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Improving cognitive control: Is theta neurofeedback training associated with proactive rather than reactive control enhancement?

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Abstract

Frontal-midline (FM) theta activity (4–8 Hz) is proposed to reflect a mechanism for cognitive control that is needed for working memory retention, manipulation, and interference resolution. Modulation of FM theta activity via neurofeedback training (NFT) demonstrated transfer to some but not all types of cognitive control. Therefore, the present study investigated whether FM theta NFT enhances performance and modulates underlying EEG characteristics in a delayed match to sample (DMTS) task requiring mainly proactive control and a color Stroop task requiring mainly reactive control. Moreover, temporal characteristics of transfer were explored over two posttests. Across seven 30-min NFT sessions, an FM theta training group exhibited a larger FM theta increase compared to an active control group who upregulated randomly chosen frequency bands. In a posttest performed 13 days after the last training session, the training group showed better retention performance in the DMTS task. Furthermore, manipulation performance was associated with NFT theta increase for the training but not the control group. Contrarily, behavioral group differences and their relation to FM theta change were not significant in the Stroop task, suggesting that NFT is associated with proactive but not reactive control enhancement. Transfer to both tasks at a posttest one day after training was not significant. Behavioral improvements were not accompanied by changes in FM theta activity, indicating no training-induced modulation of EEG characteristics. Together, these findings suggest that NFT supports transfer to cognitive control that manifests late after training but that other training-unspecific factors may also contribute to performance enhancement.

KEYWORDS

cognitive control, executive functions, frontal-midline theta, neurofeedback, training, working memory

1 | INTRODUCTION

In order to effectively coordinate and modify behavior based on experiences, cognitive control processes are needed. Numerous cognitive training studies observed enhanced cognitive control processes after training of working memory (e.g., Klingberg, 2010; Morrison & Chein, 2011), task-switching (e.g., Karbach & Kray, 2009), or multi-tasking (e.g., Anguera et al., 2013). Notably, training transfer to both the trained and untrained tasks provided evidence for the remarkable capacity for plasticity of the adult brain (Lövdén et al., 2010). Despite these positive findings, not all training studies succeeded in showing transfer effects, provoking a debate about the effectiveness of cognitive trainings and the generalizability of training-induced changes (Melby-Lervåg & Hulme, 2013; Owen et al., 2010; Simons et al., 2016). Lindenberger et al. (2017) suggested that the debated questions can only be answered if research not only focuses on changes occurring pretraining to posttraining but also investigates the underlying physiological changes that take place during training and influence task performance. According to the overlap hypothesis of training transfer (Buschkuehl et al., 2012; Dahlin et al., 2008; Jonides, 2004; Lustig & Flegal, 2008), cognitive training leads to transfer if trained and transfer task engage similar functional processes (functional overlap) and activate similar brain regions (neural overlap). For transfer to occur, overlapping cognitive processes and shared brain activity need to change over the course of training (Lövdén et al., 2010). Given that functional processes and brain activations are both reflected in EEG dynamics, direct modulation of oscillatory characteristics should lead to transfer in tasks, in which the modulated EEG oscillations are engaged.

An interesting neuroscientific method that allows to actively train particular EEG oscillations is neurofeedback training (NFT). Thereby, participants learn to volitionally control their brain activity by receiving feedback, for example, about the amplitude of a particular frequency. Over recent years, an increasing number of studies has tried to enhance cognitive performance with the help of neurofeedback (Dessy et al., 2018; Gruzelier, 2014; Vernon, 2005). Many NFT studies focused on training of frontal-midline (FM) theta oscillations (4–8 Hz) and found transfer to attentional and working memory processes (Enriquez-Geppert et al., 2014; Reis et al., 2016; Wang & Hsieh, 2013), memory control processes in source memory retrieval (Eschmann et al., 2020), and item and motor memory consolidation (Reiner et al., 2014; Rozengurt et al., 2016, 2017). These findings support the view that FM theta oscillations reflect a general cognitive control mechanism that is required in a large variety of cognitive tasks (Cavanagh & Frank, 2014; Helfrich & Knight, 2016; Hsieh & Ranganath, 2014; Klimesch et al., 2008; Sauseng et al., 2010). It is assumed that FM theta power reflects the need for cognitive control that is implemented as a top-down control mechanism via theta phase synchronization between FM theta source regions, such as the midcingulate cortex (Sauseng et al., 2007), and other task-relevant brain regions (Cavanagh & Frank, 2014; Sauseng et al., 2010). In support of this view, FM theta activity was shown to support both proactive and reactive control processes. For instance, FM theta activity was enhanced during working memory maintenance with high memory load (Jensen & Tesche, 2002; Onton et al., 2005) and in interference situations, in which the appropriate stimulus or response had to be selected out of two conflicting ones (Cohen & Cavanagh, 2011; Nigbur et al., 2011). According to the dual mechanisms of control (DMC) framework by Braver (2012), proactive control is a top-down selection process occurring before a cognitively demanding event. It facilitates processing of task-relevant information by maintaining task goals and biasing sensory processing. Contrarily, reactive control is a late correction process taking place after the detection of an erroneous or conflicting event. It allows for the selection of adequate responses by inhibiting interfering ones. Interestingly, theta oscillations were shown to have a focal frontal distribution in a mainly proactive control recruiting delayed match to sample (DMTS) task whereas the topographical distribution of theta oscillations was broader in a primarily reactive control recruiting Stroop task (Eschmann et al., 2018). This finding indicates that even though FM theta activity reflects a general mechanism of cognitive control, its topographic distribution and thus the recruited theta network may differ as a function of the specific task requirements at hand (Cooper et al., 2015, 2017).

Despite the evidence that FM theta NFT transfers to a large variety of cognitive and memory tasks, it did not show transfer to all transfer tasks under investigation and transfer effects were not consistently accompanied by changes in underlying EEG characteristics, resulting in a mixed pattern of results (Enriquez-Geppert et al., 2014; Reis et al., 2016; Rozengurt et al., 2016, 2017; Wang & Hsieh, 2013). For instance, Wang and Hsieh (2013) demonstrated that young adults were less susceptible to interference in an attention task after performing 12 theta NFT training sessions. In contrast, working memory performance in a Sternberg task failed to increase as a function of NFT in the same study. In a similar vein, Enriquez-Geppert et al. (2014) found transfer of an eight-session theta NFT to an *n*-back and a task-switching task, but not to a Stroop and a stop-signal task. In a posthoc interpretation, these results have been suggested to show that FM theta NFT improves proactive rather than reactive control processes. Although the DMC framework might explain some of the heterogeneous behavioral transfer findings of FM theta NFT, training-induced changes in theta activity during the transfer tasks either have been inconsistent with the behavioral findings

(Enriquez-Geppert et al., 2014) or have not been investigated (Reis et al., 2016; Rozengurt et al., 2016, 2017; Wang & Hsieh, 2013). While training-induced FM theta power increases were found in an *n*-back transfer task (Enriquez-Geppert et al., 2014), FM theta decreases have been associated with enhanced source memory retrieval (Eschmann et al., 2020). Consequently, it remains an open question what type of cognitive control processes are enhanced by FM theta NFT and whether behavioral transfer is accompanied by training-induced increases or decreases in underlying EEG dynamics. Moreover, temporal characteristics of both behavioral transfer to cognitive control processes and their underlying EEG characteristics to later follow-up measurements have not been systematically investigated (Enriquez-Geppert et al., 2014; Reis et al., 2016; Wang & Hsieh, 2013), leading to the question whether NFT is an effective intervention technique for long-lasting cognitive enhancement.

