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Bidirectional Alpha Power EEG Neurofeedback During a Focused Attention Meditation Practice in Novices

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Abstract

Background. Neurofeedback and meditation practices are techniques aimed at enhancing awareness and self-regulation. Training of alpha power has been found to increase mindfulness outcomes, and increases in alpha power seem relatively consistent during focused attention meditation practices. Considering the commonalities between these self-regulation techniques, we here examined the trainability of alpha power while engaging in a focused attention meditation, allowing novice practitioners to attain self-regulation with an integrated training. In a within-subject design, 31 participants (25 women, 6 men, aged 23.16, range 18–30) engaged in two types of alpha neurofeedback training conditions, one aimed at upregulating alpha, the other aimed at downregulating global alpha absolute power. **Results**. Linear mixed-effect analyses showed a differential effect of the two neurofeedback training conditions, indicating that alpha power was overall higher during upregulation compared to downregulation training. While differential alpha power was evident "online" during training, there appeared to be no "offline" transfer, as measured during a resting-state recording posttraining. **Conclusion**. These results provide relevant insights into the applicability of alpha neurofeedback combined with focused attention meditation instructions that may guide future work into the application of neurofeedback approaches for supporting meditation practice.

Keywords: EEG neurofeedback; BCI; alpha; meditation; focused attention; self-regulation

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Background

Mindfulness entails the enactment of an attitudinal quality characterized by a state of complete presence in the ongoing moment, further distinguished by a nonjudgmental and accepting stance towards the instant emerging experience (Kabat-Zinn, 2013). This quality can be dispositional—a stable idiosyncratic tendency to be mindful—and can also be cultivated further with training (Burzler & Tran, 2022). In recent years, there has been a medical and popular increasing recognition of the relevance of mindfulness to mental health, leading to a growing focus on promoting and enhancing skills such as self-regulation as a fundamental component of overall well-being (Heatherton, 2011). The interest in improving individuals' abilities to cope with stressors and regulate one's own emotional state has further given rise to the appearance of a vast number of mindfulness-related media, such as free guided meditations on media platforms, and mobile apps (Mani et al., 2015; Plaza et al., 2013). Altogether, these tools have facilitated the integration of mindfulness practices into daily routines, providing individuals with accessible options to reap mindfulness's positive effects independently (Cavanagh et al., 2014). The effects of regular mindfulness practice arise through processes of attention regulation, body awareness, emotion regulation, and a shift in one's perspective of the self (Hölzel et al., 2011). Moreover, evidence has demonstrated that mindfulness practices exert a beneficial influence on individuals' physical well-being, as evidenced by its ability to improve stress resilience (Creswell et al., 2019), mitigate stress reactivity (Goldin & Gross, 2010; Gotink et al., 2016; Kral et al., 2018), and lower levels of physiological stress markers (Bortolla et al., 2022; Heckenberg et al., 2018; Ooishi et al., 2021; Sun et al., 2019).

The integration of technology into mindfulness practices presents a promising avenue for enhancing the level of guidance available to individuals during meditation. Furthermore, it has the potential to enhance engagement, ultimately yielding more favorable outcomes derived from the practice. Biometric sensors and wearable devices can track physiological signals providing users with valuable insights about their physiological state during the practice. For example, electroencephalographic (EEG) sensors can detect neural patterns that indicate whether individuals find themselves in the desired meditative brain state, or whether their mind has wandered off in self-generated thoughts (Pandey et al., 2022). Through the utilization of neurofeedback training, which involves continuously monitoring and presenting changes in neural activity to the mindfulness practitioner, awareness of the neurally reflected characteristics of the mindfulness session can be expanded. Individuals can thus gain insights about the adequacy and necessary adjustments to their practice (e.g., redirecting the attention towards the intended object of focus in focused attention meditations [FAM]) and improve the quality of the mindfulness session.

Regarding candidate neural signal parameters reflecting aspects related to mindfulness practices, the neural alpha band, comprehended between 8 and 14 Hz, has been extensively studied and its changes are proposed as relevant for the development of meditative skills during early stages of learning (Cahn et al., 2013; Fell et al., 2010). Alpha synchronization, the increase in alpha band activity, has been found to reflect internally directed attention during processes such as mental imagery as opposed to externally perceived stimuli (Cooper et al., 2003). This phenomenon has been robustly observed in the context of mindfulness meditation practices (Brandmeyer & Delorme, 2018; Lee et al., 2018) which are also commonly associated in the literature with increases in relaxed alertness (Britton et al., 2014; Lomas et al., 2015). Indeed, numerous studies have consistently found mindfulness meditation to be reflected by an increase in alpha power when compared to rest, in both novices (Ahani et al., 2014; Dunn et al., 1999; Milz et al., 2014) and experienced meditators (Cahn et al., 2013; Lagopoulos et al., 2009).

