Bidirectional alpha power EEG-neurofeedback during a focused attention meditation practice in novices.

Javier R. Soriano
Neuromodulation Lab, Research Group for Neurorehabilitation, Department of Rehabilitation Sciences, KU Leuven
Eduardo Bracho Montes de Oca
IACCHOS, Université Catholique de Louvain
Angeliki-Ilektra Karaiskou
ESAT, Stadius Centre for Dynamical Systems, Signal Processing and Data Analytics, KU Leuven
Hendrik-Jan De Vuyst
Neuromodulation Lab, Research Group for Neurorehabilitation, Department of Rehabilitation Sciences, KU Leuven
Carolina Varon
ESAT, Stadius Centre for Dynamical Systems, Signal Processing and Data Analytics, KU Leuven
Kaat Alaerts (✉ kaat.alaerts@kuleuven.be)
Neuromodulation Lab, Research Group for Neurorehabilitation, Department of Rehabilitation Sciences, KU Leuven

---

Research Article

Keywords: EEG-Neurofeedback, BCI, Alpha, Meditation, Focused Attention, Self-regulation

Posted Date: September 29th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3377138/v1

Abstract

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, here we examined the trainability of alpha power in the context of a focused attention meditation, to provide novice practitioners with an integrated training to attain improved self-regulation. In a within-subject design, 31 participants (25 women, aged 23.16, range 18–30) engaged in two runs of six trials each, aimed at up-regulation of global alpha absolute power (average of electroencephalography electrodes). Instructions were to focus the attention on a point above the crown of the head, while perceiving continuous auditory feedback. As an active control, participants took part in two alpha power down-regulation runs. Linear mixed-effect analyses showed that alpha power was overall higher during up- compared to down-regulation training. However, subsequent analyses indicated that the differential training effect was predominantly driven by a successful reduction in alpha power during down-regulation training, while the up-regulation training condition did not significantly yield increases. Differential changes in alpha power induced by both trainings were not significantly sustained during a resting-state recording post training. While these results provide insights into the applicability of alpha neurofeedback combined with meditation, future work is needed to establish the most optimal conditions for facilitating training, with successful up-training of alpha likely requiring more training sessions, consistent with the need of regular practice in meditation trainings.

INTRODUCTION

Mindfulness entails the enactment of an attitudinal quality characterized by a state of complete presence in the ongoing moment, further distinguished by a non-judgmental 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 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 a numerous appearance of 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’ 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; Ra 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).

Although short mindfulness interventions have also been shown to exert beneficial effects (Mahmood et al., 2016), mindfulness trainings typically involve 8-week mindfulness-based stress reduction (MBSR) programs (Kabat-Zinn, 2013). The usage of apps and guided meditations has provided greater access to the practice of mindfulness, but the lack of structured continuity and the presence of experienced instructors as in typical MBSR interventions posits some disadvantages to the engagement with the practice and its potential benefits. For example, self-guided practice can hinder comprehension of the mindfulness concepts and practice, with information quality also depending on the selection of the mindfulness app (Schultchen et al., 2021). Thus, personalized feedback and guidance can be essential for individuals to address specific challenges related to the practice, and make significant progress.

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 (Larios & Pandey, 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., re-directing the attention towards the intended object of focus in focused attention meditations), 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 up-regulation 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 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 up-regulation 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 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 up-regulation neurofeedback training with a focused attention meditation practice. Additionally, we included an active control condition aimed at alpha power down-regulation. The following hypotheses are hereby tested: up-regulation training runs will be characterized by trial-by-trial increases in global alpha power as compared to the active control down-regulation training runs, where trial-by-trial decreases in alpha power are expected. Furthermore, in order to test whether the effects of training are maintained outside 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 up-regulation runs and a decrease during down-regulation runs.