In order to evaluate the effectiveness of NFT, the present study investigated transfer of FM theta NFT to cognitive control processes. More specifically, it was assessed (a) whether seven sessions of FM theta NFT lead to performance improvement in two tasks requiring mainly proactive and reactive control, namely, a DMTS and a color Stroop task, (b) whether behavioral transfer is accompanied by training-induced changes in EEG characteristics underlying cognitive control processes, and (c) whether training-induced behavioral and EEG changes are present only one day after the last NFT session or also persist to a second posttraining session 13 days later. Therefore, a training group who trained to upregulate their individually estimated FM theta activity was compared to an active control group who received feedback to frequency ranges that were randomly chosen for each session (see Wang & Hsieh, 2013 for a similar procedure). Pretest to posttest measurement changes in both tasks were expected to be associated with the extent of FM theta upregulation during NFT. Hence, participants who are able to increase their FM theta activity during training to a greater extent should also demonstrate a larger pretraining to posttraining behavioral change. Although the DMTS and color Stroop task do not allow for process-pure measurements of proactive and reactive control, they are assumed to recruit one or the other to a greater extent (e.g., Braver et al., 2020; Enriquez-Geppert et al., 2014; Eschmann et al., 2018). In the DMTS task, stimulus manipulation and active maintenance for comparison with an anticipated probe is thought to primarily involve proactive control, which supports maintenance of goal-relevant information. In the Stroop task, the color word strongly activates a reading response that needs to be inhibited in order to successfully name the ink color. In order to suppress the prepotent reading response reactive control is expected to be recruited. It is noteworthy that both tasks presumably also require the other type of cognitive control but to a smaller extent. For example, if many incongruent trials follow each other in the Stroop task, an adaptation of cognitive control takes place that reduces Stroop interference and is assumed to reflect changes in proactive control (e.g., Braver et al., 2020; Gonthier et al., 2016). However, congruency conditions were presented intermixed in the present study and item-specific Stroop effects can thus be ascribed to reactive control. Training-induced modulations of EEG dynamics in the transfer tasks were expected to be present in the form of increases or decreases of FM theta activity, reflecting either increased recruitment or more efficient use of cognitive control processes (Kelly & Garavan, 2005). If these training-induced FM theta changes are directly influenced by the NFT gain, pretest to posttest EEG changes should be related to FM theta change during NFT for the training but not the control group.

2 | METHOD

2.1 | Participants

Altogether, 36 German students who were recruited from Saarland University's student community participated in the NFT study (same as in Eschmann et al., 2020). Participants were assigned to a training group (TG; $n = 17$, five male, $M_{TG} = 22.65$ years, age range = 20–30 years) and an active control group (CG; $n = 18$, six male, $M_{CG} = 23.33$ years, age range = 19–27 years) that were matched in sex, age, and study subject. One additional participant of the training group had to be excluded from the analyses because of being an outlier in NFT theta increase as defined by the Tukey method with three interquartile ranges (Tukey, 1977) and due to incorrect execution of the DMTS task. Prior to the study, participants conducted an online questionnaire, in which they indicated that they enjoy rollercoaster driving with a score > 4 on a 7-point Likert scale. Training group and control group did not differ in their preference for rollercoaster driving ($M_{TG} = 6.11$, $M_{CG} = 6.22$; $t(34) = 0.11$, $p = .710$, $d = 0.12$). Participants indicated that they were healthy, had normal or corrected-to-normal vision, and showed no history of neurological or psychiatric diseases. Furthermore, all participants were right-handed as indicated by the Edinburgh Handedness Inventory (Oldfield, 1971). According to participant's chronotype measured with the German version of the Morningness-Eveningness Questionnaire (D-MEQ; Griefahn et al., 2001), testing times were scheduled. Written informed consent was provided prior to the study and participants were paid 8€ per hour in return for their participation. If desired, the payment was partially

replaced by course credit. The experimental procedure was approved by the local ethics committee in accordance with the declaration of Helsinki.

2.2 | Experimental design and data acquisition

Transfer effects from individual FM theta upregulation to performance in the cognitive tasks were assessed in a pre-post design (Figure 1). In a pretraining and two posttraining sessions, all participants performed a delayed match to sample (DMTS) and a color Stroop task, in which cognitive control processes have previously been shown to be accompanied by FM theta oscillations (Berger et al., 2016; Eschmann et al., 2018; Griesmayr et al., 2014; Hanslmayr et al., 2008). Additionally, participants performed a source memory task that investigated transfer to memory control processes in episodic memory. NFT sessions took place on seven fixed days between the pretraining and posttraining sessions for both the training and control group. Based on another NFT study that showed high participant commitment for 10 testing sessions within two weeks and a greater FM theta increase after more distributed NFT sessions (Enriquez-Geppert et al., 2014), it was decided that all NFT sessions, the pretraining session, and the first posttraining session take place within two weeks. Thereby, the first three NFT sessions, during which participants were encouraged to find their preferred strategy for theta upregulation, were separated by 24 hr whereas the last four NFT sessions, during which participants applied their preferred strategy, were further distributed by 48 hr. This design allowed to test new participants every two weeks while administering the second posttraining session 13 days after the last NFT session for the previously trained participants. For every testing and training session, participants were seated comfortably in a dimly lit and quiet experimental room. Computer-based tasks and NFT were presented on a Dell Computer with a Dell 24-inch monitor placed at a viewing distance of approximately 70 cm.

2.2.1 | Task procedures

All transfer tasks were presented using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, USA). Task order of the DMTS and Stroop task was counterbalanced across participants but remained fixed across pretraining and posttraining sessions. Before conduction of the DMTS and the color Stroop task, participants performed the encoding phase of a source memory task. During each pretraining and posttraining session, participants learned 200 concrete nouns by judging the object denoted by the noun by its pleasantness or animacy. After the DMTS and color Stroop task, participants performed the recognition test of the source memory task, during which they were asked to indicate whether the presented nouns were learned in the previous encoding phase or not. If participants indicated that the word was old, they were asked about the source context (pleasantness or animacy), in which the noun was encoded. Transfer findings of FM theta NFT to episodic memory measured in the source memory task are reported in Eschmann et al. (2020).

The DMTS task consisted of two conditions, namely a retention condition and a manipulation condition, which each consisted of 12 practice trials and 70 task trials per condition (Figure 2). Stimuli consisted of either one or four colored squares integrated in a 6 × 6 matrix with a visual angle of 9.8° × 9.8°. In the retention condition, participants were instructed to simply maintain the position of one green colored