Several previous studies have demonstrated increases in alpha power upon neurofeedback upregulation training (Brickwedde et al., 2019; Chikhi et al., 2023; Escolano et al., 2011, 2014; Hanslmayr et al., 2005; Nan et al., 2012; Navarro Gil et al., 2018; Nicholson et al., 2023; Radüntz et al., 2017; Su et al., 2021; Uslu & Vögele, 2023; Zoefel et al., 2011). Interestingly, some studies have targeted alpha power regulation in relation to mindfulness practices. For example, Stieger et al. (2021) investigated the effects of mindfulness-based stress reduction (MBSR) training on the volitional upregulation of alpha power with a brain computer interface (BCI). The authors found that, compared to controls, participants receiving the MBSR training learned to control the BCI faster and exhibited increased upregulation of alpha power (Cohen's d = 0.68) when in rest (Stieger et al., 2021). In a further exploration of the same dataset, Jiang et al. (2021) expanded upon this finding and showed that the association between those receiving a mindfulness training and achieving better BCI control was not evident at first but instead gradually increased over the course of the BCI task, and that with more meditation practice outside of the formal training, the better the BCI control. Along the same line, da Costa et al. (2021) primed participants with mindfulness meditation prior to an alpha neurofeedback training and found an enhanced ability to regulate when compared to those not primed. Furthermore, Navarro Gil et al. (2018) found alpha power neurofeedback to increase self-reported mindfulness scores. Taken together, the literature indicates a reciprocal relationship between mindfulness and alpha neurofeedback training, wherein the effects of one positively influence the other.

In light of the parallels between mindfulness training and alpha neurofeedback training, both of which involve an enhanced self-regulation of alpha power, we set up a study combining both approaches. Specifically, to offer participants an integrative approach to improve their self-regulation skills, we examined the feasibility of combining alpha power upregulation neurofeedback training with a FAM practice. Additionally, we included an active control condition aimed at alpha power downregulation. The following hypotheses are hereby tested: upregulation training runs will be characterized by "online" trial-by-trial increases in global alpha power as compared to the active control downregulation training runs, where trial-by-trial decreases in alpha power are expected. Furthermore, in order to test whether the effects of training are maintained "offline" outside of the training context, we measured alpha activity during resting periods before and after the training, whereby the following hypotheses are tested: comparison between the rest period after training and before training will reflect a differential increase in alpha power during upregulation runs and a decrease during downregulation runs.

Methods

Participants

Thirty-one healthy participants (25 women, 6 men, aged 23.16, range 18–30 years) with no prior experience in meditation practices participated in this study. They were recruited via flyers on social media and using personal communication. Written informed consent was obtained from all participants prior to the start of the study. Consent forms and study design were approved by the Social and Societal Ethics Committee (SMEC) of the KU Leuven university (G-2018 12 1,463), in accordance with the World Medical Association Declaration of Helsinki. Participants were compensated for their participation at a rate of 10€ per hour.

Design and Task

EEG recordings were obtained while participants sat in a comfortable chair, facing the computer screen, and were taking part in four experimental runs in pseudorandomized order. Each run comprised an initial "pre" 3-min resting-state period, followed by six individual 2-min neurofeedback training trials and a final "post" 3-min resting-state period. A constant auditory background stimulus (the echo of a bell sound) was provided during all rest and training trials via earpods, and an additional continuous and varying feedback sound (cascade water running) was provided during neurofeedback training trials. The start and end of each rest period and training trial were indicated by a start/stop sound, prompting the participants to either close their eyes or open them and to follow instructions on the computer screen.

Prior to the start of the experiment, a short, standardized introduction was provided to the participants to familiarize them with the concept of neurofeedback and self-regulation of neurophysiological signals. This introduction included a brief explanation of autonomic nervous system activity and the objective to upregulate parasympathetic activity. Also, more detailed information regarding the specific instructions during the neurofeedback training and the structure and duration of the experiment was explained. Lastly, a volume adjustment on the to-be-presented auditory stimuli was performed individually per participant to ensure that all sounds were audible but not distracting.

