

Combining Mindfulness and Implicit Neurofeedback to Upregulate Frontal Alpha Asymmetry

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ABSTRACT: This contribution presents an experimental design that integrates an implicit auditory neurofeedback protocol in a mindfulness intervention to pursue an upregulation of frontal alpha asymmetry (FAA). The following sections detail the design of such an experiment, together with the development and implementation of the materials in use. Lastly, preliminary data are provided to support its feasibility and discuss future improvements and applications.

INTRODUCTION

Neurofeedback (NF) originates with the neural signal of interest and the neuroimaging method used for its acquisition, as in standard observational studies but adds two more steps: the online processing of the neural signal received and its real-time return to the source in form of comprehensible sensory stimuli. Through the iteration of this finely tuned closed-loop communication, participants can learn to modulate their neural activity in a target direction by adjusting their internal states or behavior accordingly [1].

Explicit and Implicit NF modalities are distinguished by the level of awareness experimentally afforded to participants regarding the feedback signal. In the explicit modality, participants achieve experimental goals through intentional effort while in contrast, the implicit modality withholds explicit feedback and let the underlying learning process operate independently of conscious awareness [2]. Explicit NF protocols currently predominate the literature, a trend largely driven by their proven efficacy for specific neural targets e.g., the sensorimotor rhythm (SMR) [3]. We argue that implicit NF offers a functional framework for those brain-behaviour correlates that are less responsive to traditional explicit protocols as is the case for Frontal Alpha Asymmetry (FAA).

FAA is the power difference in the alpha band (8–13 Hz) between frontal cortices. Since alpha power is inversely related to cortical activation, relatively lower left-alpha is a measure of greater left-frontal activation, while lower right-alpha represents greater right-frontal activation. A FAA upregulation results from a right-alpha increase, a left-alpha decrease or both, the opposite trend defines a FAA downregulation [4]. Lower left-alpha is associated with approach motivation and positive affect, except for anger, while lower right-alpha is associated to

withdrawal and negative emotional states [5].

FAA NF and the Capability Model: Many baseline recordings and classical approach-avoidance and/or NF tasks did not yield significant FAA modulation, particularly when the objective was FAA upregulation [6,7]. These findings can be explained by the capability model, which states that active emotional entanglement is an essential requisite of any FAA investigation [8]. We hypothesize that the use of traditional explicit NF for the upregulation of FAA may not be adequate. Neutral stimuli, such as visual scales or simple tones, lack the emotional salience required to effectively elicit FAA; this could explain the absence of modulation often reported in the FAA literature. Even when a FAA modulation is elicited via explicit NF, it may be intrinsically biased toward downregulation. For instance, if the experimental goal is FAA upregulation and the participants cannot succeed, repeated failed trials might bias them toward frustration or disengagement. In such cases, the resulting negative emotional state acts as a functional barrier, keeping FAA consistently downregulated regardless of the intended training.

Mindfulness-based Implicit NF: The strategy behind the experimental design here is to provide solely positive implicit feedback (PIF) when FAA is upregulated. The implicit modality should help to reduce evaluation-related FAA downregulation [9]. However, presenting PIF to the participants in a way such that they perceive it as pleasant but do not detect it as feedback is a challenge. We aimed at addressing it by masking the PIF within a mindfulness meditation.

Mindfulness is the process of regulating attention to bring a quality of non-elaborative awareness to current experience and a quality of relating to one's experience within an orientation of curiosity, experiential openness, and acceptance [10]. Given that practicing mindfulness is proven to upregulate FAA [11,12], mindfulness can serve as a robust implicit strategy for the proposed NF protocol. In this contribution, we present a mindfulness-based auditory NF protocol, outlining solutions to potential pitfalls and pilot data confirming its feasibility.

METHODS AND MATERIALS

Participants: Three expert meditators: two young instructors and one senior advanced practitioner

participated in the study (biological women ≥ 18 years old, right-handed, without a history of neurological disorders age:). All participants were recruited through digital advertising and were experienced practitioners with 3 to 10 years of experience in meditation and regular mindfulness practice over the last year. All participants were invited to the EEG lab at the Department of Clinical Psychology and Psychotherapy, Section Intervention Psychology at the Julius-Maximilian Universität (JMU) in February 2026 and received monetary compensation (13.00 € per hour) for their participation. 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 [13].