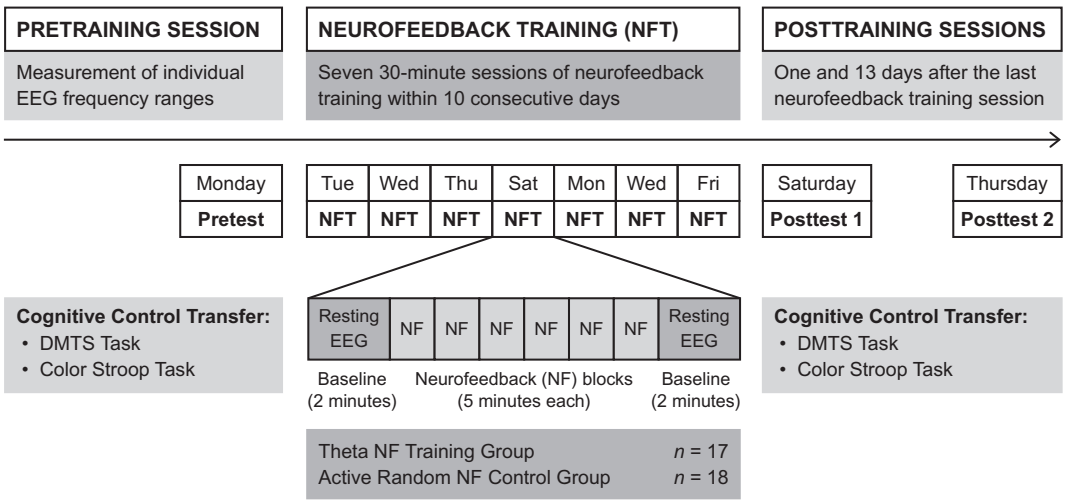

FIGURE 1 Neurofeedback training schedule. Neurofeedback training consisted of seven neurofeedback sessions and transfer to cognitive control processes in a delayed match to sample (DMTS) task and a color Stroop task was investigated from one pretraining to two posttraining sessions. All sessions took place at the same fixed days for each participant

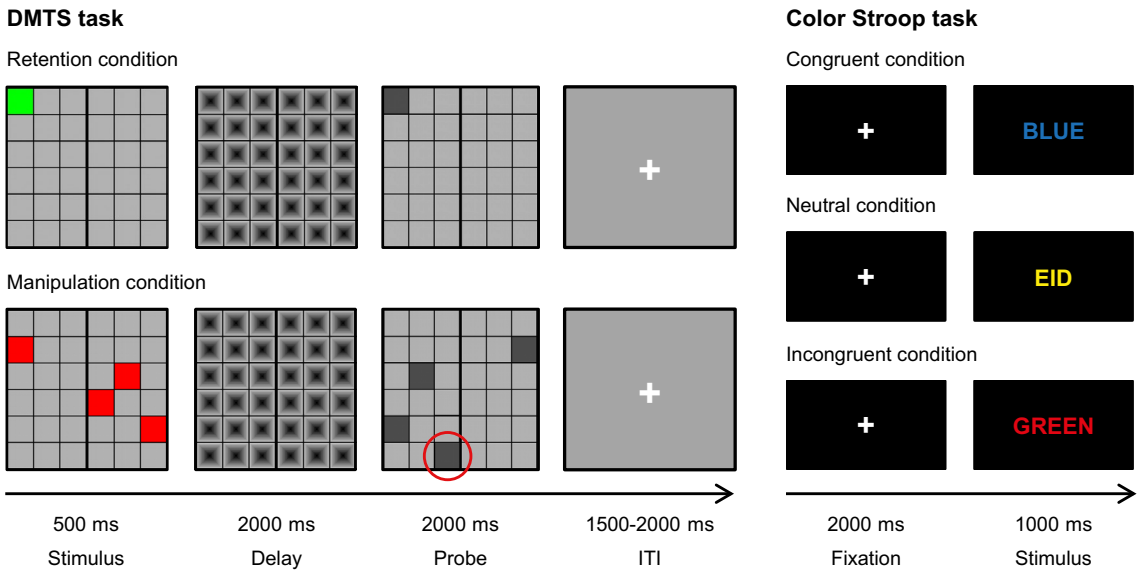

FIGURE 2 Trial procedures of the DMTS and color Stroop task. In the DMTS task, participants were asked to simply maintain the stimulus in the retention condition whereas they had to mirror the colored squares at the vertical stimulus midline in the manipulation condition. After a delay period, participants had to indicate whether the positions of the maintained or mirrored squares of the stimulus matched the positions of the dark gray squares of a probe. The red circle, which was not displayed in the experiment, indicates the square of the probe that is at the wrong position, making the displayed manipulation trial a non-match. In the Stroop task, participants had to name the ink color while ignoring to read the color word in a congruent, neutral, and incongruent condition

square over a delay period. In the manipulation condition, participants had to mentally mirror the position of four red colored squares at the vertical stimulus midline and maintain their mirrored locations. Stimuli were presented for 500 ms followed by a delay period of 2,000 ms, during which a mask consisting of gradational gray colored squares was presented in order to prevent any after image effects. Afterwards, a probe matrix with gray squares either matching or not matching the position of the colored squares of the encoded stimulus was presented for 2,000 ms. Participants were asked to indicate via mouse button press with their left or right thumb whether the gray squares of the probe were identical (match) or different (nonmatch) from the maintained colored squares' locations. In the nonmatch trials of the manipulation condition, only one of the four squares did not match the correct mirrored position. For half of the trials the correct response was match and for the other half nonmatch. Participants were instructed to respond as fast and accurately as possible during the presentation of the probe. During the adjacent jittered intertrial interval (ITI), a central fixation cross was presented for a duration of 1,500–2,000 ms. Both conditions of the DMTS task were presented in 35-trial blocks and the order of conditions was counterbalanced across participants but stayed fixed across all pretraining and posttraining sessions. All instructions and stimuli were presented centrally against a gray background.

The Stroop task consisted of a congruent, neutral, and incongruent condition (Figure 2). In all pretraining and posttraining sessions, trials of all Stroop conditions were presented in randomized order within eight blocks that consisted of 24 trials each. Before conduction of the 192 task trials in the pretraining session, participants were able to familiarize with the task in 24 practice trials. All stimuli were presented with a visual angle of 4.1° × 1.2° for 1,000 ms against a black background and were preceded by a central white fixation cross, which was presented for 1,000 ms. In the congruent condition, the German color words for blue ("BLAU"), green ("GRÜN"), red ("ROT"), and yellow ("GELB") were presented in their respective ink color. In contrast, the incongruent condition consisted of the color words presented in a color different from their meaning. In the neutral condition, the four neutral German words for leak ("LECK"), oath ("EID"), joke ("WITZ"), and misfortune ("PECH") were presented in the four ink colors. These letters have comparable length and do not share initial letters with the color words. Participants were asked to indicate the respective ink color as fast and accurately as possible while ignoring the word meanings. Responses were given by pressing the colored keys "C" and "S" with the left and "M" and "L" with the right index and middle finger on a conventional German keyboard. The color to key assignment was fixed across participants, blocks, and pretraining and posttraining sessions.

2.2.2 | Pre-/posttraining EEG recordings and processing

During the transfer tasks, electroencephalographic (EEG) activity was continuously recorded with a sampling rate of

500 Hz from 32 Ag/AgCl electrodes using a Brain Amp EEG amplifier and Brain Vision Recorder software (Brain Products GmbH, Gilching, Germany). Scalp electrodes were mounted on a fitted cap according to the extended 10–20 system. The electrooculogram was recorded for eye movement detection by four additional electrodes placed at the outer canthi of the eyes and above and below the right eye. During continuous EEG recordings, electrode impedances were kept below 5 kΩ and signals were filtered with an online low-pass filter of 100 Hz. All electrodes were referenced to the left mastoid electrode during data acquisition and re-referenced offline to averaged mastoids.