Throughout the duration of the experiment, stimuli were presented to participants using PsychToolbox (Brainard, 1997). During the 3-min resting-state period (pre- and postneurofeedback training), participants were instructed to keep their eyes closed and sit comfortably while avoiding movement. During the neurofeedback training trials, and in line with FAM practices, participants were again asked to sit comfortably with eyes closed and, in addition, to focus their attention on top of the crown of their head while perceiving the feedback sound (running water) related to their brain activity. Importantly, participants were indicated not to try to influence the feedback sound directly but were informed that, by engaging in the focused attention on the crown of their head, self-regulatory processes would allow attaining the highest level of positive feedback (i.e., increasing volume of the running water sound).

In two of the four neurofeedback training runs, the running water feedback sound increased in volume with increasing global (average scalp) alpha power (alpha upregulation condition). In the other two training runs, the feedback sound increased with decreasing global alpha power (alpha downregulation condition). In every run, after each block of three training trials, participants were asked to report via a numerical keyboard their levels of tiredness, pleasantness, and calmness and the degree of focus on the crown of the head, as well as focus on the auditory stimuli.

The five questions were as follows, on a scale of 1 to 9:

(a) how tired are you?
(b) how pleasant are you feeling?
(c) how agitated are you?

(d) how well did you focus on the crown of your head?
(e) how well did you focus on the sounds?

For all questions, the response scale contained visual or textual cues. Since the study was not specifically designed to assess training-induced changes in the behavioral scores, results from these behavioral assessments are reported in supplementary information (Appendix Figure A1). In short, no significant training-specific changes were noted in any of the behavioral scores.

EEG Recordings

The Nexus-32 system (version 2015a, Mind Media, The Netherlands) was used for EEG recordings. Data was streamed to MATLAB (2019a) and recorded through the software Lab Stream Layer (LSL). The OpenVibe software was used for data quality checks during sensor placement and for data monitoring during the experiment. Continuous EEG was recorded with a 22-electrode cap (one ground electrode and two on the mastoids for reference) positioned according to the 10–20 system (MediFactory). Electrode paste (Nuprep) was used to reduce the electrode impedances during the recordings. The EEG signal was amplified using a unipolar amplifier with a sampling rate of 1024 Hz. EEG recordings were synchronized to the presented task using Matlab and Lab Stream Layer.

EEG Online Preprocessing, Feature Extraction, and Feedback

EEG preprocessing was performed through custom MATLAB scripts and EEGlab functions (Delorme & Makeig, 2004). After collection of the initial 3-min resting state at the beginning of each run, data was filtered between 1 Hz and 40 Hz to attenuate nonphysiological EEG artifacts (function *pop_eegfiltnew*). Subsequently, artifact subspace reconstruction was used with the function *asr_calibrate_r* (Chang et al., 2020) with a cutoff of 20, for further cleaning of the baseline. Lastly, points with absolute amplitudes exceeding 100 µV were set to 0. Then, short-term fast Fourier transformation (STFFT) was performed on the clean data in 1-s windows, with 90% overlap between 8 and 14 Hz (in steps of 1 Hz) per electrode. Then the absolute alpha power was averaged across electrodes and the time domain deriving a single initial resting-state alpha absolute power value. Subsequently, during each of the 2-min neurofeedback training trials, incoming data in chunks of 1 s were preprocessed with the same steps as the baseline, and resulting average absolute alpha power was used to calculate a *z*-score dependent on the resting-state period absolute power. With a table of matching *z*-score alpha power values and corresponding auditory feedback volumes, the feedback was delivered to participants by changing the volume of the sound (i.e., with continuously increasing volume in the case of alpha upregulation training trials upon increasing alpha absolute power and increasing volume upon decreasing alpha absolute power during downregulation training trials). A dynamic smoothing over time was introduced to maintain smooth feedback transitions for enhancing or diminishing the feedback sound volume.

