

Mission Impossible? Inhibiting Frontal Midline Theta with Neurofeedback

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ABSTRACT: Frontal midline theta (FMT) is an oscillation closely linked to cognitive control and performance monitoring. A recent meta-analysis suggests that FMT can be upregulated via neurofeedback (NF), yet successful downregulation remains largely unsubstantiated and has primarily been tested in single-session designs.

We tested whether multi-session training enables FMT inhibition via NF. Five participants completed six NF sessions targeting FMT reduction (4-8 Hz at Fz). Contrary to the training goal, FMT increased during NF relative to the pre-session resting-state baseline. A similar pattern was observed in a previous pilot study using individualized FMT peak-frequency NF. Together, these findings suggest that traditional NF approaches may face fundamental difficulties in achieving reliable FMT downregulation.

INTRODUCTION

Neurofeedback (NF) is realised through a closed-loop brain-computer interface (BCI) which provides participants with real-time information about their brain activity and thereby allows them to learn its intentional modulation [1]. Early demonstrations of electroencephalography (EEG) NF already showed that oscillatory activity can be shaped through operant conditioning principles [2]. NF is a broadly used method in cognitive and clinical neuroscience, particularly with EEG due to its high temporal resolution and practical feasibility in repeated-session training paradigms [1].

Frontal Midline Theta (FMT; 4–8 Hz) is a well-established electrophysiological marker of the need for cognitive control. Increases in FMT are consistently observed during tasks requiring sustained attention, conflict monitoring, error detection, and feedback-based learning [3,4]. FMT is thought to reflect the recruitment of top-down control processes in situations demanding behavioural adjustment. It is also involved in memory formation and retrieval [5] and increases during meditation [6] or the experience of a flow state [7]. Converging evidence implicates the midcingulate cortex (MCC; often referred to as dorsal anterior cingulate cortex, dACC) as a primary generator of FMT, further linking the rhythm to reinforcement learning and adaptive control mechanisms [8,9].

Neurofeedback of Frontal Midline Theta has received increasing attention as a target to enhance performance of memory or other executive functions [10]. Consistent

with the positive link between FMT and cognitive performance, most NF studies have aimed at FMT upregulation for enhanced performance in task-switching, episodic and working memory tasks or behavioural inhibition [11].

Although theta downregulation has been investigated in other NF contexts, most prominently theta/beta protocols for ADHD, these protocols typically target theta/beta ratio changes at central or frontocentral sites rather than FMT as a specific cognitive-control rhythm [12]. Attempts to inhibit FMT via NF have received considerably less attention despite potential relevance for domains where excessive control or conflict-related processing may be maladaptive (e.g., anxiety-related hypervigilance or persistent conflict processing). In our recent meta-analysis, we showed that only a few studies aimed at decreasing FMT, either as a control group or to improve golf putting performance. We found that evidence for FMT upregulation by NF is more consistent than evidence for FMT downregulation [11].

Reducing Frontal Midline Theta with Neurofeedback: While we identified multiple studies aiming at FMT reduction, only one reported a clear reduction of FMT [13] and this emerged only as a first-to-last run decrease. When NF was compared to the preceding baseline, FMT increased, suggesting that apparent reductions may reflect a gradual attenuation of an initial NF-induced FMT rise. However, all included studies were single-session protocols and none used more narrow, individualized frequency bands. We therefore hypothesized that extended training combined with more precise frequency targeting might enable FMT downregulation. Hence, we implemented a multi-session NF protocol targeting FMT reduction motivated by the broader aim of reducing excessive conflict-related processing in approach–avoidance contexts.