Offline analyses of EEG signals were performed using Brain Vision Analyzer 2.1 software (Brain Products GmbH, Gilching, Germany). Only correct trials were used for time-frequency analyses. First, raw data of both tasks were inspected visually and pronounced artifacts were removed manually in order to improve artifact correction by ICA decomposition. Second, data were band-pass filtered at 0.5 and 40 Hz (48 dB/oct) before being re-referenced to linked mastoids. An infomax ICA was used to identify and remove components representing eye movements and other muscle artifacts. Afterwards, the continuous EEG of the DMTS task was segmented from −1,250 ms prior to stimulus presentation until 3,500 ms thereafter, comprising both the 500 ms encoding and the 2,000 ms maintenance interval. The EEG of the Stroop task was cut from −1,250 ms prior to word presentation until 2,000 ms thereafter. A baseline correction in the time domain from −200 ms to 0 ms prior to stimulus and word presentation and an automatic artifact rejection was applied. Segments exceeding a voltage step of 30 μV/ms, a maximum-minimum difference of 100 μV, and an amplitude of ±60 μV were removed. Finally, any segments with remaining artifacts were removed by hand.

For calculation of frequency amplitude estimates, single trial activity from 1 to 40 Hz was decomposed using a complex Morlet wavelet with 79 linear 0.5 Hz frequency steps and a time-frequency resolution indicated by a parameter c of 6. Subsequently, event-related synchronization/desynchronization (ERS/ERD) was calculated for every condition. ERS/ERD is defined as the percent power change relative to a baseline, which was measured in the time interval of −800 to −200 ms before stimulus onset for both tasks. Segments of both tasks were separated into five equally sized time intervals, resulting in five 500 ms time intervals in the DMTS task (0–500 ms, 500–1,000 ms, 1,000–1,500 ms, 1,500–2,000 ms, and 2,000–2,500 ms) and five 200 ms time intervals in the Stroop task (0–200 ms, 200–400 ms, 400–600 ms, 600–800 ms, 800–1,000 ms). For regression analyses, the average of each participant's ERS/ERD values of the mean theta activity (4–8 Hz) in these time intervals were extracted from electrode Fz.

2.2.3 | NFT protocol and processing

A self-built neurofeedback protocol using a ProComp5 Infinity amplifier and BioGraph Infinity software (Thought Technology Ltd., Montreal, Canada) was administered for the training of FM theta upregulation over seven training sessions, each consisting of six 5-min training blocks and two 2-min resting EEG measurements before and after the training (Figure 1). For a detailed description of the NFT protocol, see Eschmann et al. (2020). Participants of the training group received feedback to their individual FM theta activity, that is, participant's mean individual theta peak (ITP) ±1 Hz within the 4–8 Hz theta range that was determined at electrode Fz in the transfer tasks and averaged across conditions. In contrast, participants of the active control group trained to upregulate another randomly chosen 2 Hz frequency band each session (10–12 Hz, 12–14 Hz, 14–16 Hz, 16–18 Hz, 18–20 Hz, 20–22 Hz, and 22–24 Hz). During NFT, frequency bands for feedback generation were extracted with an infinite impulse response (IIR) filter from raw EEG data measured with a sampling rate of 256 Hz at electrode Fz. Amplitude changes were calculated as the root mean square (RMS) over a one second sliding window and presented on a numerical speed indicator and as the speed of a rollercoaster animation that participants were instructed to accelerate as fast and long as possible. Participants of both groups were given the same list of strategies in order to speed up the rollercoaster movement (e.g., mental imagery, arithmetic operations, motor imagery). Eye and muscle artifacts were extracted by two frequency bands (0.5–2 Hz and 43–59 Hz) and indicated to participants by a color change from green to red of a light, which was presented next to the rollercoaster feedback. Participants did not know whether they belonged to the training or active control group but were debriefed after the last posttraining session.

Offline analyses of NFT data was conducted with Brain Vision Analyzer 2.1 software (Brain Products GmbH, Gilching, Germany). Raw data of training and baseline blocks were filtered with a 0.1–40 Hz bandpass filter (48 dB/oct) and segmented into 1-s intervals. Intervals with a voltage step greater ±35 μV were discarded from further analyses in order to account for artefacts. Frequency analysis was performed with a fast Fourier transformation (FFT) with a 10% hamming window and normalization to overall power (1–24 Hz). Results were then averaged over all 1-s intervals for each block and each NFT session and amplitude values of individual theta (ITP ± 1 Hz), alpha (ITP + 3–5 Hz), and beta (ITP + 7–9 Hz) frequencies were extracted.

2.3 | Data analyses

2.3.1 | NFT effects

The increase of each participant's individual FM theta amplitude during NFT was calculated separately for each session. Therefore, a within-session baseline correction was used, that is, theta increase was calculated as the percentage change from the resting EEG baseline before the respective training session to the mean theta amplitude of the session's training blocks. This procedure has the advantage that inter-individual differences in FM theta amplitudes and measurement variability across the seven training sessions are deducted from the training gain. Training effects were analyzed with a repeated-measures ANOVA with the between-subject factor Group (TG vs. CG) and the within-subject-factor Sessions (1–7). In order to investigate the specificity of FM theta NFT, the same analysis was conducted with individual alpha and beta activity. Training-induced changes of FM theta activity during the transfer tasks might be biased by resting-state theta changes that are caused by NFT and can be measured in the end baseline after training. Increased resting-state theta activity may have reduced the possibility for finding further theta increases in the transfer tasks. Contrarily, decreased resting-state theta activity may have led to theta decreases in the transfer tasks. In order to test whether resting-state EEG activity changed on the basis of NFT, a repeated-measures ANOVA with the factors Baseline (start vs. end) and Sessions (1–7) was conducted for the training group.

2.3.2 | Behavioral transfer

Reaction times and accuracy in the conditions of the DMTS and Stroop task were used to investigate NFT transfer to proactive and reactive control processes, respectively. For statistical analyses, only correct trials were used. Task repetition effects, that is, performance enhancement based on repetitive execution of a task, are a common phenomenon in the training literature (e.g., Enriquez-Geppert et al., 2014; Karbach & Kray, 2009; Schneiders et al., 2011). In order to explore repetition-induced performance enhancements within each group, we calculated paired *t* tests that compared performance at pretest with performance at the second posttest separately for the training and control group. However, these performance increases do not allow for inferences on training-induced transfer effects. In order to extract truly training-induced transfer effects that are solely caused by FM theta enhancement, it is crucial to compare a training group to an active control group (Enriquez-Geppert et al., 2017). Both groups only differ in FM theta upregulation whereas all other task and transfer aspects (e.g., repetitive task execution and training procedure) are the same. Therefore, the main analyses focused on transfer effects that were investigated by comparing training and control group performances. First, performance differences between both groups in the posttraining sessions were assessed by separate regression analyses with the predictors Pretraining Performance and Group (TG vs. CG). By including pretraining performance in the regression analyses we accounted for possible performance differences before training that might have biased transfer effects. For these analyses, regression coefficients *b* and *t* tests solely for the predictor of interest, namely Group, are reported since pretraining performance was controlled for. Second, the influence of participants' NFT theta change on their pretraining to posttraining performance gains were investigated with linear regression analyses. Therefore, participants' individual FM theta amplitude relative to the respective session's start baseline was used. NFT theta change was calculated as the increase from the first three NFT sessions, during which participants tested different strategies, to the last four NFT sessions, during which participants used their preferred strategy to upregulate theta activity. Participants' performance gain was calculated as the percentage increase from pretraining to the respective posttraining session.