EEG Offline Preprocessing and Analysis

Offline preprocessing was performed through custom MATLAB scripts (MATLAB version r2020b) and EEGlab functions (Delorme & Makeig, 2004). After removal of the first 3 s of the recording, raw EEG data were filtered with the *eegfiltnew* function first with a high-pass filter over the 1 Hz frequency to suppress the low-frequency noise, then with a notch filter on 50 Hz, used to remove the line noise (5th order butterworth filter with cutoff frequencies on 49–51 Hz) and lastly with a low-pass filter (40 Hz). Flat channels were detected and removed (function *clean_flatlines*) and reconstructed using spherical interpolation. The remaining epochs were then concatenated, and the continuous signals were mathematically rereferenced offline to common average. Subsequently, Independent Component Analysis (ICA) was performed (using the function *pop_runica*), to automatically reject components in the data associated with muscle, heart, or channel noise artifacts. Then data was downsampled from 1024 Hz to 256 Hz and epoched into 1-s segments.

The time-frequency representation of the EEG data was obtained using STFFT computed through the MATLAB *spectrogram* function (Hanning window length of 1 s; 90 % overlap, 1 Hz resolution between 1 and 40 Hz. A total of 29 relative amplitudes (% of overall power, in µV) within the alpha (8–14 Hz) band were estimated per participant, electrode, resting-state recording (prerest and postrest), neurofeedback training trial (trial 1 to 6) and run (run 1 and 2).

Statistical Analyses

All statistical analyses were executed with Statistica version 14 (Tibco Software Inc.). Linear mixed-effect models were used to test the training intervention effect on alpha absolute power (8–14 Hz), with the random factor *participant*, and fixed factors *training condition* (up- vs. downregulation), *run* (first vs. second), *training trial* (1, 2, 3, 4, 5, and 6) and *electrode* (19 scalp electrodes), as well as interactions amongst all fixed factors.

To explore whether training-induced up- or downregulation of alpha power would persist outside the explicit training context (i.e., to the resting-state period recorded posttraining), the 3-min pre- and post-resting-state period recordings were subjected to a linear mixed-effect model with the random factor *participant*, and the fixed factors *training condition* (up- vs. downregulation), *run* (first vs. second), *rest period* (pre- vs. posttraining period) and *electrode* (19 scalp electrodes), as well as interactions amongst all fixed factors. These analyses allowed examining whether the up- and downregulation of alpha power upon the experimental training session were transferable to the subsequent resting-state recording, indicating transfer of the trained neural parameter outside the explicit training context.

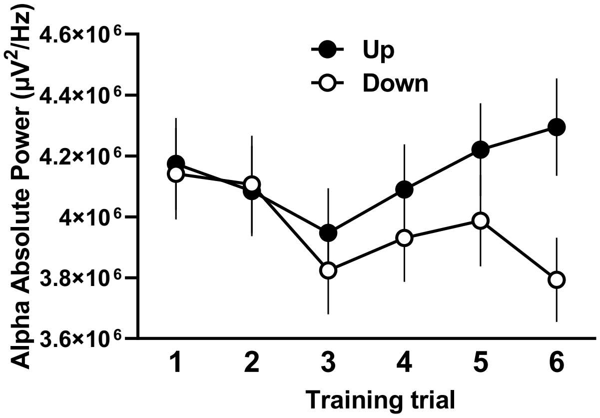
Results

Alpha Up- and Downregulation Across Neurofeedback Training Trials

The linear mixed-effect model revealed a significant main effect of training, $F(1, 30) = 10.49$, $p < .001$, $\eta^2 < .001$. This indicated an overall higher alpha power for the upregulation (mean up = $4.14x10^{+6}$ µV, $SD = 2.25x10^{+5}$) compared to the downregulation training condition (mean down = $3.96x10^{+6}$ µV, $SD = 2.32x10^{+5}$). In addition, as visualized in Figure 1, a tentative but nonsignificant trial by training interaction effect was found, $F(18, 30) = 2.05$, $p = .07$, $\eta^2 < .001$. This suggested a differential effect of training across trials. Post hoc analyses confirmed that only at the last, sixth trial ($p_{Bonferroni} = .007$) but not at the first training trial ($p_{Bonferroni} = 1.00$), alpha power was significantly higher in the upregulation when compared to the downregulation training condition.

