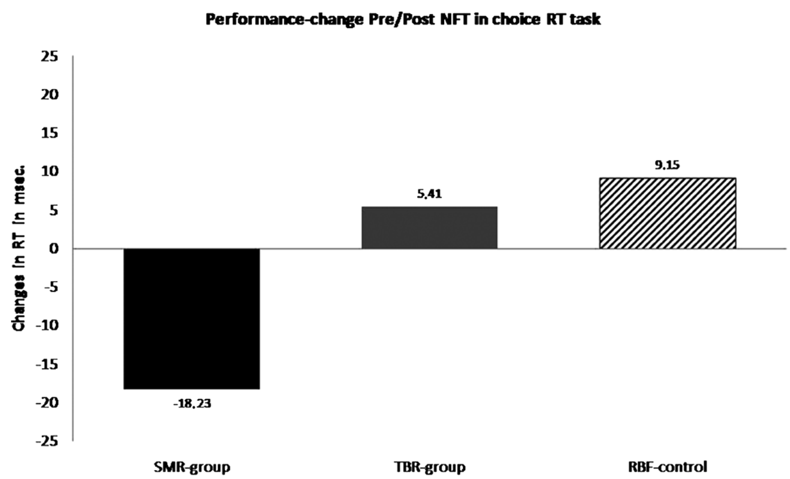
Theta/beta training is frequently used in the treatment of ADHD, and several studies (Arns et al., 2009; Gevensleben, Holl, Albrecht, Vogel, et al., 2009; Rossiter, 2004) report that this type of training is effective. Several of the participants in the cited studies were able to modify their TBR (Kropotov et al., 2007; Leins et al., 2007). However, the work of Leins et al. was based on a very different type of theta/beta training, which included activation and deactivation tasks; this may explain the failure to replicate their results.

Unlike healthy participants, ADHD children have an (arguably pathologically) increased theta rhythm. Thus, in such children, the theta reduction, as a part of the theta/beta protocol is a modification of a deviant enhanced rhythm. Although in children (and adults) with ADHD, increased theta amplitudes are related to attentional problems, in healthy participants increased theta, namely, increased frontal midline theta is related to focused (Doppelmayr, Finkenzeller, & Sauseng, 2008), sustained (Sauseng, Hoppe, Klimesch, Gerloff, & Hummel, 2007) or internalized attention (Aftanas & Golocheikine, 2001), to concentration (Nakashima & Sato, 1993), action regulation (Luu & Tucker, 2001), or cognitive activity (Gevins, Smith, McEvoy, & Yu, 1997). Thus, high amplitudes in ADHD or non-ADHD participants might reflect substantively different processes. An interesting aspect for future work would be to analyse and compare the amount of increase in frontal midline theta amplitude between a sample with and without ADHD.

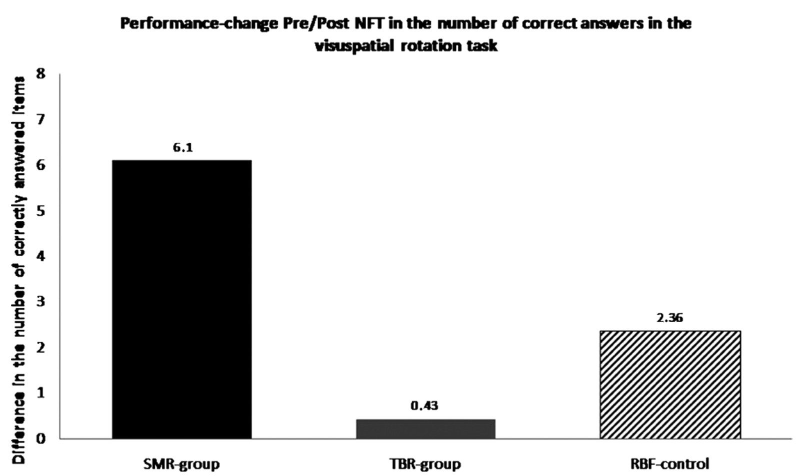
Our finding, that healthy participants were not able to alter their TBR, is consistent with that of Vernon and colleagues (Vernon et al., 2003), who reported that participants trained to modify theta amplitude failed to do so. However, it should be noted that in their study, participants were instructed to increase theta, whereas our participants were instructed to decrease TBR (such that theta is reduced or beta is increased). Most studies that focus on theta or theta/beta ratios have been done with children suffering from ADHD. However, with increasing age, frequencies shift to some extent; thus,