2.3.3 | EEG characteristics of the transfer tasks

Comparable to the analyses of behavioral transfer, multiple regression analyses with the predictor Group (TG vs. CG) while accounting for pretraining activity were conducted for FM theta activity during both the DMTS and Stroop task. For the DMTS task, FM theta ERS/ERD in the retention and manipulation condition was investigated for all 500 ms time intervals. For the Stroop task, FM theta ERS/ERD in the congurent, neutral, and incongruent condition was analyzed for all 200 ms time windows.

All statistical analyses were computed with IBM SPSS statistics 25 software (IBM Corp., New York, USA). For ANOVAs, the general linear model was used and regressions were analyzed with the linear regression enter method. Before analyses, data was visually inspected in order to check whether ANOVA and regression assumptions were met. Furthermore, normal distribution was checked with the Kolmogorov-Smirnov test, homogeneity with the Levene's test, error independency for regressions with the Durbin-Watson test, and multicollinearity of multiple regressions with the variance inflation factor (VIF). Whenever sphericity was violated as indicated by a significant Mauchly test, the Greenhouse-Geisser correction was applied and adjusted *p* values are given. For all analyses, the significance level was set to $\alpha = .05$ and if not indicated differently, two-tailed results are reported. In order to correct the α-level for multiple comparisons in the analyses of different EEG time windows, the Bonferroni method was applied. For all regression analyses,

univariate outliers were detected with the Tukey method using three interquartile ranges (Tukey, 1977) and bivariate outliers were calculated and excluded with the Mahalanobis distance method (Mahalanobis, 1936). Based on these outlier detection methods, two participants of the training group and three participants of the control group were removed for different multiple and linear regression analyses of behavioral data. For regression analyses of EEG characteristics, another four participants of the training group and five participants of the control group were excluded for different analyses. Only one of these outliers of the control group was also removed from behavioral analyses. Notably, none of the outliers was excluded from all statistical analyses.

3 | RESULTS

3.1 | NFT effects

The training group was able to successfully enhance FM theta activity over the seven NFT training sessions relative to the control group as revealed by a repeated-measures ANOVA with a significant main effect of Group ($F(1,33) = 6.31$, $p = .017$, $\eta_p^2 = 0.16$), a significant Group by Session interaction ($F(6,198) = 2.45$, $p = .026$, $\eta_p^2 = 0.07$), and a significant linear interaction contrast ($F(1,33) = 9.17$, $p = .005$, $\eta_p^2 = 0.22$), suggesting that the difference between groups increased linearly over the course of training. In separate one-way repeated-measures ANOVAs, the main effect of Session was significant for the training group ($F(2.79,47.45) = 2.98$, $p = .044$, $\eta_p^2 = 0.15$) but not for the control group ($F(3.39,57.68) = 0.73$, $p = .552$, $\eta_p^2 = 0.04$). This indicates that the training group increased their FM theta amplitude linearly across the NFT sessions whereas the control group did not achieve the same. Please see Eschmann et al. (2020) for a figure and a more detailed description of NFT results. Individual alpha and beta activity did not change over the course of training or differ between both groups (all p values $> .063$), indicating that the training group specifically enhanced FM theta oscillations via NFT. In order to explore whether NFT led to any changes in resting-state theta activity that could have biased training-induced changes in EEG characteristics, baseline theta activity of the training group was analyzed with a repeated-measures ANOVA with the factors Baseline (start vs. end) and Sessions (1–7). Neither the main effects of Baseline and Session nor the Baseline by Session interaction were significant (all p values $> .109$). Hence, there is no evidence for significant changes of resting-state theta activity that could have biased training-induced changes in EEG characteristics.

3.2 | Behavioral transfer

The effects of task repetition on performance in the DMTS and Stroop task were analyzed with paired t tests that compared performance at pretest with performance at the second posttest separately for the training and the control group. In the retention condition of the DMTS task, only the training group showed faster reaction times ($t(16) = 5.30$, $p < .001$, $d = 1.29$) and better accuracy ($t(16) = 2.66$, $p = .017$, $d = 0.65$) at the second posttest whereas performance did not significantly improve for the control group (all p values $< .101$). In contrast, both the training group (reaction times: $t(16) = 5.62$, $p < .001$, $d = 1.36$; accuracy: $t(16) = 3.90$, $p < .001$, $d = 0.95$) and the control group (reaction times: $t(17) = 2.15$, $p = .047$, $d = 0.51$; accuracy: $t(17) = 3.46$, $p = .003$, $d = 0.82$) showed better performance in the manipulation condition at the second posttest relative to pretest. Given that the manipulation condition is more difficult than the retention condition and, thus, allows for greater improvement, both groups might have profited from task repetition. In all three conditions of the Stroop task, both the training group (congruent: $t(16) = 3.05$, $p = .008$, $d = 0.74$; incongruent: $t(16) = 4.23$, $p = .001$, $d = 1.03$; neutral: $t(16) = 3.34$, $p = .004$, $d = 0.81$) and the control group (congruent: $t(17) = 2.76$, $p = .013$, $d = 0.65$; incongruent: $t(17) = 3.40$, $p = .003$, $d = 0.80$; neutral: $t(17) = 2.22$, $p = .040$, $d = 0.52$) showed faster reaction times at the second posttest whereas accuracy remained the same (all p values $> .075$). Altogether, these results show that both groups profited from repetitive task execution except in the retention condition, in which only the training group showed performance enhancement. However, these effects reflect a mixture of repetition-related and training-induced performance enhancements and, hence, do not allow for inferences on transfer effects that are solely induced by FM theta upregulation. Consequently, the focus of the following analyses lies on the direct comparison of training and control group performance.

In order to investigate pure training-induced behavioral transfer effects of NFT to the DMTS and the Stroop task in the first and second posttraining session, regression analyses that accounted for pretraining performance were analyzed separately for reaction times and accuracy (Figure 3). For the DMTS task, analyses of the retention condition revealed faster reaction times ($b = 56.62$, $t(32) = 2.37$, $p = .012$, one-tailed) and higher accuracy ($b = 0.01$, $t(32) = 2.01$, $p = .026$, one-tailed) for the training compared to the control group in the second but not the first posttest (all p values $> .072$, one-tailed). This indicates that FM theta NFT improved performance in the retention condition, in which participants had to simply maintain the position of one stimulus square that imposes only a low