In addition to the main effect of *training*, a main effect of *electrode* was also found, $F(18, 30) = 591.97$, $p < .001$, $\eta^2 = .44$. This indicated overall higher levels of absolute alpha power at occipital and temporal electrodes (O1, O2, T5, and T6), as well as a main effect of *run*, $F(1, 30) = 34.36$, $p < .001$, $\eta^2 = .002$. This indicated an overall higher alpha power during the second run when compared to the first run (mean run 1 = $3.89x10^{+6}$ µV, $SD = 1.48x10^{+5}$; mean run 2 = $4.20x10^{+6}$ µV, $SD = 2.15x10^{+5}$). However, these factors did not yield any significant interactions with the factor *training* (all $p > .05$), indicating that training effects were not significantly different between conditions, with respect to electrode effects and for the first compared to the second training run (see Appendix Figure A2 for a visualization of the training effects over trials, separately for the first and second training runs). Lastly, for the *trial* factor, a trend but nonsignificant main effect was found, $F(5, 30) = 2.16$, $p = .06$, $\eta^2 < .001$.

Figure 1. *Change in Alpha Absolute Power During Neurofeedback Training.*



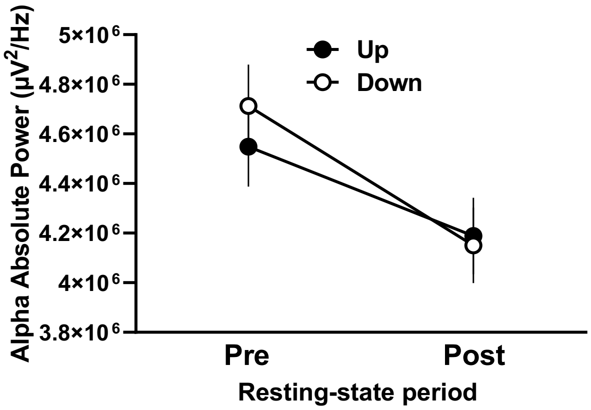
Note. Average global alpha absolute power recorded during neurofeedback training is visualized separately for each of the six training trials, across the two runs, and separately per training condition (white: downregulation training; black: upregulation training). Vertical bars denote ± standard errors.

Further, to specifically explore the change in alpha power over trials for each training condition, mixed-effect models testing the main effect of *trial* were employed separately per condition. For the downregulation condition, a significant main effect of *trial* was present, $F(5, 30) = 2.46$, $p = .03$, $\eta^2 = .002$. This indicated a reduction in alpha absolute power across trials (mean trial 1 = $4.14x10^{+6}$, $SD = 5.16x10^{+6}$; mean trial 6 = $3.79x10^{+6}$, $SD = 4.76x10^{+6}$). For the uptraining condition, however, no significant main effect of *trial* was identified, $F(5, 30) = 1.77$, $p = .12$, $\eta^2 = .002$. This indicated a nonsignificant increase in alpha absolute power over trials (mean trial 1 = $4.17x10^{+6}$, $SD = 5.18x10^{+6}$; mean trial 6 = $4.29x10^{+6}$, $SD = 5.51x10^{+6}$).

Transfer of Alpha Up- and Downregulation Training Effects Outside of the Training Context

To examine whether the induced up- or downregulation of alpha power was transferable to the subsequent resting-state recording, we investigated differences in alpha power from pre- to posttraining rest periods (see Figure 2). A significant main effect of *rest period* was identified, indicating an overall lower alpha power at the post- compared to the pre-resting-state recording, $F(1, 30) = 6.70$, $p = .01$, $\eta^2 = .1$, mean pre = $4.63 \times 10^{+6}$, $SD = 5.65 \times 10^{+6}$, mean post = $4.17 \times 10^{+6}$, $SD = 5.08 \times 10^{+6}$). No significant *rest period x training condition* interaction effect was identified, $F(1, 30) = 1.11$, $p = .29$, $\eta^2 < .001$. This indicated that the pre-to-post decrease in resting period alpha power was evident for both the up- and downregulation training condition. Additionally, no significant main effect of *run*, $F(1, 30) = 2.78$, $p = .09$, $\eta^2 < 0.001$, or any interactions with this factor were identified (all $p > .05$). See Appendix Figure A3 for a visualization of the training effects over rest periods, separately for the first and second training runs.

Figure 2. *Alpha Absolute Power Recorded During a Resting-State Period, Pre- and Postneurofeedback Training.*



Note. Average global alpha absolute power is visualized separately for the resting state period recorded pre- and postneurofeedback training, across the two runs, and separately per training condition (white: downregulation training; black: upregulation training). Vertical bars denote ± standard errors.