METHODS

Participants

Thirty-one healthy participants (25 women, 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-minute resting-state period, followed by six individual 2-minute neurofeedback training trials and a final ‘post’ 3-minute 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, was indicated by a start/stop sound prompting the participants to either close their eyes or open them and 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 up-regulate 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 post-neurofeedback training), participants were instructed to keep their eyes closed and sit comfortably while avoiding movement. During the neurofeedback training trials, and in line with focused attention meditation 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 up-regulation condition). In the other two training runs, the feedback sound increased with decreasing global alpha power (alpha down-regulation condition). In every run, after each block of 3 training trials, participants were asked to report via a numerical keyboard their levels of tiredness, pleasantness, calmness, and degree of focus on the crown of the head, as well as focus on the auditory stimuli. The five questions were as follows: (1) On a scale from 1 to 9, how tired are you? (2) On a scale from 1 to 9, how pleasant are you feeling? (3) On a scale from 1 to 9, how agitated are you? (4) On a scale from 1 to 9, how well did you focus on the crown of your head? (5) On a scale from 1 to 9, 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. 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 pre-processing was performed through custom MATLAB scripts and EEGlab functions (Delorme & Makeig, 2004). After collection of the initial 3-minute resting state at the beginning of each run, data was filtered between 1 Hz and 40 Hz to attenuate non-physiological 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-second 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 two-minute neurofeedback training trials, incoming data in chunks of 1 second were pre-processed 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 up-regulation training trials upon increasing alpha absolute power, and increasing volume upon decreasing alpha absolute power during down-regulation 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 three seconds 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 cut-off 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 re-referenced 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-second segments.

The time-frequency representation of the EEG data was obtained using STFFT computed through the MATLAB *spectrogram* function (Hanning window length of 1 second; 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 (pre-rest and post-rest), 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. down-regulation), *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 down-regulation of alpha power would persist outside the explicit training context, i.e., to the resting-state period recorded post-training, 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. down-regulation), *run* (first vs. second), *rest period* (pre- vs. post-training period) and *electrode* (19 scalp electrodes) as well as interactions amongst all fixed factors. These analyses allowed examining whether the up- and down-regulation 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 down-regulation across neurofeedback training trials

The linear mixed-effect model revealed a significant main effect of *training* ($F(1,30) = 10.49$; $p < .001$; $\eta^2 < .001$), indicating an overall higher alpha power for the up-regulation (Mean up = 4.14 e^{+6} µV ; *SD* = 2.25 e^{+5}) compared to the down-regulation training condition (Mean down = 3.96 e^{+6} µV ; *SD* = 2.32 e^{+5}). In addition, as visualized in Fig. 1, a tentative but non-significant *trial by training interaction* effect was found ($F(18,30) = 2.05$; $p = .07$; $\eta^2 < .001$), suggesting 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 up-, compared to the down- regulation training condition.

In addition to the main effect of *training*, also a main effect of *electrode* was found ($F(18,30) = 591.97$; $p < .001$; $\eta^2 = .44$), indicating 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* ($F(1,30) = 34.36$; $p < .001$; $\eta^2 = .002$), indicating overall higher alpha power during the second run, compared to the first run (Mean run 1 = 3.89 e^{+6} µV ; $SD = 1.48\ e^{+5}$, Mean run 2 = 4.20 e^{+6} µV ; $SD = 2.15\ e^{+5}$). 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 **Supplementary Fig. 1** 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 non-significant main effect was found ($F(5,30) = 2.16$; $p = .06$; $\eta^2 < .001$).

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 down-regulation condition, a significant main effect of *trial* was present ($F(5,30) = 2.46$; $p = .03$; $\eta^2 = .002$), indicating a reduction in alpha absolute power across trials (mean trial 1 = $4.14e^{+6}$ $SD = 5.16e^{+6}$; mean trial 6 = $3.79e^{+6}$ $SD = 4.76e^{+6}$). For the up-training condition, however, no significant main effect of *trial* was identified ($F(5,30) = 1.77$; $p = .12$; $\eta^2 = .002$), indicating a non-significant increase in alpha absolute power over trials (mean trial 1 = $4.17e^{+6}$ SD = $5.18e^{+6}$; mean trial 6 = $4.29e^{+6}$ SD = $5.51e^{+6}$).