Procedure: Participants were initially informed that the study aimed at testing a novel, hybrid mindfulness intervention combining a reduced voice-over with instrumental components. This framing was used to maintain the implicit nature of the NF protocol and ensure the authenticity of the evaluation. Participants completed a single session of the custom-made mindfulness intervention. In detail, they listened to pre-recorded mindfulness guidelines, performed a resting state recording and four meditation-practice blocks. The meditation-practice blocks will henceforth be referred to as 'blocks'. At the end of the experiment, they filled in a questionnaire about state mindfulness. Following the session participants were debriefed.

EEG Setup: EEG data were recorded using 64 ActiCap active electrodes and two BrainAmp DC amplifiers (Brain Products GmbH, Gilching, Germany). Electrodes were positioned according to the international 10–20 system, with the reference at FCz and the ground at Fpz. The impedance check was performed using ActiCap Control Software (v. 1.2.5.5); all initial impedance levels were below 5 k Ω before data collection started. Data were streamed via the BrainAmp LSL Connector (v. 1.18) using liblsl (v. 1.16). Recording was performed at 500 Hz using LabRecorder (v. 1.16), and signal quality was monitored online through BrainVision LSL Viewer (v. 1.1.1).

FAA Resting State: Various methods exist for calculating FAA [14], this contribution adopts the formula from Coan et al. [15], which involves subtracting log-transformed alpha power at the electrode site F3 (left frontal hemisphere) from that at electrode site F4 (right-frontal hemisphere). We recorded individual baselines following the guidelines proposed by Hagemann et al. [16] to calibrate the system for the derivation of artifact thresholds and to obtain a baseline FAA distribution for z-normalization and further comparison between spontaneous thinking and meditation. The resting state lasted 8 minutes and consisted of 8 1-min blocks of spontaneous thinking with eyes opened (EO) or closed (EC) in the following fixed sequence: EO - EC - EC - EO - EC- EO - EO - EC. Participants have been

instructed to either keep their gaze on the fixation cross (EO) or close their eyes (EC) and to avoid movement or muscle contractions. In the baseline instructions, it was specified that this was not yet a meditation-practice block and that the participants were invited to let their thoughts run spontaneously as in everyday life.

NF Processing was achieved by a Python framework [17], adapted for this study.

Online Processing Before the NF: Since the participants were asked to meditate with eyes opened, for calibration and online processing, just the EO blocks of the resting state were used. The signal was re-referenced online to common average reference (CAR), detrended (DC offset removal) and down sampled to 250 Hz. 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 Riemannian Artifact Subspace Reconstruction (rASR) for online artifact correction. Data were then transformed using current source density (CSD). Power spectral density (PSD) was computed using Welch's method. Mean and standard deviation of band power between 8–13 Hz at F3 and F4 were stored independently and then used to calculate FAA baseline distribution.

Online Processing During the NF: FAA was computed from a 2 s sliding window updated every 100 ms. The stream was referenced to a common average reference (CAR), detrended, bandpass filtered, corrected using the pre-trained rASR, transformed to CSD before PSD was computed with Welch's method. Power in alpha band at F3 and F4 electrode sites was extracted, log-transformed and used to calculate FAA. FAA was normalized to baseline z-scores which were mapped to the auditory feedback stimulus with a direct logic such that higher z-scores (FAA upregulation) corresponded to an increase in the volume of the positive feedback stimulus.

Offline Processing after the NF: Continuous data were referenced to a Common Average Reference (CAR), processed with a 1–100 Hz bandpass filter (8th-order Butterworth IIR) and then segmented into 5s epochs. Independent Component Analysis (ICA) (Infomax; max 500 iterations) was used for artifact rejection. Components accounting for 99% of the variance were retained and classified using ICLabel; any non-brain components identified with $\geq 70\%$ certainty were removed. After discarding remaining epochs with amplitudes exceeding 150 μ V, we applied the same processing used in our online pipeline: data were re-referenced to CSD and bandpass-filtered to a 1–40 Hz range. PSD at electrodes F3 and F4 was then estimated using Welch's method (Hamming window, 50% overlap), and alpha power was extracted and log transformed to calculate FAA. This offline processing pipeline was developed in Python 3.14.3.