As multiple successful FMT modulation protocols focused on individual peak training, we first implemented a similar approach (pilot 1). Participants performed a task designed to elicit approach-avoidance conflicts and hence FMT [14]. From this task an individual peak frequency was derived. NF was then delivered within a narrow 2 Hz band surrounding this peak frequency. However, we found that the peak frequency was not stable across sessions [15], rendering the provided feedback band unreliable despite its

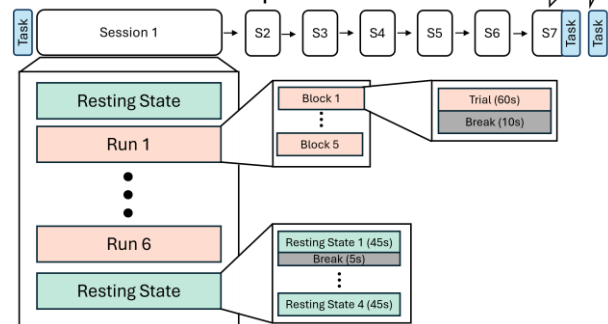


Figure 1: Timeline of pilot 1: Seven sessions were scheduled over the course of two weeks. Each session started and ended with four 45 second recordings of resting-state, separated by 5 seconds breaks. The NF training consisted of six runs, interleaved by self-paced breaks. Each run contained five blocks of 60 seconds NF trial and 10 second break. An approach–avoidance task that reliably elicits FMT bursts was conducted before the first session, immediately after the final NF session, and again seven days later.

narrower bandwidth. NF modulation of FMT was not achieved. We therefore conducted a second pilot study using a conventional broadband FMT target (4–8 Hz) rather than individualized peak frequencies. Yet this approach likewise failed to produce reliable FMT downregulation.

We here present data from both pilot studies. In each study, five participants trained to reduce their FMT in multiple NF sessions distributed over the course of two weeks. Together, these two pilot studies provide converging evidence regarding the difficulty of achieving FMT downregulation using conventional NF approaches. Only data from the task used to determine peak frequency in the first pilot study were reported previously [15]. The NF data were not reported at the time because the lack of successful modulation was initially attributed to unstable peak frequency estimates, which may have resulted in an unreliable individualized feedback signal.

MATERIALS AND METHODS

Participants: Five participants were recruited for each pilot study via the university’s online portal (pilot 1: three female, age: $M = 24.4$ years, $SD = 1.5$; pilot 2: four female; age $M = 25$ years, $SD = 2.8$). All participants provided written informed consent, were ≥ 18 years old, right-handed, non-color blind, without a history of psychiatric disorder, and naïve to NF. Participants received either course credit or monetary compensation (12.50€ per hour). All procedures were carried out in accordance with the ethical standards of the Association of German Professional Psychologists (Deutsche Gesellschaft für Psychologie, DGPs) and the Declaration of Helsinki, and were approved by the Ethics Committee of the Institute of Psychology, Julius-Maximilians-University Würzburg (GZEK 2023-45).

Study Procedure: An overview of the session structure for pilot 1 with the individualized frequency is shown in Fig. 1 and for pilot 2 with the 4-8 Hz band in

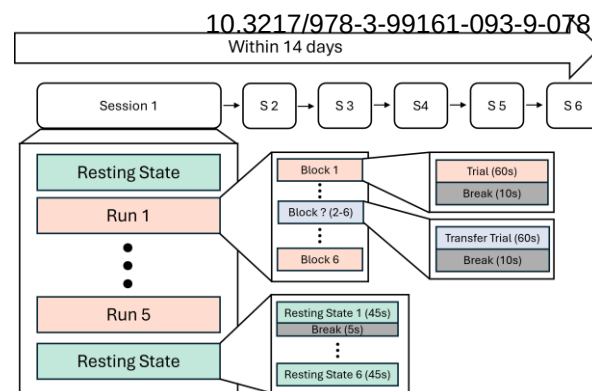


Figure 2: Timeline of pilot 2: Six sessions were scheduled over the course of two weeks. Each session started and ended with six 45 second recordings of resting-state, which were interleaved by 5 seconds breaks. The NF training consisted of five runs, interleaved by self-paced breaks. Each run contained six blocks of 60 seconds NF trial and 10 second break, during each run, one of the trials was a transfer trial, which did not contain any feedback.