Transfer of alpha up- and down-regulation training effects outside the training context

To examine whether the induced up- or down-regulation of alpha power was transferable to the subsequent resting-state recording, we investigated differences in alpha power from pre- to post-training rest periods (see Fig. 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 ($F(1,30) = 6.70$; $p = 0.01$; $\eta^2 = .1$) (mean pre = $4.63e^{+6}$ $SD = 5.65e^{+6}$; mean post = $4.17e^{+6}$ $SD = 5.08e^{+6}$). No significant *rest period x training condition* interaction effect was identified ($F(1,30) = 1.11$; $p = .29$; $\eta^2 < .001$), indicating that the pre-to-post decrease in resting period alpha power was evident for both the up- and down-regulation training condition. Additionally, no significant main effect of *run* ($F(1,30) = 2.78$; $p = 0.09$; $\eta^2 < 0.001$) or any interactions with this factor were identified (all $p > .05$). See **Supplementary Fig. 2** for a visualization of the training effects over rest periods, separately for the first and second training runs.

DISCUSSION

In this study we developed and implemented an EEG neurofeedback protocol to train alpha power in the context of a focused attention meditation practice. In a single training session, 31 young adults took part in two runs aimed at training alpha power up-regulation, and an additional two runs aimed at alpha power down-regulation, serving as an active control condition. We hypothesized that up-regulation training runs would induce trial-by-trial increments in global alpha power in contrast to the active control down-regulation training runs, which were anticipated to induce trial-by-trial reductions in alpha power.

Moreover, to assess the 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 up-regulation runs and a decrease during down-regulation runs.

With respect to our hypothesized increase in global absolute alpha power across trials during the up-regulation condition, we did not find a significant increase. Only our active control condition, alpha power down-regulation, significantly induced alpha power decreases over the course of the trials. Interestingly, despite the lack of successful training during the target up-regulation condition, the linear mixed effect model revealed significant differences between the two conditions, indicating higher alpha power levels during the up-regulation, compared to the down-regulation conditions. Previous studies have consistently found increases in alpha power upon up-regulation 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 down-regulation of alpha power during training (Brickwedde et al., 2019; Deiber et al., 2020; Kluetsch et al., 2014; Ros et al., 2010, 2013a). Similar to our study, Kluetsch and colleagues (2014) succeeded to reduce alpha amplitude during a single 30-minute session desynchronization neurofeedback when comparing training to baseline. However, opposite to our results, when comparing the pre-training 3-minute baseline to the post-training baseline, an increase in alpha amplitude was found, reflecting a rebound effect after training.

As opposed to most studies, our design included bidirectional alpha power up- and down-regulation. Although literature about training bidirectional regulation of alpha power is scarce, Brickwedde, Krüger, & Dinse, (2019) successfully trained somatosensory alpha power and found facilitation of tactile perceptual learning upon alpha up-regulation and hindering of learning upon alpha down-regulation. 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 effects of training-induced alpha power changes, as measured comparing pre- to post- rest periods, our analyses revealed that, for both conditions, a significant overall reduction of alpha power followed the training. Although this transfer effect was expected for the down-regulation condition, it contrasted with our hypothesis regarding up-regulation training. Previous studies investigating the transferability of up-regulation 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 down-regulation trainings, other studies have demonstrated that down-regulation of alpha can lead to decreases in the resting alpha power level (Ros et al., 2010, 2013b). However, other studies have found no influence of down-regulation 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 non-clinical populations (Dekker et al., 2014; Nicholson et al., 2023). Interestingly, regarding non-clinical populations, Uslu & 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.

Limitations

There are several limitations in our study that require consideration. Our protocol utilized as feedback parameter the global average of alpha absolute power, thus not focusing on specific electrode sites as in previous studies. Other studies have selected Pz as the electrode location where alpha can be maximally recorded (Ros et al., 2013b) and have disregarded the global average option in terms of loss of local cortical dynamics of interest during training (Ros et al., 2013b). Thus, it is possible that the small effect sizes, and the non-significant trend in the up-regulation condition stems from the lack of neural regional specificity in our training protocol, which could have benefitted from targeting specific sites, such as Pz. However, it is relevant to note that previous studies training at specific sites such as Pz, have also found their training outcomes to be consistent when considering the global alpha average (Ros et al., 2013b). Averaging across several electrodes has been proposed as beneficial due to the increase in signal to noise ratio, however the set of electrodes should be limited to those relevant to the feature and related region to be trained (Enriquez-Geppert et al., 2017).