Auditory Implicit NF: Designing the PIF for the blocks posed a complex balancing act. The stimulus had to be noticeable and recognizable to enable implicit learning yet remain aesthetically consistent with the background audio. Smooth transitions were essential as well; any sudden 'on/off' switching of the PIF would have created a discordant sound, breaking the participant's immersion. At the same time, the challenge behind smooth transitions was ensuring these seamless fades did not compromise the precise timing required for real-time NF. To address these design challenges, we implemented several key solutions. First, we opted for instrumental background audio over a guided meditation to ensure the voice-over would not overshadow the PIF. To guarantee harmonic compatibility between the background audio and the PIF, instead of using two different audio tracks, we chose one and decomposed it into two distinct but complementary layers: a static, non-evolving audio for the background and a more salient, "short-peaking" one for the PIF. We adjusted the melody from myNoise [18] relying also on pleasantness ratings coming from the platform users in the forum.

Although previous FAA studies utilized fixed thresholds (e.g., ± 0.85 SD) [7,15], we mapped z-scores to a continuous volume scale (0–100%). However, initial testing revealed that the PIF was still discontinuous near the threshold of human hearing due to rapid FAA fluctuations. To prevent abrupt audio cut-offs, we introduced a buffered decay zone within the lower 10% of the volume range. In this zone, volume changes were restricted to 1% change per sample, ensuring that even if the FAA value dropped suddenly, the audio would take at least 10 samples (1s) to fade out completely. While this introduces a minor trade-off in temporal precision, it was necessary to maintain a seamless meditative flow. Above this 10% threshold, the volume tracked the timing and magnitude of the FAA modulation in real-time. The auditory pipeline was implemented using PyQt5 with supplementary audio processing performed in Audacity (v3.7.7).

Mindfulness Guidelines: The mindfulness guidelines consisted of a 7-minute script, which has been recorded with Audacity 3.7.7 in a soundproof booth at the lab.

Adjustments to the Lab Setting: While meditators are traditionally encouraged to remain non-reactive to external distractions—such as the buzzing of an insect or distant traffic, these examples were adapted to the lab environment. Participants were invited to maintain this same patience and non-judgmental awareness toward sensations specific to the setup, such as the EEG cap on their head, the contact with the conductive gel, or the cables connecting them to the equipment. To help participants feel at ease in an unfamiliar laboratory setting, the script also employed a specific communication style characterized by a welcoming tone of voice, simple language, the use of a direct second person singular and classic mindfulness metaphors, such

as 'watching your thoughts like clouds passing through the sky'. While the instructions were delivered through a conversational narrative—designed to feel like a personal sharing of practical tips—the script followed a rigorous, cyclical structure intended to systematically address the foundational principles of mindfulness, consistently returning to the core concept of present-moment awareness [10,19].

Participants' Auditory Priming: The mindfulness guidelines were overlaid with the auditory stimulus reserved for the PIF in the subsequent meditation sessions. This approach was designed to prime the participants, ensuring that the first instance of FAA-driven PIF would effectively facilitate the implicit recognition of the signal as a marker of present-moment awareness. Audio implementation was performed with Audacity (v3.7.7).

Meditation-Practice Blocks: The meditation was not guided to prioritize the auditory saliency of the PIF. However, the background stimulus had to be mildly pleasant and immersive nonetheless to ensure the participant succeeded being presented with the PIF (FAA successful upregulation). A strategy to keep the participants engaged in a meditative state involved the insertion of short verbal anchors. These mindfulness reminders followed the thematic progression of the initial mindfulness guidelines and were presented every 50 seconds. A more detailed description can be found in Tab. 1. The participants performed four 5min identical blocks.

Table 1. Mindfulness Intervention – Core Elements

Mindfulness Principles in the Guidelines	Reminders during the Meditation with English Translation
Present-focused Awareness	1 Dieser Moment gehört nur dir. <i>This moment belongs entirely to you.</i>
	2 Lausche deinen Gedanken, ohne sie zu beurteilen. <i>Listen to your thoughts without judging them.</i>
Non-Judgment	3 Sei geduldig, sei freundlich zu dir selbst. <i>Be patient, be kind with yourself.</i>
	4 Entspanne deinen Körper, befreie deinen Geist. <i>Relax your body, free your mind.</i>
Patience and Self-Compassion	5 Kehre zurück zum gegenwärtigen Augenblick. <i>Return to the present moment.</i>

Subjective Measure of State Mindfulness: Instruments for measuring state mindfulness are limited, as most existing scales focus on trait mindfulness and/or lack validation in German [20]. The State Mindfulness Scale (SMS) [21] is one of the few state mindfulness questionnaires translated and validated in German (SMS-PA) [22]. The

SMS-PA consists of 12 items divided into two subscales: Mindfulness of the Mind (items 1–6) and Mindfulness of the Body (items 7–12). Given that the physical subscale only contains items irrelevant to the current sedentary intervention (e.g. movement, temperature changes, or physical fatigue), participants completed only the 'Mindfulness of the Mind' subscale. Original items and their validated translations are presented in Tab. 2.