Fig. 2. Participants completed seven NF sessions within 14 days, scheduled at approximately the same time of day. Each session began and ended with a three-minute resting-state recording. During resting-state, participants watched an animation of a slowly rotating 3D sphere. Pilot 2 was structured identically but shortened to six sessions containing 5 runs and had extended 5 minutes resting state measurements. To determine the individual FMT peak frequency and assess potential changes during conflict processing, participants performed an approach–avoidance task [14] at three time points: before NF training, immediately after the final session, and at a seven-day follow-up (only for pilot 1). Specifics on how the peak frequency was obtained are described in detail in [15].

Each session comprised six NF runs (pilot 2: five runs). Each run consisted of five trials lasting one minute each, separated by 10-second breaks. In pilot 2, each run comprised one additional, transfer trial, in which no feedback was presented. During transfer trials participants were instructed to continue applying their current mental strategy to modulate brain activity. Transfer trial positions were pseudo-randomized such that each trial position (except the first) served once as transfer; the first trial of a run was never assigned as transfer. Between runs, participants could take breaks of self-determined length and were asked to write down their thoughts and strategies during the preceding run.

Neurofeedback: Visual feedback was presented on a black screen using three bar charts. A wide central dark-cyan bar provided real-time feedback of FMT activity; a thinner pink bar indicated artifacts in the EEG in real time; and a thin light-cyan bar on the left provided continuous feedback of correct modulation across each trial. Participants were instructed to sit still, keep their eyes open, face the monitor, and attend to the bars. They were asked to increase the height of the dark-cyan bar via their thoughts and to minimize the pink artifact bar by relaxing and reducing muscle activity. No specific mental strategy instructions were provided; participants

EEG acquisition: EEG was recorded using ActiCap electrodes and BrainAmp amplifiers (Brain Products GmbH, Gilching, Germany). Two electrodes (O1/O2) were repurposed for the electrooculogram (EOG) recording (right eye), and the remaining 30 electrodes were placed according to the international 10–20 system. The reference electrode was placed at FCz and the ground at FPz. Data were streamed and recorded via LabStreamingLayer (LSL-Connector/LabRecorder) at 250 Hz.

Online signal processing and feedback computation: Online processing relied on a Python-based NF framework. The pre-NF resting-state was used to calibrate the system by deriving (i) artifact thresholds for EEG and EOG channels, (ii) an Artifact Subspace Reconstruction (ASR) model, and (iii) the baseline distribution of FMT activity used for z-normalization. For calibration and online processing, signals were re-referenced to a common average reference (CAR) and detrended (DC offset removal). Artifact thresholds were determined as the smallest absolute value at which the z-score exceeded 2.58, constrained to 80–180 μ V. Data were then bandpass-filtered (1–40 Hz) and used to fit ASR for online artifact correction. PSD was computed using Welch’s method. Mean and standard deviation of band power in a 2-Hz band surrounding the peak frequency at Fz were stored as the baseline distribution (pilot 2: band power between 4–8 Hz).

During NF trials, FMT was computed from a 2-second sliding window updated every 100 ms. The stream was CAR-referenced, detrended, bandpass-filtered (1–40 Hz), corrected using the pre-trained ASR, and transformed to PSD with Welch’s method. Power in the respective band (pilot 1: individualized 2 Hz, pilot 2: 4–8 Hz) at Fz was extracted and normalized to baseline z-scores. These z-scores were mapped to the central dark-cyan feedback bar with an inverted y-axis such that lower z-scores (FMT desynchronization) produced a higher bar; bar limits were set to -2 and $+2$.