Discussion

In this study we developed and implemented an EEG neurofeedback protocol to train alpha power in the context of a FAM practice. In a single training session, 31 young adults took part in two runs aimed at training alpha power upregulation, and an additional two runs aimed at alpha power downregulation, serving as an active control condition. We hypothesized that upregulation training runs would induce "online" trial-by-trial increments in global alpha power in contrast to the active control downregulation training runs, which were anticipated to induce trial-by-trial reductions in alpha power. Moreover, to assess the "offline" persistence of training effects beyond the training environment, we examined alpha activity during periods of rest prior to and following the training. We hypothesized that the comparison between the rest period after training and the rest period before training would reveal a distinct increase in alpha power during upregulation runs and a decrease during downregulation runs.

With respect to online neurofeedback training effects, we revealed a significant difference between the up- and down-training condition, indicating higher alpha power levels during the upregulation, compared to the downregulation neurofeedback training. Particularly for the alpha power downregulation, significant alpha power decreases were evident from the first to the last training trial.

Previous studies have consistently found increases in alpha power upon upregulation training (Brickwedde et al., 2019; Chikhi et al., 2023; Escolano et al., 2011, 2014; Hanslmayr et al., 2005; Nan et al., 2012; Navarro Gil et al., 2018; Nicholson et al., 2023; Radüntz et al., 2017; Su et al., 2021; Uslu & Vögele, 2023; Zoefel et al., 2011). Similarly, other studies have found successful downregulation of alpha power during training (Brickwedde et al., 2019; Deiber et al., 2020; Kluetsch et al., 2014; Ros et al., 2010, 2013). Similar to our study, Kluetsch and colleagues (2014) succeeded to reduce alpha amplitude during a single 30-min session desynchronization neurofeedback when comparing training to baseline.

As indicated, our design included bidirectional alpha power up- and downregulation. Although literature about training bidirectional regulation of alpha power is scarce, Brickwedde et al., (2019) successfully trained somatosensory alpha power and found facilitation of tactile perceptual learning upon alpha upregulation and hindering of learning upon alpha downregulation. In this study, they also showed that higher baseline alpha activity was required to achieve the behavioral learning outcome. This is in line with other studies predicting trainability of alpha based on baseline alpha activity (Chikhi et al., 2023; Nan et al., 2018; Su et al., 2021; Wan et al., 2014).

Regarding the retention of 'offline' training effects, as measured comparing pre- to post-rest periods, our analyses revealed that, for both conditions, a significant overall reduction of alpha power was evident following the training. Although this transfer effect was expected for the downregulation condition, it contrasted with our hypothesis regarding upregulation training. Previous studies investigating the offline transferability of upregulation alpha power training to subsequent rest recordings have found increases in alpha power (Escolano et al., 2011; Nicholson et al., 2023; Zoefel et al., 2011) as compared to the control group, whereas others have not (Escolano et al., 2014; Nan et al., 2012; Navarro Gil et al., 2018; Uslu & Vögele, 2023). With respect to downregulation trainings, other studies have demonstrated that downregulation of alpha can lead to decreases in the resting alpha power level (Ros et al., 2010, 2013). However, other studies have found no influence of downregulation on the alpha power on subsequent recordings of resting periods (Nan et al., 2018; Ros et al., 2017). It might be the case that, for neurofeedback effects to be maintained, the intervention requires several training sessions, in particular when addressing clinical as opposed to nonclinical populations (Dekker et al., 2014; Nicholson et al., 2023). Interestingly, regarding nonclinical populations, Uslu and Vögele (2023) argue that instead of the number of sessions, self-paced neurofeedback, providing participants with the possibility to arrange the timing of their training, has a positive impact on cognitive performance changes upon neurofeedback.

While our work adds new insights into the application of alpha neurofeedback during FAM, the following limitations and directions for future research are highlighted.

With respect to the control condition choice in neurofeedback experiments, there is a plethora of options (Sorger et al., 2019), and the optimal one depends on the objectives of the experiment. In this study, we found significant differences between the active alpha up- and alpha downtraining condition. Although an active control condition allowed for assessing the specificity of our training with respect to regulation direction, future studies should address whether training-specific effects are also evident in comparison to a sham control condition. Further, neurofeedback studies frequently encounter subgroups of participants that are not able to control the target parameter (i.e., nonresponders or BCI illiterates). Future studies should warrant the assessment of predictors of individual trainability as recommended in previous literature (Alkoby et al., 2018). For example, there is growing evidence that alpha power levels at baseline predict the ability to further self-regulate alpha during a neurofeedback protocol (Chikhi et al., 2023; Nan et al., 2018; Su et al., 2021; Wan et al., 2014). Additionally, mindful skills and their priming have also been regarded as a possible predictors and facilitators for neurofeedback training (da Costa et al., 2021; Stieger et al., 2021).