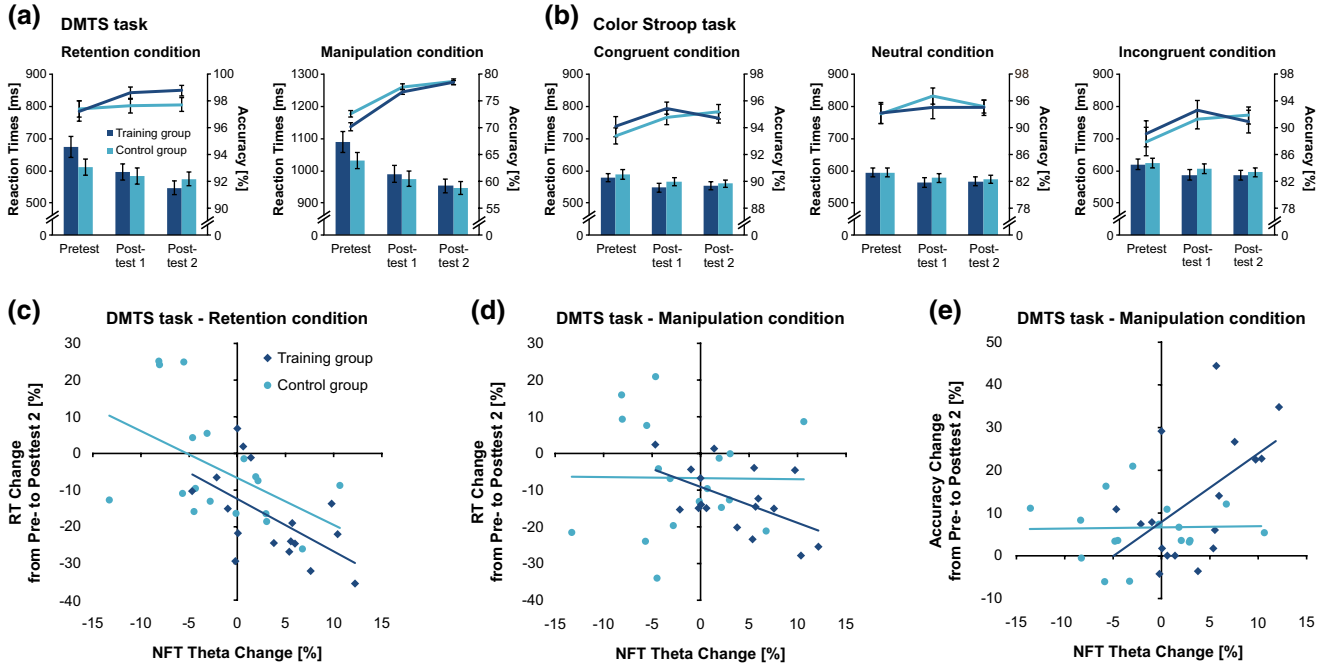

FIGURE 3 Behavioral results and NFT effects on behavioral transfer for the training and control group. Reaction times (bars) and accuracy (lines) in (a) the DMTS task and (b) the color Stroop task at pretest, first posttest, and second posttest are shown separately for the training and control group. Error bars indicate standard error of the group means. As indicated by analyses that controlled for pretest performance, the training group showed faster reaction times and better accuracy than the control group in the retention condition of the DMTS task at the second posttest. (c) NFT theta change was associated with the reaction time decrease in the retention condition from pretest to the second posttest for both the training and control group. (d) NFT theta change was related to the reaction time decrease in the manipulation condition from pretest to the second posttest for the training but not for the control group. (e) NFT theta change was associated with the accuracy increase in the manipulation condition from pretest to the second posttest specifically for the training but not for the control group

level of cognitive control recruitment (Figure 3a). Contrary to our hypotheses, reaction times and accuracy in the manipulation condition did not differ between the training and control group in both the first and second posttraining session (all p values $> .242$, one-tailed).

In order to explore the influence of NFT on performance enhancement from pretraining to posttraining sessions, linear regressions with the predictor NFT theta change were conducted. NFT theta change was associated with the reaction time decrease in the retention condition of the second posttest for both the training ($b = 1.44$, $t(15) = 2.64$, $p = .019$) and control group ($b = 1.28$, $t(16) = 2.20$, $p = .043$), explaining 31.7% and 23.2% of the variance, respectively (Figure 3c). This finding suggests that although significant performance differences between the training and control group were found in the second posttest, reaction time decreases driven by NFT were not specific for the training group. Linear regression analyses of neither reaction time changes from pretest to the first posttest nor accuracy changes from pretest to both posttests were significant (all p values $> .062$). Interestingly, analyses of the manipulation condition showed that performance enhancement from pretraining to the second posttraining session was related to NFT theta change solely for the training group (reaction times: $b = 0.98$, $t(15) = 2.40$, $p = .030$; accuracy: $b = 1.60$, $t(15) = 2.34$, $p = .030$), explaining 27.8% and 27.7% of the variance, respectively (reaction times: Figure 3d; accuracy: Figure 3e). Regression analyses investigating performance increases in the manipulation condition from pretest to the first posttraining session were not significant (all p values $> .164$). Additionally, performance changes to both posttraining sessions of the control group were also not associated with NFT theta change (all p values $> .684$). These results indicate that FM theta NFT induced selective performance changes for the training group in the more difficult manipulation condition: The more successfully participants upregulated their FM theta activity during NFT, the greater were manipulation performance enhancements after training.

For the Stroop task, both reaction times and accuracy in the congruent, neutral, and incongruent condition did not differ between training and control group in the first and second posttest (all p values $> .095$, one-tailed; Figure 3b). Moreover, linear regression analyses revealed that NFT theta change did not relate to performance changes in any of the conditions from pretraining to both posttraining sessions for both groups (all p values $> .164$). These results suggest that FM theta NFT did not induce any changes in Stroop task accuracy and performance speed.