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 selected an active control condition that aimed at training alpha power in the opposite direction (down-regulation) to the main targeted one. Although an active control condition allowed for assessing the specificity of our training with respect to regulation direction, the choice of instructions was the same across conditions, which might have been suboptimal for differentiating the effects of the target vs. the control condition. Additionally, we employed a single session in a within-subject design, and thus, the same participants sequentially participated in opposite direction regulation trainings (pseudorandomized across participants) without their knowledge or other clear distinction in the protocol. Therefore, whilst an increase in alpha power was rewarded during certain trials, also rewarding a decrease in alpha power, shortly before or after, could have hindered the training process due to an inconsistency in the contingency of the feedback during regulation training. Future studies should warrant a clearer separation of the two conditions, across different sessions, which can aid in obtaining more stable trainings per condition, as well as in establishing a distinction between the differential learning goals if a within-subject design is used. In this context, a sham condition would have allowed to assess whether there is a protocol specific (regardless of training direction) effect on alpha being down-regulated, which was prevented during the alpha up-regulation condition, reflected by the non-significant trend to an increase in alpha power and the difference in alpha power between the conditions.

Additionally, neurofeedback studies frequently encounter subgroups of participants that are not able to control the target parameter (i.e., non-responders 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 absence of successful alpha up-regulation training indicates that this target might require more training trials and sessions. In order to foster specific skills, studies should ensure that adequate training durations are allocated. In the case of meditation practices, which can be particularly demanding for individuals who are new to the practice, it is common for training programs to span across multiple weeks. Accordingly, particularly for individuals who are new to the practice of mediation, establishing a parallel relationship between the targeted up-regulation of alpha power during neurofeedback and meditation expertise might necessitate more trials and sessions.

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 down-regulation. Training effects did however not sustain during a subsequent resting-state recording, indicating no transfer of up-regulated 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.

Declarations

CREDIT STATEMENT

Javier R. Soriano: Conceptualization, Methodology, Software, Validation, Formal Analysis, Writing-Original Draft, Visualization, Investigation, Resources, Data Curation, Supervision, Project Administration, Writing-Review & Editing**. Eduardo Bracho Montes de Oca**: Methodology, Software, Writing-Review & Editing**. Angeliki-Ilektra Karaiskou**: Formal Analysis, Writing-Review & Editing**. Hendrik-Jan de Vuyst**: Data Curation, Writing-Review & Editing**. Carolina Varon:** Supervision, Writing-Review & Editing. **Kaat Alaerts:** Conceptualization, Formal Analysis, Visualization, Writing-Review & Editing, Supervision, Funding Acquisition**.**

FUNDING STATEMENT

This work was supported by grants from the Flanders Fund for Scientific Research (FWO projects G079017N and G046321N), an Interdisciplinary network project of the KU Leuven (IDN21022) and the Branco Weiss fellowship of the Society in Science–ETH Zurich granted to KA.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