Finally, the observation that particularly alpha downtraining was successful indicates that upregulation of alpha might require more training trials and/or sessions. Indeed, it can be anticipated that particularly for individuals who are new to the practice of mediation and/or self-regulatory neurofeedback, establishing a parallel relationship between the targeted upregulation of alpha power during neurofeedback and meditation expertise might necessitate a higher intensity or longer duration of the training.

Conclusion

The present study provides initial evidence that up- versus down-training of global alpha power during a focused attention meditation practice yielded a significant differential pattern, particularly indicating a significant decrease in alpha power upon downregulation. Training effects did however not sustain during a subsequent resting-state recording, indicating no transfer of upregulated alpha power outside the active training context. Together, these results provide important insights into the applicability of alpha neurofeedback training as an adjunct to and in support of meditation practice.

Author Disclosure

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Author Contributions

Javier R. Soriano: conceptualization, methodology, software, validation, formal analysis, writing original draft, visualization, investigation, resources, data curation, supervision, project administration, writing review and editing.

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Hendrik-Jan de Vuyst: data curation, writing review and editing.

Julio Rodriguez-Larios: funding acquisition.

Naishi Feng: data curation.

Carolina Varon: supervision, writing review and editing.

Kaat Alaerts: conceptualization, formal analysis, visualization, writing review and editing, supervision, funding acquisition.

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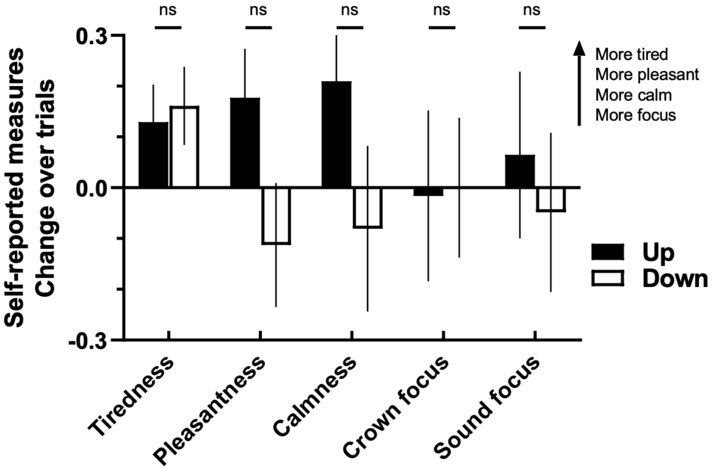
Appendix A

Changes in Self-Reported Measures Across Neurofeedback Training Trials

On an exploratory basis, differential changes in levels of self-reported measures of tiredness, pleasantness, calmness, focus on the crown of the head, and focus on the sounds upon receiving alpha up- or downregulation feedback were assessed. To do so, change scores were calculated for each self-reported measure (change from mid [after Trial 3] to end reports [after Trial 6] within each run) and subjected to a linear mixed-effect model with the random factor *participant*, and fixed factors *training condition* (up vs. downregulation) and *run* (first vs. second), as well as interactions amongst the fixed factors.

Analyses revealed no significant main effects of *training* for self-reported tiredness, $F(1, 30) = .1$, $p = .76$, $\eta^2 < .01$; calmness, $F(1, 30) = 2.01$, $p = .16$, $\eta^2 = .02$; focus on the crown, $F(1, 30) < .01$, $p = .94$, $\eta^2 < 0.01$; or focus on the feedback sound, $F(1, 30) = .23$, $p = .63$, $\eta^2 < .01$. For self-reported pleasantness, a trend but nonsignificant main effect of *training*, $F(1, 30) = 3.13$, $p = .08$, $\eta^2 = .03$, indicated tentative increases in reports of pleasantness over trials during alpha upregulation compared to downregulation. None of the remaining main or interaction effects were significant (all $p > .05$).