Offline processing and FMT quantification: For offline analyses, EEG was re-referenced to CAR and bandpass-filtered (1–100 Hz; 8th-order Butterworth IIR). Continuous data were segmented into 5-second epochs. Artifacts were addressed using ICA (infomax; max 500 iterations). Components explaining 99% of the variance were retained and labelled via ICLabel; non-brain components were removed if classified with $\geq 70\%$ certainty. Remaining epochs exceeding 150 μ V were discarded. Data were then transformed using surface Laplacian (current source density) and bandpass-filtered again (1–40 Hz; 8th-order Butterworth IIR). PSD at Fz was computed using Welch’s method (Hamming window, 50% overlap), and theta power (4–8 Hz for both studies) was extracted as the FMT measure.

Statistical analysis: FMT power was log-transformed and averaged within participants across runs of each session for each condition (resting-state baseline, NF, transfer). To avoid carry-over effects of the NF, only the

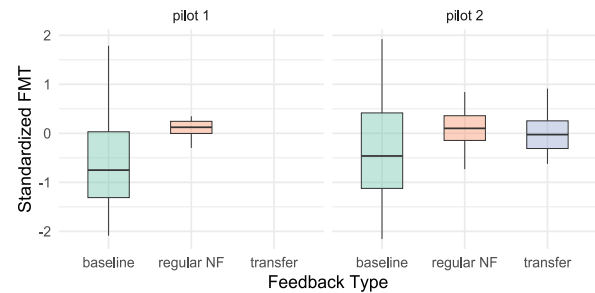


Figure 3: Frontal midline theta (FMT) activity for both datasets across the three task conditions. Values were standardized within each participant and session relative to the pre-NF resting-state baseline. Model estimates indicated higher FMT in the NF condition compared to baseline for both datasets. To avoid overinterpretation, statistical contrasts are not marked in the figure.

resting-state recording before NF served as baseline. For both pilots, we tested the effect of condition with three linear mixed-effects models. Given the small sample size of both datasets, we refrained from a stepwise parameter selection approach for the mixed-model and employed a theoretically motivated model structure with condition as fixed effect and participant as a random intercept: $FMT \sim \text{condition} + (1 | \text{participant})$.

The first two models examined condition differences relative to resting-state baseline (reference level) in the two different datasets. The third model analysed baseline-adjusted FMT values, using the regular NF condition as reference, to assess differences between feedback and transfer trials while reducing between-session variability. All statistical analyses were conducted using R [16] and the glmmTMB package [17].

RESULTS

All recordings were processed with the offline pipeline described above. One transfer trial from a single participant of pilot 2 was excluded due to poor data quality; all remaining runs were retained for analysis.

Participant-standardized condition means are shown in Fig. 3. Given the pilot nature of both studies, statistical results should be interpreted as exploratory and illustrative rather than confirmatory. No participant showed consistent decreases below baseline across sessions. Instead, FMT values during NF were generally elevated relative to baseline throughout the training period.

Reported Strategies: In both pilots, participants reported using diverse strategies (e.g., positive thoughts, recalling the day, imagining music, breath control), but frequent within-run switching and the small sample size prevented evaluating their effects on FMT regulation.

FMT increases relative to baseline:

The linear mixed-effect model was first fitted to log-transformed FMT values averaged within participants across runs. The resting-state baseline served as the reference level. In both datasets FMT activity was higher

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 condition than during the baseline ($\beta = 0.14$, $SE = 0.05$, $z = 3.07$, $p < 0.01$). Similar increases were observed in the transfer trials of pilot 2 ($\beta = 0.10$, $SE = 0.05$, $z = 2.32$, $p < 0.05$). Both model fits included a random intercept for participants (pilot 1: $\sigma^2 = 0.26$; pilot 2: $\sigma^2 = 0.57$), indicating substantial between-participant variability. While both models explained a large proportion of total variance (conditional R^2 : pilot 1 = 71.1%; pilot 2 = 91.8%), the variance attributable to condition alone was small (both marginal $R^2 < 1\%$), suggesting that most explained variance reflected between-subject variability independent of condition.