(a)



(b)



(c)

FIGURE 4. The significant results for performance tests are depicted graphically. *Note.* Figure 4a shows results of simple reaction time (RT) tasks, Figure 4b shows the results of the choice reaction time task, and Figure 4c shows the results (number of correct responses) in the spatial rotation task. Asterisks indicate significant differences at $p = .05$. NFT = neurofeedback training; SMR = sensomotoric rhythm; TBR = theta/beta ratio; RBF = randomized broadband feedback.

TABLE 1. The Pre, Post, and Difference Values of Those Parameters That Revealed Significant Group Differences

	Pre	Post	Difference	*T* value	*df*	*p*
Simple reaction time task (ms)						
SMR	273.9	256.4	−17.4	2.27	11	.044
TBR	250.2	251.8	1.6	−0.22	11	*ns*
RBF	253.8	275.3	21.5	−2.01	11	*.069*
Choice reaction time task (ms)						
SMR	378.9	360.6	−18.3	2.13	12	*.055*
TBR	354.4	359.8	5.4	−0.93	12	*ns*
RBF	370.1	379.3	9.2	−2.87	13	.013
No. of correct visuspatial rotations						
SMR	24.5	30.5	6.1	−4.01	12	.002
TBR	29.9	30.3	0.4	−0.36	12	*ns*
RBF	28.4	30.8	2.4	−2.11	13	*.55*

Note. The *t*-test results indicate significant pre/post differences. For a better comparison and overview we added those *p* values that marginally failed the 5% level in italic. SMR = sensomotoric rhythm; TBR = theta/beta ratio; RBF = randomized broadband feedback (i.e., control group's training).

it could be argued that those frequencies relevant for ADHD might be different in adults. Focusing on this question, Bresnahan and Barry (2002) reported an elevated theta power and elevated theta/beta ratios in adult ADHD patients (as compared to a control group). However, the ADHD group showed higher alpha power as well. Similarly, Koehler and colleagues (Koehler et al., 2009) reported that EEG abnormalities are different for children versus adult sufferers of ADHD. Snyder and Hall (2006) have also reported age-related shifts in the TBR of persons suffering from ADHD. Thus, future studies should consider shifting the theta frequency, possibly toward lower alpha.

Although TBR could not be modulated by our participants, the results for increasing the SMR amplitude are well in line with earlier reports for amplitudes in this frequency range (Doppelmayr et al., 2009; Egner & Gruzelier, 2001; Hoedlmoser et al., 2008; Vernon et al., 2003). As can be seen in Figure 2, the amplitude increase is steady and significant; however, the percentage increase reaches a significant level only for the last time interval (i.e., Training Days 26–30). This slow change might be the reason that other studies (Logemann et al., 2010) did not find a significant increase within 16 sessions. This accentuates the fact that SMR NFT seems to be a long-lasting process. Of interest, in other studies SMR amplitude changes have been found in as few as eight sessions (Vernon et al., 2003).

In this study, neither the TBR nor any of the separately analyzed frequency bands of theta or beta changed significantly during the 30-session training period. Thus, our EEG amplitude data indicate that although healthy adult individuals are able to learn to modify the SMR amplitudes, they are not able to alter the theta/beta ratio—at least not if theta and beta frequencies are defined in the way we have done. The findings concerning the threshold values are well in line with those of the amplitude data. Only the thresholds of the SMR group increased significantly; the TBR thresholds remained unchanged after 30 training sessions.

The important conclusion we can draw from amplitude and threshold results is that the increase in the SMR frequency band is not mediated by any other effects, thus a consequence of the training. Neither TBR nor control group training had any effect on the amplitudes of the SMR band; thus, the increase in this band during SMR training is, in fact, specific.