Table 2: Items from the State Mindfulness of the Mind Subscale (SMS-PA-M)

No	Original English Items (Cox et al., 2016)	Validated German Items (Wallner et al., 2024)
M1	I was aware of different emotions that arose in me.	Ich war mir verschiedener Emotionen bewusst, die in mir entstanden sind.
M2	I noticed pleasant and unpleasant emotions.	Ich habe angenehme und unangenehme Emotionen wahrgenommen.
M3	I noticed pleasant and unpleasant thoughts.	Ich habe angenehme und unangenehme Gedanken wahrgenommen.
M4	I noticed emotions come and go.	Ich habe wahrgenommen, wie Emotionen kamen und gingen.
M5	I noticed thoughts come and go.	Ich habe wahrgenommen, wie Gedanken kamen und gingen.
M6	It was interesting to see the patterns of my thinking.	Es war interessant, meine Denkmuster zu beobachten.

RESULTS

As we present here a feasibility study, we report results only descriptively.

Figure 1: Fig. 1 (A) illustrates the standardized FAA for each participant during each block using box- and strip plots. Each data point represents a 5s epoch, color-coded to distinguish between the resting state (pink; spontaneous thinking) and meditation-practice blocks (turquoise; meditation). Horizontal black lines in the boxplot indicate the median FAA score per block. The y-axis indicates the block type, where 0 represents the resting state and 1–4 represent the subsequent meditation-practice blocks. All recordings were processed with the offline pipeline described above and visualized with R (v. 4.5.2). The last two blocks for Participant 1 were excluded due to technical problems in the lab. Fig. 1(B) displays individual participant responses to the six items of the State Mindfulness of the Mind Subscale reported in Tab. 1. Ratings range from 0 ('not at all') to 4 ('very much'). The bars are coloured turquoise to maintain visual consistency with the meditation-practice blocks in Figure 1(A), as the evaluation focused explicitly on the meditation-practice

period rather than the resting state.

FAA and SMS-PA-M Descriptives: our results indicate that FAA levels were modulated by the experimental condition: in detail, while a downregulation was observed across all subjects for the first meditation-practice block, subsequent blocks were marked by a shift toward upregulation. One exception was Participant 3, whose data reflected higher variance across all blocks. Participant 2 reported the highest state mindfulness ratings and exhibited the most pronounced shift toward FAA upregulation, in fact, after the first meditation-practice block, this participant's values remained consistently equal or above baseline. Interestingly, the data revealed a collective decrease in ratings for items 2 and 3.

Post-experimental Interviews: confirmed that participants remained unaware of the NF. None reported unusual observations or held correct prior assumptions. Notably, they could not differentiate the PIF from the baseline audio until they listened to them separately. Regarding study duration, participants noted that while four blocks were manageable for experts, a 15-minute intervention might be more appropriate for non-expert populations to avoid fatigue. One participant suggested maintaining the 5-min block duration, noting that physical immobility—rather than the meditative state itself—becomes challenging over longer periods. The auditory materials were consistently described as 'pleasant', 'calming' or 'relaxing,' with no modifications suggested for the mindfulness guidelines or reminders. The first two participants reported concerns regarding their performance, noting that they required additional time to reach a meditative state within the experimental environment. All participants, especially 1 and 3, found the eye-open requirement highly counterintuitive. Participant 2 noted that although the experience with eyes open was unusual, she was able to acclimate quickly, instead, participant 1 reported that upon entering a deep meditative state, she began to close her eyes almost unintentionally, only to be momentarily distracted by the need to consciously re-open them to comply with the protocol.

DISCUSSION

Achieving a meditative state is rarely instantaneous, even outside a laboratory; here, experimental constraints likely exacerbated this latency and may have elicited performance anxiety. This could explain the initial FAA downregulation observed across the sample. Furthermore, the effort required to maintain open eyes, especially for those with different meditation habits, may have increased cognitive workload and disrupted the meditative flow. For instance, Participant 1 reported the need to actively counteract the urge to close her eyes when a deeper meditation state unfolded. In contrast, Participant 2 struggled less with this requirement, potentially explaining her higher mindfulness ratings and