FMT increases differ between feedback conditions:
 For pilot 2, the model was fitted to FMT values adjusted relative to the pre-NF resting-state baseline of the respective day to reduce inter-individual and inter-session variability. The NF condition served as the reference level. Relative to the regular NF, FMT activity was only slightly lower during the transfer condition ($\beta = -0.04$, $SE = 0.03$, $z = -1.3$, $p = 0.19$) but more so during resting-state ($\beta = -0.14$, $SE = 0.05$, $z = -3.05$, $p < 0.01$). This model explained less total variance (conditional $R^2 = 33.0\%$) but a slightly larger proportion was attributable to condition (marginal $R^2 = 1.9\%$).

DISCUSSION

The present study examined whether FMT can be reliably downregulated using multi-session NF. Across two pilot studies employing different targeting approaches, we found no evidence for successful FMT downregulation. Instead, FMT activity increased relative to resting-state baseline during NF in both protocols. In pilot 1, feedback was based on an individualized peak-frequency band derived from a task chosen to elicit FMT bursts. Individualized frequency targeting has been proposed as a potentially more precise approach for oscillatory NF. However, we observed that peak frequencies were not stable across sessions, consistent with previous findings [15]. This instability likely reduces the reliability of individualized feedback bands and may partly explain the lack of modulation observed in this pilot. In pilot 2, we therefore reverted to a conventional broadband theta range (4–8 Hz). Despite this simplification, the pattern remained unchanged: FMT activity during NF was again elevated relative to baseline and no consistent decreases were observed across participants.

Our results are not only consistent with the reported negative effect size computed from studies attempting downregulation [11] but also with a most recent study which reported FMT decreases only after, but not during the NF training [18]. This pattern suggests that increases in FMT during NF may be a recurring phenomenon rather than a study-specific artifact.

While the modulation of certain oscillatory rhythms via NF has been demonstrated in various contexts, rhythms that are tightly coupled to cognitive control processes may be more difficult to voluntarily suppress within the typical NF paradigm.

However, the studies presented here included only small samples ($N=5$ participants per pilot) and thus do not allow for generalization. Furthermore, NF studies are highly heterogeneous in their design, including differences in feedback modality, session number, and signal processing pipelines. While the present protocols attempted to address some of these factors (e.g., individualized frequency targeting in Pilot 1 and multi-session training in both pilots), other design variations may yield different outcomes. Future studies with larger samples and systematically varied NF parameters (e.g. longer training periods) will be necessary to determine under which conditions FMT modulation may be achievable.

Despite these limitations, the present work highlights the importance of reporting negative or nil findings in NF research [19]. Since multi-session NF studies are resource-intensive, meaningful sample sizes are often only achieved through the aggregation of studies by meta-analysis. However, the absence of reported failures may bias the literature toward overly optimistic conclusions regarding modulation success. Transparent reporting of unsuccessful protocols is therefore essential for the cumulative evaluation of NF methodologies and growth of the field [20].

CONCLUSION

Across two pilots we found no evidence for successful downregulation of FMT. Contrary to the training goal, however consistent with previous reports, FMT activity was consistently elevated during NF relative to resting-state baseline. We highlight a potential challenge when attempting to modulate neural rhythms that are closely linked to cognitive control processes. Future research should be directed at the systematic evaluation of the task-specific effects of NF and their interference with specific targets.