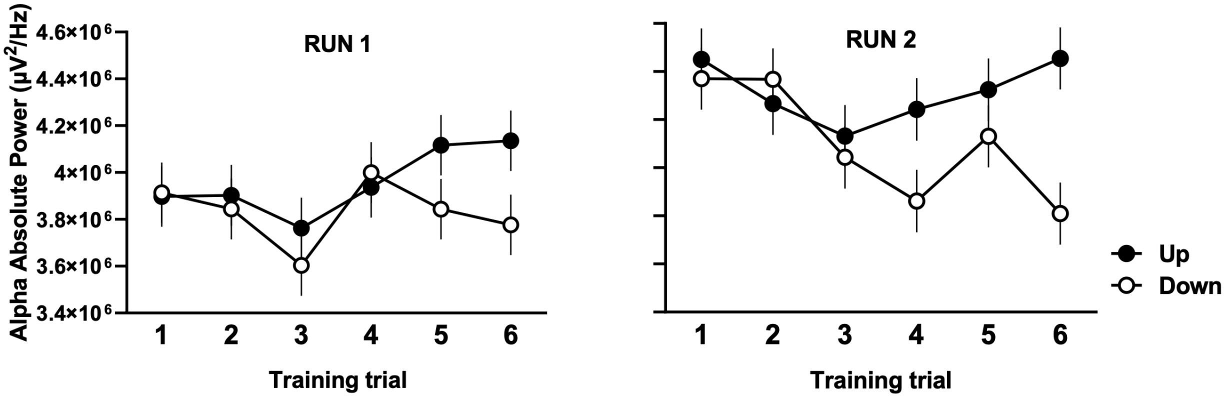
Figure A1. *Changes in Self-Reported Measures Across Neurofeedback Training Trials.*



Note. Changes in self-reported scores (change from mid [after Trial 3] to end [after Trial 6] are depicted across runs, separately per training condition (white: downregulation training; black: upregulation training). Vertical bars denote ± standard errors; “ns” indicates nonsignificant effects ($p > .05$).

Alpha Absolute Power Recorded During Neurofeedback Training Trials in Run 1 and Run 2

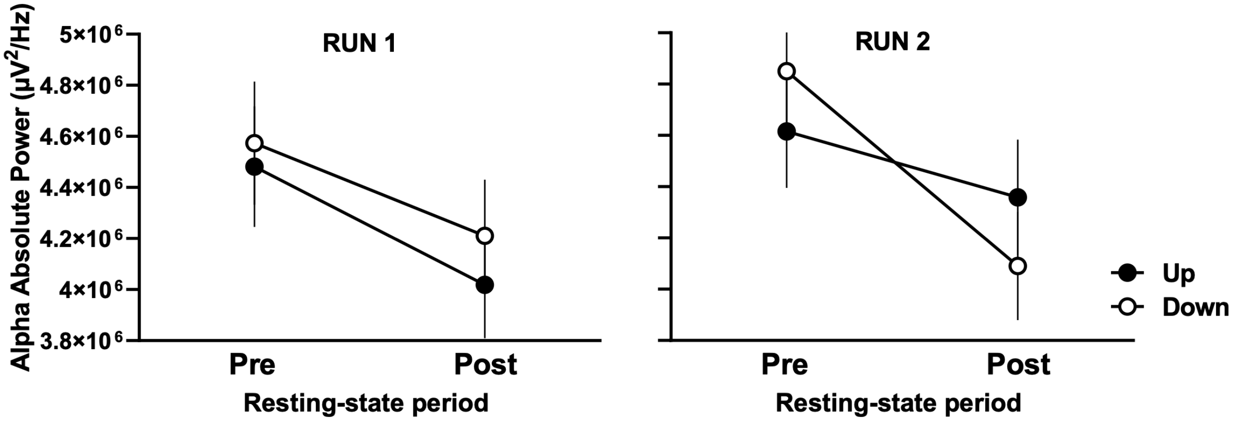
Figure A2. *Alpha Absolute Power Recorded During Neurofeedback Training Trials in Run 1 and Run 2.*



Note. Average global alpha absolute power recorded during neurofeedback training is visualized separately for each of the six training trials, separately for each run and training condition (white: downregulation training; black: upregulation training). Vertical bars denote ± standard errors.

Alpha Absolute Power Recorded During a Resting-State Period, Pre- and Postneurofeedback Training During Run 1 and Run 2

Figure A3. *Alpha Absolute Power Recorded During a Resting-State Period, Pre- and Postneurofeedback Training During Run 1 and Run 2.*



Note. Average global alpha absolute power is visualized separately for the resting-state period recorded pre- and postneurofeedback training, separately for each run and training condition (white: downregulation training; black: upregulation training). Vertical bars denote ± standard errors.