References

1. Ahani, A., Wahbeh, H., Nezamfar, H., Miller, M., Erdogmus, D., & Oken, B. (2014). Quantitative change of EEG and respiration signals during mindfulness meditation. *Journal of NeuroEngineering and Rehabilitation*, *11*(1), 87. https://doi.org/10.1186/1743-0003-11-87.
2. Alkoby, O., Abu-rmileh, A., Shriki, O., & Todder, D. (2018). Can We Predict Who Will Respond to Neurofeedback ? A Review of the Inefficacy Problem and Existing Predictors for Successful EEG Neurofeedback Learning. *Neuroscience*, *378*, 155–164. https://doi.org/10.1016/j.neuroscience.2016.12.050.
3. Bortolla, R., Galli, M., Spada, G. E., & Maffei, C. (2022). Mindfulness Effects on Mind Wandering and Autonomic Balance. *Applied Psychophysiology Biofeedback*, *47*(1), 53–64. https://doi.org/10.1007/s10484-021-09527-x.
4. Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436.
5. Brandmeyer, T., & Delorme, A. (2018). Reduced mind wandering in experienced meditators and associated EEG correlates. *Experimental Brain Research*, *236*(9), 2519–2528. https://doi.org/10.1007/s00221-016-4811-5.
6. Brickwedde, M., Krüger, M. C., & Dinse, H. R. (2019). Somatosensory alpha oscillations gate perceptual learning efficiency. *Nature Communications*, *10*(1), 1–9. https://doi.org/10.1038/s41467-018-08012-0.
7. Britton, W. B., Lindahl, J. R., Cahn, R., Davis, B., J. H., & Goldman, R. R. (2014). Awakening is not a metaphor: the effects of Buddhist meditation practices on basic wakefulness. *Annals of the New York Academy of Sciences*, *1307*, 64–81. https://doi.org/10.1111/nyas.12279.Awakening.
8. Burzler, M. A., & Tran, U. S. (2022). Dispositional Mindfulness and the Process of Mindfulness Cultivation: A Qualitative Synthesis and Critical Assessment of the Extant Literature on the Five Facet Mindfulness Questionnaire (FFMQ). *Collabra: Psychology*, *8*(1), 1–27. https://doi.org/10.1525/collabra.56176.
9. Cahn, B. R., Delorme, A., Polich, J., Diego, S., & Jolla, L. (2013). *Event-related delta, theta, alpha and gamma correlates to auditory oddball processing during Vipassana meditation*. 100–111. https://doi.org/10.1093/scan/nss060.
10. Cavanagh, K., Strauss, C., Forder, L., & Jones, F. (2014). Can mindfulness and acceptance be learnt by self-help? A systematic review and meta-analysis of mindfulness and acceptance-based self-help interventions. *Clinical Psychology Review*, *34*(2), 118–129. https://doi.org/10.1016/j.cpr.2014.01.001.
11. Chang, C., Member, S., Hsu, S., & Pion-tonachini, L. (2020). Evaluation of Artifact Subspace Reconstruction for Automatic Artifact Components Removal in Multi-Channel EEG Recordings. *IEEE*

Transactions on Biomedical Engineering, *67*(4), 1114–1121. https://doi.org/10.1109/TBME.2019.2930186.

12. Chikhi, S., Matton, N., Sanna, M., & Blanchet, S. (2023). Mental strategies and resting state EEG: Effect on high alpha amplitude modulation by neurofeedback in healthy young adults. *Biological Psychology*, *178*(August 2022), 108521. https://doi.org/10.1016/j.biopsycho.2023.108521.
13. Cooper, N. R., Croft, R. J., Dominey, S. J. J., Burgess, A. P., & Gruzelier, J. H. (2003). Paradox lost? Exploring the role of alpha oscillations during externally vs. internally directed attention and the implications for idling and inhibition hypotheses. *International Journal of Psychophysiology*, *47*(1), 65–74. https://doi.org/10.1016/S0167-8760(02)00107-1.
14. Creswell, J. D., Lindsay, E. K., Villalba, D. K., & Chin, B. (2019). Mindfulness Training and Physical Health: Mechanisms and Outcomes. *Psychosomatic Medicine*, *81*(3), 224–232. https://doi.org/10.1097/PSY.0000000000000675.
15. da Costa, N. M. C., Bicho, E., Ferreira, F., Vilhena, E., & Dias, N. S. (2021). A multivariate randomized controlled experiment about the effects of mindfulness priming on eeg neurofeedback self-regulation serious games. *Applied Sciences (Switzerland)*, *11*(16), https://doi.org/10.3390/app11167725.
16. Deiber, M. P., Hasler, R., Colin, J., Dayer, A., Aubry, J. M., Baggio, S., Perroud, N., & Ros, T. (2020). Linking alpha oscillations, attention and inhibitory control in adult ADHD with EEG neurofeedback. *NeuroImage: Clinical*, *25*(December 2019), 102145. https://doi.org/10.1016/j.nicl.2019.102145.
17. Dekker, M. K. J., Sitskoorn, M. M., Denissen, A. J. M., Boxtel, G. J. M., & Van (2014). The time-course of alpha neurofeedback training effects in healthy participants. *Biological Psychology*, *95*, 70–73. https://doi.org/10.1016/j.biopsycho.2013.11.014.
18. Delorme, A., & Makeig, S. (2004). EEGLAB: an open sorce toolbox for analysis of single-trail EEG dynamics including independent component anlaysis. *Journal of Neuroscience Methods*, *134*, 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.
19. Dunn, B. R., Hartigan, J. A., & Mikulas, W. L. (1999). Concentration and Mindfulness Meditations: Unique Forms of Consciousness ? *Applied Psychophysiology and Biofeedback*, *24*(3), 147–165. https://doi.org/https://doi.org/10.1023/A:1023498629385.
20. Enriquez-Geppert, S., Huster, R. J., & Herrmann, C. S. (2017). EEG-neurofeedback as a tool to modulate cognition and behavior: A review tutorial. *Frontiers in Human Neuroscience*, *11*(February), 1–19. https://doi.org/10.3389/fnhum.2017.00051.
21. Escolano, C., Aguilar, M., & Minguez, J. (2011). EEG-based upper alpha neurofeedback training improves working memory performance. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, 2327–2330. https://doi.org/10.1109/IEMBS.2011.6090651.
22. Escolano, C., Navarro-Gil, M., Garcia-Campayo, J., Congedo, M., De Ridder, D., & Minguez, J. (2014). A controlled study on the cognitive effect of alpha neurofeedback training in patients with major depressive disorder. *Frontiers in Behavioral Neuroscience*, *8*(SEP), 1–12. https://doi.org/10.3389/fnbeh.2014.00296.