REFERENCES

- [1] Sitaram R, Ros T, Stoeckel L, Haller S, Scharnowski F, Lewis-Peacock J, et al. Closed-loop brain training: the science of neurofeedback. *Nature Reviews Neuroscience* 2017;18(2):86–100.
- [2] Kamiya J. Conditioned discrimination of the EEG alpha rhythm in humans. *Proceedings of the Western Psychological Association* 1962.
- [3] Cavanagh JF, Frank MJ, Klein TJ, Allen JJB. Frontal theta links prediction errors to behavioral adaptation in reinforcement learning. *NeuroImage* 2010;49(4):3198–209.
- [4] Cavanagh JF, Frank MJ. Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences* 2014;18(8):414–21.
- [5] Hsieh L-T, Ranganath C. Frontal midline theta oscillations during working memory maintenance and episodic encoding and retrieval. *NeuroImage* 2014;85:721–9.
- [6] Cahn BR, Polich J. Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychological Bulletin* 2006;132(2):180–211.
- [7] Katahira K, Yamazaki Y, Yamaoka C, Ozaki H, Nakagawa S, Nagata N. EEG Correlates of the

- Alpha Rhythm in the Mental Arithmetic Task. *Front Psychol* 2018;9:300.
- [8] Hayden BY, Platt ML. Neurons in Anterior Cingulate Cortex Multiplex Information about Reward and Action. *J Neurosci* 2010;30(9):3339–46.
- [9] Vogt BA. Midcingulate cortex: Structure, connections, homologies, functions and diseases. *Journal of Chemical Neuroanatomy* 2016;74:28–46.
- [10] Yeh W-H, Ju Y-J, Liu Y-T, Wang T-Y. Systematic Review and Meta-Analysis on the Effects of Neurofeedback Training of Theta Activity on Working Memory and Episodic Memory in Healthy Population. *IJERPH* 2022;19(17):11037.
- [11] Pfeiffer M, Kübler A, Hilger K. Modulation of Human Frontal Midline Theta by Neurofeedback: A Systematic Review and Quantitative Meta-Analysis. *Neuroscience & Biobehavioral Reviews* 2024:105696.
- [12] Van Doren J, Arns M, Heinrich H, Vollebregt MA, Strehl U, K. Loo S. Sustained effects of neurofeedback in ADHD: a systematic review and meta-analysis. *European Child & Adolescent Psychiatry* 2019;28(3):293–305.
- [13] Chen TT, Wang KP, Chang WH, Kao CW, Hung TM. Effects of the function-specific instruction approach to neurofeedback training on frontal midline theta waves and golf putting performance. *Psychology of Sport and Exercise* 2022;61(December 2021):102211.
- [14] Rodrigues J, Müller M, Mühlberger A, Hewig J. Mind the movement: Frontal asymmetry stands for behavioral motivation, bilateral frontal activation for behavior. *Psychophysiology* 2018;55(1):1–19.
- [15] Pfeiffer M, Masson E, Kübler A, Rodrigues J. Reliability of individual task-related frontal-midline-theta frequency for neurofeedback training –exploratory investigations. *Proceedings of the 9th Graz Brain-Computer Interface Conference* 2024.
- [16] R Core Team. R: A language and environment for statistical computing. 2020.
- [17] Brooks M E, Kristensen K, Benthem K J ,van, Magnusson A, Berg C W, Nielsen A, et al. glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *The R Journal* 2017;9(2):378.
- [18] Kanatschnig T, Berger LM, Schrapf N, Tilp M, Kober SE. The Theta Paradox – Delayed Reduction of Frontal Midline Theta Following Downregulation Neurofeedback Training. *bioRxiv*. 2026 Feb 5. Preprint. doi:10.64898/2026.02.03.703090v1.
- [19] Lotte F, Jeunet C, Chavarriaga R, Bougrain L, Thompson DE, Scherer R, et al. Turning negative into positives! Exploiting ‘negative’ results in Brain–Machine Interface (BMI) research. *Brain-Computer Interfaces* 2019;6(4):178–89.
- [20] Ros T, Enriquez-Goppo S, Zorzi F, Young KD, Wood G, Whitfield-Gabrieli S, et al. Consensus on the reporting and experimental design of clinical and cognitive-behavioural neurofeedback studies (CRED-nf checklist). *Brain* 2020;143(6):1674–85.