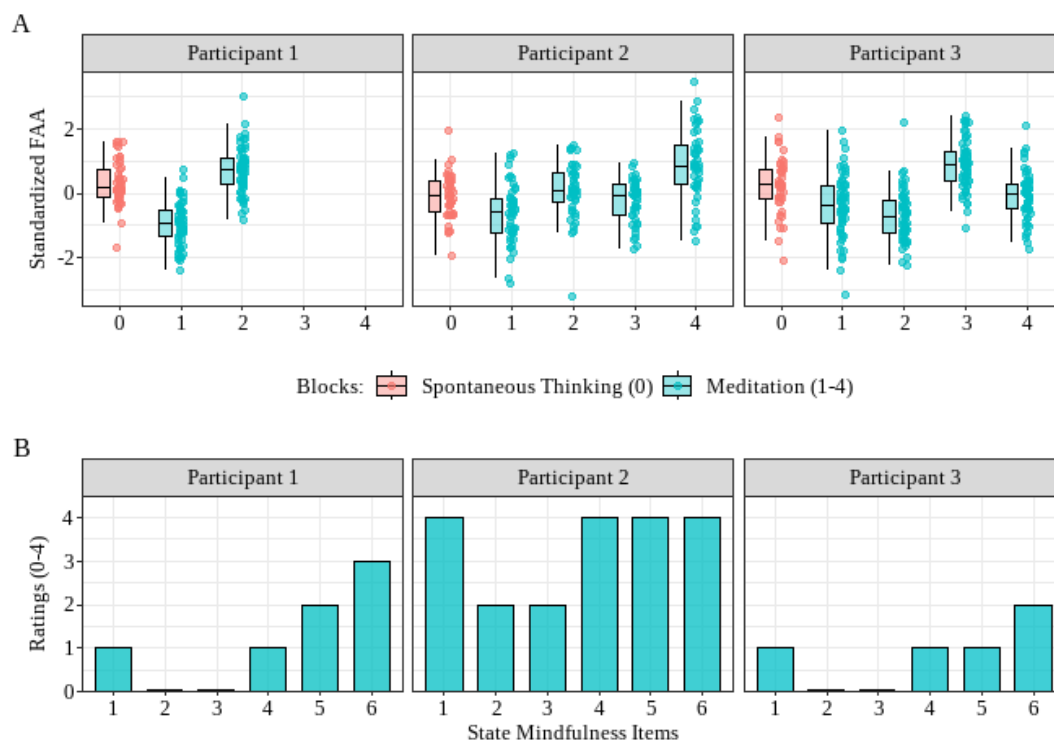


Figure 1: Combined visualization of (A) standardized Frontal Alpha Asymmetry (FAA) across experimental blocks and (B) behavioral ratings for State Mindfulness items. Data are presented for three individual participants.

clearer FAA upregulation. Together, these factors may when a deeper meditation state unfolded. Together, these factors may account for the lack of consistent upregulation across blocks. The general lower ratings for items 2 and 3 of the SMS-PA-M warrant further investigation.

Eyes Open/Closed in FAA Literature: Approach-avoidance FAA research is more focused on eyes-open designs [5,23] and the same applies to NF research both aimed at investigating FAA [6,7,24] or meditation [12,25,26], likely because the NF protocols adopted were visual. To date, eyes-closed NF-FAA research has been limited to a single publication investigating its role as a baseline predictor for learners/non-learners [27]. Our eyes-open design contrasts with the broader meditation literature, where studies targeting FAA exclusively employed eyes-closed protocols [11,28,29]. Given that our protocol does not strictly require active gazing, exploring an eyes-closed direction is a logical next step.

Choice of Meditation: Mindfulness remains one of the most successful meditation techniques for targeting FAA, alongside breathwork meditation [29]. We opted against breathing-based protocols to protect the signal-to-noise ratio, as irregular or deep breathing patterns can introduce artifacts that compromise EEG signal quality and NF accuracy. Coherently, our mindfulness guidelines focus on present-moment awareness with minimal bodily reference beyond general relaxation.

CONCLUSION

As a proof-of-concept, this contribution confirms that positive auditory feedback can be integrated into an instrumental mindfulness meditation without compromising the qualitative depth of the practice. To establish whether sustained FAA modulation is achievable, future research should move beyond the illustrative single sessions by programming a minimum of 5-6 sessions in accordance with previous NF-FAA literature. Moreover, rigorous control groups are necessary to disentangle the effects of mindfulness from the NF, alongside more comprehensive psychometric testing and experimental tasks enabling us to measure pre-to-post-performance changes.

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