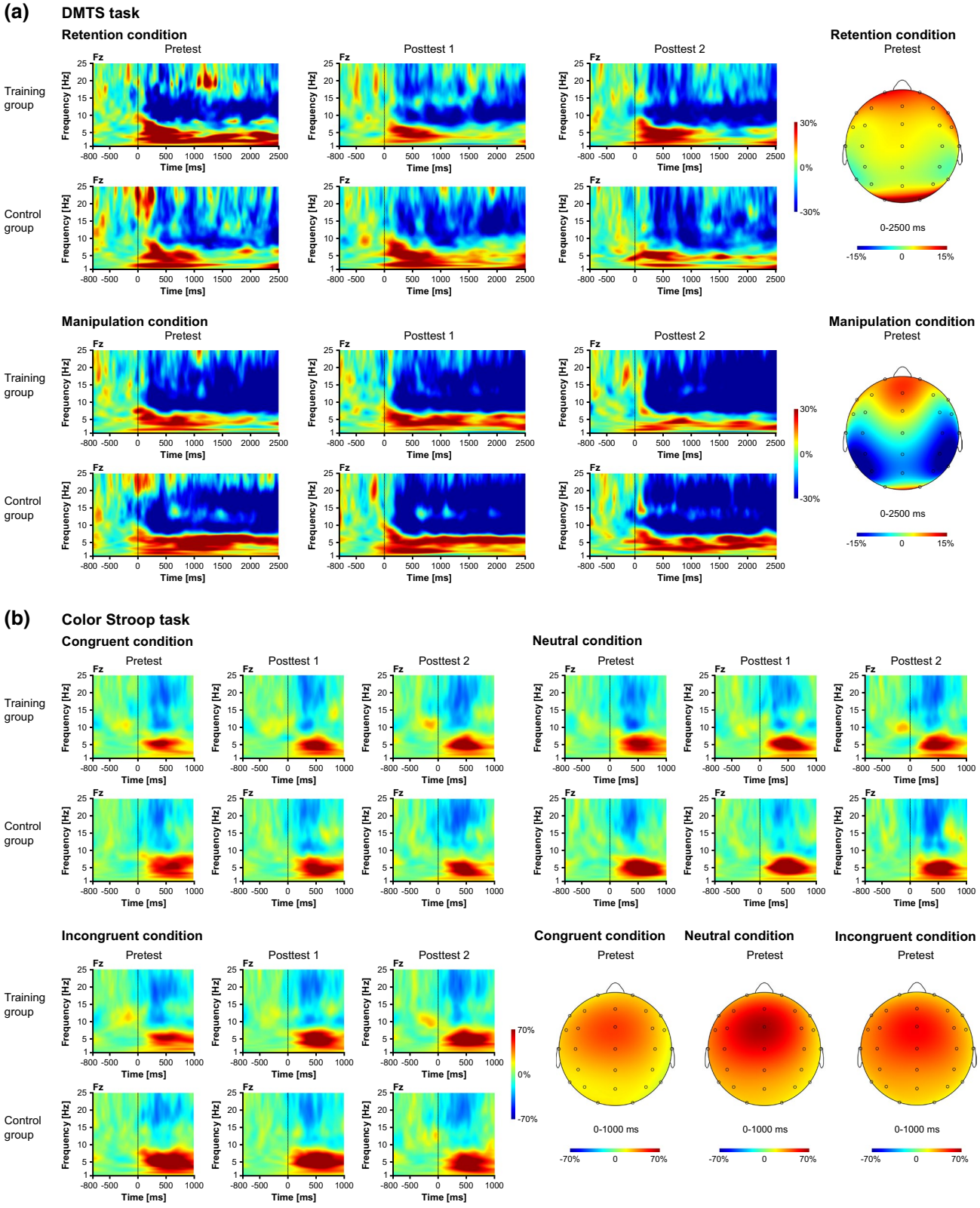

FIGURE 4 EEG characteristics of (a) the DMTS task and (b) the color Stroop task across all pretraining and posttraining sessions. EEG activity at electrode Fz at pretest, first posttest, and second posttest, which was included in the respective analyses, is depicted separately for the training and control group. Topographies of theta ERS/ERD (4–8 Hz) averaged over all participants are shown for pretest at 0–2,500 ms in the DMTS task and 0–1,000 ms in the Stroop task, respectively. No training-induced modulations of FM theta activity were detected

3.3 | EEG characteristics of the transfer tasks

FM theta ERS/ERD in the transfer tasks was investigated for all poststimulus time intervals of the DMTS and Stroop task (Figure 4). For the retention condition of the DMTS task, FM theta ERS/ERD in the 1,500–2,000 ms time interval of the second posttest tended to be lower for the training compared to the control group ($b = 14.23$, $t(32) = 2.25$, $p = .031$) but was not significant with a Bonferroni-corrected α-level of .01 (Figure 4a). All other differences in any other time interval of both posttraining sessions and the manipulation condition were also not significant (all p values $> .100$). Consequently, better performance of the training group in the DMTS task was not accompanied by an overall change in FM theta activity. It is conceivable that activity of neighboring alpha and delta frequencies was partially included in the extracted FM theta activity due to the characteristics of Morlet wavelet convolution and, thus, influenced the present result. In line with the behavioral findings of the Stroop task, FM theta ERS/ERD in all time intervals of the congruent, neutral, and incongruent condition did not differ between the training and the control group in both posttraining sessions (all p values $> .160$), suggesting that no changes in theta activity of the Stroop task were present after NFT (Figure 4b).[1]

4 | DISCUSSION

Based on the overlap hypothesis of training transfer (Dahlin et al., 2008) and the prominent role of FM theta oscillations in reflecting cognitive control processes (Cavanagh & Frank, 2014), the present study investigated three research questions. It was assessed (a) whether seven sessions of FM theta NFT lead to differential performance improvements in two tasks requiring mainly proactive or reactive control, (b) whether behavioral transfer is accompanied by training-induced changes in EEG characteristics, and (c) whether training-induced behavioral and EEG changes are present only one day after the last NFT session or also persist to a second posttraining session 13 days later. Both training and control group showed better task performance in the second posttest compared to the pretest, which might be explained by increased performance due to task repetition. Behavioral analyses comparing both groups revealed that participants of the training group, who successfully enhanced their FM theta activity relative to an active control group (Eschmann et al., 2020), showed better performance in the DMTS but not in the Stroop task after training, supporting previous findings of transfer to tasks requiring proactive rather than reactive control processes (Enriquez-Geppert et al., 2014). Specifically, participants of the training group, who successfully upregulated their FM theta activity during training, showed better performance in the retention condition of the DMTS task at the second posttest compared to the active control group (Figure 3a). Furthermore, linear regression analyses revealed that performance increases from pretest to the second posttest were related to the FM theta training gain for both the training and control group in the retention condition of the DMTS task, indicating that both groups profited from NFT in the easy retention condition, in which stimuli simply had to be maintained (Figure 3c). This might be because both groups had to apply proactive control processes in order to upregulate their own brain activity successfully (Gaume et al., 2016; Ros et al., 2014). Thus, even though both groups received feedback to different frequency bands, minor changes in FM theta activity in the control group may had a positive impact on simple stimulus retention. Interestingly, in the more difficult manipulation condition, FM theta upregulation was specifically associated with performance increases solely for the training group (Figure 3d,e). Given that successful performance in the manipulation condition included additional working memory processes (Sauseng et al., 2010), more pronounced FM theta upregulation during NFT, such as in the training group, may have been necessary for performance enhancement to occur. However, this relationship should be interpreted with caution because pretest to posttest performance increases in both groups preclude from inferring a causal effect of FM theta NFT on performance. Nevertheless, the finding that participants, who successfully enhanced their FM theta activity during training, showed greater performance enhancement underscores the importance of taking individual differences in the ability to upregulate FM theta activity into account. Even if individually estimated theta frequency bands are trained, participants greatly vary in their ability to upregulate their own brain activity (Alkoby et al., 2018). It is conceivable that due to individual differences in FM theta upregulation, transfer in the manipulation condition was not present in the group level analysis but solely in individual level analyses. In contrast, group differences in all conditions of the Stroop task were not significant and pretest to posttest performance changes in the Stroop task were not related to FM theta increase during

[1]As pointed out by a reviewer, EEG characteristics in the transfer tasks that served to extract individual theta frequency ranges might have been influenced by differential theta topographies. As can be seen in Figure 4, FM theta activity seems to be more focused at frontal electrode sites in the manipulation condition of the DMTS task as compared to the conditions of the Stroop task. Hence, changes in EEG characteristics might not be significant because FM theta activity has not been extracted at its topographical center. However, an additional analysis of a frontal cluster consisting of electrode sites Fp1, Fz, and Fp2 revealed the same results as analyses at electrode Fz. FM theta ERS/ERD in the 1,500–2,000 ms time window of the second posttest tended to be lower for the training relative to the control group ($b = 12.50$, $t(32) = 2.21$, $p = .035$) but was not significant with a Bonferroni-corrected α-level of .01. All other EEG analyses were also not significant (all p values $> .058$).

NFT (Figure 3b). Even though the transfer tasks in the present study do not allow for process-pure measurements of proactive and reactive control, they were assumed to require one or the other to a greater extent. Consequently, the findings of effects in the DMTS but not in the Stroop task favor the assumption that FM theta NFT supports proactive rather than reactive control processes.