23. Fell, J., Axmacher, N., & Haupt, S. (2010). From alpha to gamma: Electrophysiological correlates of meditation-related states of consciousness. *Medical Hypotheses*, *75*, 218–224. https://doi.org/10.1016/j.mehy.2010.02.025.
24. Goldin, P. R., & Gross, J. J. (2010). Effects of Mindfulness-Based Stress Reduction (MBSR) on Emotion Regulation in Social Anxiety Disorder. *Emotion*, *10*(1), 83–91. https://doi.org/10.1037/a0018441.
25. Gotink, R. A., Meijboom, R., Vernooij, M. W., Smits, M., & Hunink, M. G. M. (2016). 8-week Mindfulness Based Stress Reduction induces brain changes similar to traditional long-term meditation practice – A systematic review. *Brain and Cognition*, *108*, 32–41. https://doi.org/10.1016/j.bandc.2016.07.001.
26. Hanslmayr, S., Sauseng, P., Doppelmayr, M., Schabus, M., & Klimesch, W. (2005). Increasing individual upper alpha power by neurofeedback improves cognitive performance in human subjects. *Applied Psychophysiology Biofeedback*, *30*(1), 1–10. https://doi.org/10.1007/s10484-005-2169-8.
27. Heatherton, T. F. (2011). Neuroscience of Self and Self-Regulation. *Annual Review of Psychology*, *62*, 363–390. https://doi.org/10.1146/annurev.psych.121208.131616.
28. Heckenberg, R. A., Eddy, P., Kent, S., & Wright, B. J. (2018). Do workplace-based mindfulness meditation programs improve physiological indices of stress? A systematic review and meta-analysis. *Journal of Psychosomatic Research*, *114*, 62–71. https://doi.org/10.1016/j.jpsychores.2018.09.010.
29. Hölzel, B. K., Lazar, S. W., Gard, T., Schuman-Olivier, Z., Vago, D. R., & Ott, U. (2011). How Does Mindfulness Meditation Work? Proposing Mechanisms of Action From a Conceptual and Neural Perspective. *Perspectives on Psychological Science*, *6*(6), 537–559. https://doi.org/10.1177/1745691611419671.
30. Jiang, H., Stieger, J., Kreitzer, M. J., Engel, S., & He, B. (2021). Frontolimbic alpha activity tracks intentional rest BCI control improvement through mindfulness meditation. *Scientific Reports*, *11*(1), 1–8. https://doi.org/10.1038/s41598-021-86215-0.
31. Kabat-Zinn, J. (2013). *Full Catastrophe Living, revised edition: Using the Wisdom of Your Body and Mind to Face Stress, Pain, and Illness*. Dell Publishing. https://doi.org/10.1037/032287.
32. Kluetsch, R. C., Ros, T., Théberge, J., Frewen, P. A., Calhoun, V. D., Schmahl, C., Jetly, R., & Lanius, R. A. (2014). Plastic modulation of PTSD resting-state networks and subjective wellbeing by EEG neurofeedback. *Acta Psychiatrica Scandinavica*, *130*(2), 123–136. https://doi.org/10.1111/acps.12229.
33. Lagopoulos, J., Xu, J., Rasmussen, I., Vik, A., Malhi, G. S., Eliassen, C. F., & Ellingsen, Ø. (2009). Increased theta and alpha EEG activity during nondirective meditation. *The Journal of Alternative and Complementary Medicine*, *15*(11), 1187–1192. https://doi.org/http://doi.org/10.1089/acm.2009.0113.
34. Larios, J. R., & Pandey, P. (2022). *Detecting moments of distraction during meditation practice based on changes in the EEG signal Detecting moments of distraction during meditation practice based on changes in the EEG signal*. *November*. https://doi.org/10.36227/techrxiv.21572586.