Besides amplitude changes, the investigation of performance improvements was a main focus of our interest. Due to the repeated measures procedure, there were several general improvements that are only related to learning effects and thus have not been described here previously. However, an interesting aspect is the differential improvement between training groups; in comparison with the other groups only the SMR group showed significantly stronger performance improvements after NFT in three of eight different tasks. In general, a learning effect is to be expected if trainings are repeated; this and the strong individual differences in performance on the respective measures were the reasons to simply analyze the performance increases (or differences). Our results demonstrate that for the simple and the choice reaction time tasks, as well as for the number of correct answers in the spatial rotation task, the SMR group's performance was enhanced significantly, in contrast to the two other groups.

Understanding the physiology of the SMR can help explain performance improvements in the cognitive tasks. The SMR rhythm is usually defined in the frequency range of about 12–15 Hz; thus, it is adjacent to or partly overlapping with the upper alpha frequency band (Klimesch, 1998) and the mu rhythm (Pfurtscheller & Neuper, 1994). However, it is still a matter of debate whether these are actually three distinct rhythms. The SMR, as described by Sterman (the first to put SMR feedback training into practice), is a rhythm generated by thalamocortical oscillations, with partial involvement of the basal ganglia (Sterman & Egner, 2006). This loop, however, is very similar to the one proposed for the alpha frequency. SMR is assumed to be the "standby frequency" of the thalamocortical somatosensory and somatomotory pathways, and training should ostensibly result in better control of these systems.

Similar to the function of the (increased) alpha rhythm, that is relevant for timing and inhibition (Klimesch, Sauseng, & Hanslmayr, 2007), the functional meaning of increased SMR amplitudes is decreased sensomotoric excitation. The effectiveness of SMR training in ADHD children has been attributed to this reduced level of excitation (Sterman & Egner, 2006). Although on one hand, reduced sensomotoric excitation is helpful for children with hyperactivity disorders, it is unclear why this is related to shorter reaction times in healthy individuals, as was observed in our study.

The SMR group showed improved performance for the number of correctly answered items in the spatial rotation task, as well in the simple and choice reaction time tasks. Egner and Gruzelier (2004) investigated the differential effects of SMR (12–15 Hz) or beta (15–18 Hz) NFT on a series of attention tasks. With respect to the SMR training and similar to our results, they could not replicate earlier findings of commission error reductions. Those authors argued that the SMR training might have led to an improved regulatory control of the somatosensory and sensorimotor pathways, which in turn led to a more efficient attentional processing, resulting in a better cognitive integration of task-relevant stimuli. This interpretation, as well as the results of Vernon et al. (2003), who reported increased semantic memory performance after SMR NFT, might explain our results. The visuospatial task is related to several processes, such as access to semantic memory, as well as the cognitive integration of the relevant stimuli. Thus, our findings that SMR training leads to a significant stronger improvement in the spatial rotation task, as compared to TBR or RBF training, is consistent with this interpretation.

On the other hand, we have found that the SMR training led to a significantly stronger improvement in a simple and choice reaction time tasks as compared to the other training protocols. Faster reaction times have been reported for a beta 1 training (Egner & Gruzelier, 2004) but were not expected for the SMR training. However, if as described previously, increased SMR amplitudes are related to improved control of the somatosensory and sensorimotor pathways, this might very well explain more accurate and even faster processing in reaction time paradigms. To confirm this assumption, it would be interesting to perform a SMR NFT study that includes the recording of the EEG during the reaction time paradigms. This would allow one to analyze the SMR changes related to fast and slow reactions, both within a session as well as over the entire experiment.

We found that, in contrast to the TBR, SMR amplitude was increased by NFT. In addition, only SMR NFT yielded performance increases.

The fact that we found positive effects for reaction times and spatial abilities for the SMR training should foster further research on this topic. Fast reaction times—but also strong spatial abilities—are required in many practical endeavors; however, these abilities are perhaps most important in the realm of sports. Thus, future studies might focus on the potential of NFT, for example, to enhance psychological training in sports.

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