Support for the interpretation that FM theta NFT may transfer to mainly proactive control can also be derived from two specific characteristics of the neurofeedback that was applied in the present study. First, selective transfer to the DMTS task may have been present because FM theta amplitudes for NFT were measured at electrode Fz. According to the DMC framework, proactive control processes recruit the lateral prefrontal cortex (lPFC) whereas reactive control processes engage the lPFC and, additionally, a wider neural network (Braver, 2012). Brain imaging studies support this assumption by providing evidence for sustained lPFC activity during proactive control and a wider network recruitment during reactive control (e.g., Braver & Cohen, 2001; Veltman et al., 2003; Zysset et al., 2001; see Niendam et al., 2012 for review). In a previous study, we were able to show that enhanced FM theta activity differed topographically depending on whether mainly proactive or reactive control processes were needed for task performance (Eschmann et al., 2018). While FM theta activity was focally activated at frontal sites in a mainly proactive control engaging DMTS task, it had a broader topographical distribution in a predominantly reactive control recruiting Stroop task. Consequently, focally distinct upregulation of FM theta activity at a frontal electrode site in the present study may have favored proactive control processes associated with a focal FM theta topography. Second, FM theta NFT might have particularly supported transfer to the DMTS task because proactive control processes are crucial for successful FM theta modulation. During NFT, participants had to apply constant action monitoring (Gruzelier, 2014), which has previously been associated with sustained FM theta activity (Cavanagh et al., 2012), and cognitive control processes needed for self-regulation of one's own brain activity (Hofmann et al., 2012). In order to receive positive feedback, participants regulated their brain activity in the desired direction by exerting top-down control and if they achieved to do so, the upregulated brain state had to be actively maintained (Gaume et al., 2016; Ros et al., 2014). Moreover, discrepancies between inner state and external feedback had to be constantly monitored, leading to the continuous adaptation of cognitive control over one's brain activity (Ninaus et al., 2013; see Davelaar, 2018; Gaume et al., 2016; Gruzelier, 2014; Ros et al., 2014 for reviews). In the present study, both the training and control group, who used similar strategies to upregulate different frequency bands, had to apply proactive control processes during NFT in order to upregulate their brain activity. Given that these control processes are reflected in FM theta activity, the application of proactive control during NFT might explain why both groups showed an association between FM theta increase during NFT and reaction time decreases from pretest to the second posttest in the retention condition. However, while proactive control processes might have been used by both groups, successful upregulation of FM theta oscillations in the training group might have even further facilitated the control processes that are reflected in FM theta activity, leading to the result that manipulation performance enhancement was related to individual theta NFT gain selectively for the training group. Even though this interpretation is tempting, the present findings cannot disentangle how strongly FM theta upregulation participated in the performance enhancement in the training group because the control group also showed pretest to posttest performance increases. Thus, it can be concluded that proactive control enhancement was partly caused by FM theta upregulation but other factors, such as task repetition, may have also contributed to improve task performance after training. Further research is needed to firmly conclude and disentangle the training effect from task repetition or other training-unspecific effects during NFT.

Contrary to our expectation, FM theta NFT did not induce any changes in EEG characteristics of the transfer tasks, adding to previous inconsistent findings of theta increases, decreases, or no such modulations after NFT (Enriquez-Geppert et al., 2014; Eschmann et al., 2020). The same FM theta NFT protocol that was used in the present study has previously been shown to induce FM theta decreases that were associated with enhanced source memory performance (Eschmann et al., 2020). Based on the understanding of FM theta activity as a general cognitive control mechanism that reflects the need for cognitive control in the large variety of tasks (Cavanagh & Frank, 2014; Helfrich & Knight, 2016; Sauseng et al., 2010), the training-induced association between theta decrease and performance increase was interpreted to reflect fewer demands on cognitive control as a function of training. However, together with the present results, these findings suggest that training-induced changes of EEG characteristics in transfer tasks are task-specific and might occur only in certain situations. A factor that might influence whether EEG characteristics in transfer tasks are modulated is the measurement and extraction of FM theta activity for NFT. First, due to the computational characteristics of time-frequency decomposition neighboring alpha and delta activity may have contaminated the extracted FM theta activity by smearing into the theta range. In consequence, training-unspecific alpha decrease and delta increase from pretraining to posttraining sessions might have washed out any training-induced changes in FM theta activity. Second, although FM theta activity has been assumed to reflect a general cognitive control mechanism (Cavanagh & Frank, 2014), recent

studies using source localization techniques have revealed that FM theta activity in conflict situations of a single cognitive control task originates from several underlying theta source regions that are distinct and can be measured simultaneously (Töllner et al., 2017; Zuure et al., 2020). Consequently, scalp-measured FM theta activity as in the present study might be the product of differential theta generators that support different cognitive control mechanisms. For example, Töllner et al. (2017) demonstrated that only a theta cluster that was localized in the frontal cortex was associated with response conflict and trial-by-trial conflict adaptation whereas another theta cluster localized in the prefrontal cortex showed no such association. Disentangling and specifically entraining these differential FM theta oscillations might help to understand the relationship between training-induced behavioral transfer effects and underlying oscillatory theta dynamics in future neurofeedback studies. This approach might also help to investigate whether NFT differentially affects proactive and reactive control processes within the same task or whether the specific transfer effects to the DMTS task but not the Stroop task in the present study are modulated by other task characteristics.

In contrast to other FM theta NFT studies, behavioral transfer to the DMTS task was present only 13 days after the last NFT session and not one day after training (Enriquez-Geppert et al., 2014; Rozengurt et al., 2016, 2017; Wang & Hsieh, 2013), suggesting that transfer effects became apparent late after training. This finding can be interpreted in light of brain plasticity characteristics showing that training-induced behavioral and neurophysiological changes do not necessarily increase linearly (Lindenberger et al., 2017; Lövdén et al., 2010; Wenger, Brozzoli, et al., 2017). According to the expansion-renormalization model, training induces an initial regional brain volume increase that is followed by renormalization due to the selection of functionally most efficient cortical pathways (Wenger, Brozzoli, et al., 2017). Given that renormalization has been shown to occur after weeks of training (Wenger, Kühn, et al., 2017), it is conceivable that in the present study continuous FM theta upregulation led to synaptic overproduction that still might have been present at the first posttest whereas renormalization and stabilization of functional activity essentially happened between the first and second posttest. Consequently, it is tempting to speculate that increased performance in proactive control might have been present only after renormalization occurred, that is, at the second posttraining measurement. However, given the non-significant modulations of EEG characteristics in the DMTS task, this interpretation is speculative. Another explanation for the late transfer effects might be derived from task-learning characteristics that are influenced by repetitive task execution across the pretraining and posttraining sessions. A common finding of the training literature is that task performance also increases in the control group because the same transfer tasks are performed and learned (e.g., Karbach & Kray, 2009; Schneiders et al., 2011). It was shown that even one task repetition proves to be efficient for skill learning (Ofen-Noy et al., 2003). These task-learning characteristics might be the reason why both training and control group demonstrated an association between reaction time decreases in the retention condition and FM theta change. Furthermore, a certain level of task-learning and, thus, task proficiency might be necessary in order for training-induced transfer effects to become measurable. It is conceivable that while task performance of both groups was comparable directly after training, FM theta upregulation in the training group initiated task-learning in the more multi-faceted manipulation condition of the DMTS task that became apparent only when the task was performed for the second time after training. Taken together, it can be concluded that irrespective of whatever structural and functional changes underlie NFT-induced cognitive enhancement, they seem to need time to unfold.

All in all, the present study is the first to demonstrate a relationship between FM theta NFT and a DMTS but not a Stroop task that was observed 13 days after the last training session. Although these two tasks do not allow process-pure cognitive control measurements, the present findings suggest that FM theta NFT more likely improves proactive rather than reactive control processes and that these training-induced changes become manifest late after training is completed. Even though the underlying neurophysiological mechanisms need to be further explored, the present study may hint to fewer demands on proactive control processes as a function of training. Thus, FM theta NFT may constitute an efficient tool to enhance cognitive control processes in adult participants.

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AUTHOR CONTRIBUTIONS

Kathrin C. J. Eschmann: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Validation; Visualization; Writing-original draft. **Axel Mecklinger:** Conceptualization; Funding acquisition; Methodology; Supervision; Writing-review & editing.

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