35. Lee, D. J., Kulubya, E., Goldin, P., Goodarzi, A., & Girgis, F. (2018). Review of the neural oscillations underlying meditation. *Frontiers in Neuroscience*, *12*(MAR), 1–7. https://doi.org/10.3389/fnins.2018.00178.
36. Lomas, T., Ivtzan, I., & Fu, C. H. Y. (2015). A systematic review of the neurophysiology of mindfulness on EEG oscillations. *Neuroscience and Biobehavioral Reviews*, *57*, 401–410. https://doi.org/10.1016/j.neubiorev.2015.09.018.
37. Mahmood, L., Hopthrow, T., & De Moura, G. R. (2016). A moment of mindfulness: Computer-mediated mindfulness practice increases state mindfulness. *Plos One*, *11*(4), 14–16. https://doi.org/10.1371/journal.pone.0153923.
38. Mani, M., Kavanagh, D. J., Hides, L., & Stoyanov, S. R. (2015). Review and evaluation of mindfulness-based iPhone apps. *JMIR MHealth and UHealth*, *3*(3), 1–10. https://doi.org/10.2196/mhealth.4328.
39. Milz, P., Faber, P. L., Lehmann, D., Kochi, K., & Pascual-marqui, R. D. (2014). sLORETA intracortical lagged coherence during breath counting in meditation-naïve participants. *Frontiers in Human Neuroscience | Www Frontiersin Org*, *8*(303), 1–10. https://doi.org/10.3389/fnhum.2014.00303.
40. Nan, W., Rodrigues, J. P., Ma, J., Qu, X., Wan, F., Mak, P. I., Mak, P. U., Vai, M. I., & Rosa, A. (2012). Individual alpha neurofeedback training effect on short term memory. *International Journal of Psychophysiology*, *86*(1), 83–87. https://doi.org/10.1016/j.ijpsycho.2012.07.182.
41. Nan, W., Wan, F., Tang, Q., Wong, C. M., Wang, B., & Rosa, A. (2018). Eyes-closed resting EEG predicts the learning of alpha down-regulation in neurofeedback training. *Frontiers in Psychology*, *9*(AUG), 1–7. https://doi.org/10.3389/fpsyg.2018.01607.
42. Navarro Gil, M., Escolano Marco, C., Montero-Marín, J., Minguez Zafra, J., Shonin, E., & García Campayo, J. (2018). Efficacy of Neurofeedback on the Increase of Mindfulness-Related Capacities in Healthy Individuals: a Controlled Trial. *Mindfulness*, *9*(1), 303–311. https://doi.org/10.1007/s12671-017-0775-1.
43. Nicholson, A. A., Densmore, M., Frewen, P. A., Neufeld, R. W. J., Théberge, J., Jetly, R., Lanius, R. A., & Ros, T. (2023). Homeostatic normalization of alpha brain rhythms within the default-mode network and reduced symptoms in PTSD following a randomized controlled trial of EEG neurofeedback. *Brain Communications*, *5*(2), 1–16. https://doi.org/10.1093/braincomms/fcad068.
44. Ooishi, Y., Fujino, M., Inoue, V., Nomura, M., Maria, B., & De (2021). Differential Effects of Focused Attention and Open Monitoring Meditation on Autonomic Cardiac Modulation and Cortisol Secretion. *Frontiers in Physiology*, *12*, 1–16. https://doi.org/10.3389/fphys.2021.675899.
45. Plaza, I., Demarzo, M. M. P., Herrera-Mercadal, P., & García-Campayo, J. (2013). Mindfulness-based mobile applications: Literature review and analysis of current features. *JMIR MHealth and UHealth*, *1*(2), https://doi.org/10.2196/mhealth.2733.
46. Ra Kral, T., Schuyler, B. S., Mumford, J. A., Rosenkranz, M. A., Lutz, A., & Davidson, R. J. (2018). Impact of short-and long-term mindfulness meditation training on amygdala reactivity to emotional stimuli. *HHS Public Access Neuroimage*, *181*, 301–313. https://doi.org/10.1016/j.neuroimage.2018.07.013.

47. Radüntz, T., Scouten, J., Hochmuth, O., & Meffert, B. (2017). Automated EEG artifact elimination by applying machine learning algorithms to ICA-based features. *Journal of Neural Engineering*, *14*(4), https://doi.org/10.1088/1741-2552/aa69d1.
48. Ros, T., Munneke, M. A. M., Ruge, D., Gruzelier, J. H., & Rothwell, J. C. (2010). Endogenous control of waking brain rhythms induces neuroplasticity in humans. *European Journal of Neuroscience*, *31*(4), 770–778. https://doi.org/10.1111/j.1460-9568.2010.07100.x.
49. Ros, T., Théberge, J., Frewen, P. A., Kluetsch, R., Densmore, M., Calhoun, V. D., & Lanius, R. A. (2013a). Mind over chatter: Plastic up-regulation of the fMRI salience network directly after EEG neurofeedback. *Neuroimage*, *65*, 324–335. https://doi.org/10.1016/j.neuroimage.2012.09.046.
50. Ros, T., Théberge, J., Frewen, P. A., Kluetsch, R., Densmore, M., Calhoun, V. D., & Lanius, R. A. (2013b). Mind over chatter: Plastic up-regulation of the fMRI salience network directly after EEG neurofeedback. *Neuroimage*, *65*, 324–335. https://doi.org/10.1016/j.neuroimage.2012.09.046.
51. Schultchen, D., Terhorst, Y., Holderied, T., Stach, M., Messner, E. M., Baumeister, H., & Sander, L. B. (2021). Stay Present with Your Phone: A Systematic Review and Standardized Rating of Mindfulness Apps in European App Stores. *International Journal of Behavioral Medicine*, *28*(5), 552–560. https://doi.org/10.1007/s12529-020-09944-y.
52. Sorger, B., Scharnowski, F., Linden, D. E. J., Hampson, M., & Young, K. D. (2019). Control freaks: Towards optimal selection of control conditions for fMRI neurofeedback studies. *NeuroImage*, *186*(October 2018), 256–265. https://doi.org/10.1016/j.neuroimage.2018.11.004.
53. Stieger, J. R., Engel, S., Jiang, H., Cline, C. C., Kreitzer, M. J., & He, B. (2021). Mindfulness Improves Brain-Computer Interface Performance by Increasing Control over Neural Activity in the Alpha Band. *Cerebral Cortex*, *31*(1), 426–438. https://doi.org/10.1093/cercor/bhaa234.
54. Su, K. H., Hsueh, J. J., Chen, T., & Shaw, F. Z. (2021). Validation of eyes-closed resting alpha amplitude predicting neurofeedback learning of upregulation alpha activity. *Scientific Reports*, *11*(1), 1–9. https://doi.org/10.1038/s41598-021-99235-7.
55. Sun, S., Hu, C., Pan, J., Liu, C., & Huang, M. (2019). Trait mindfulness is associated with the self-similarity of heart rate variability. *Frontiers in Psychology*, *10*, 1–11. https://doi.org/10.3389/fpsyg.2019.00314.
56. Uslu, S., & Vögele, C. (2023). The more, the better? Learning rate and self-pacing in neurofeedback enhance cognitive performance in healthy adults. *Frontiers in Human Neuroscience*, *17*(January), 1–12. https://doi.org/10.3389/fnhum.2023.1077039.
57. Wan, F., Nan, W., Vai, M. I., & Rosa, A. (2014). Resting alpha activity predicts learning ability in alpha neurofeedback. *Frontiers in Human Neuroscience*, *8*(JULY), 1–7. https://doi.org/10.3389/fnhum.2014.00500.
58. Zoefel, B., Huster, R. J., & Herrmann, C. S. (2011). Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance. *Neuroimage*, *54*(2), 1427–1431. https://doi.org/10.1016/j.neuroimage.2010.08.078.

Figures

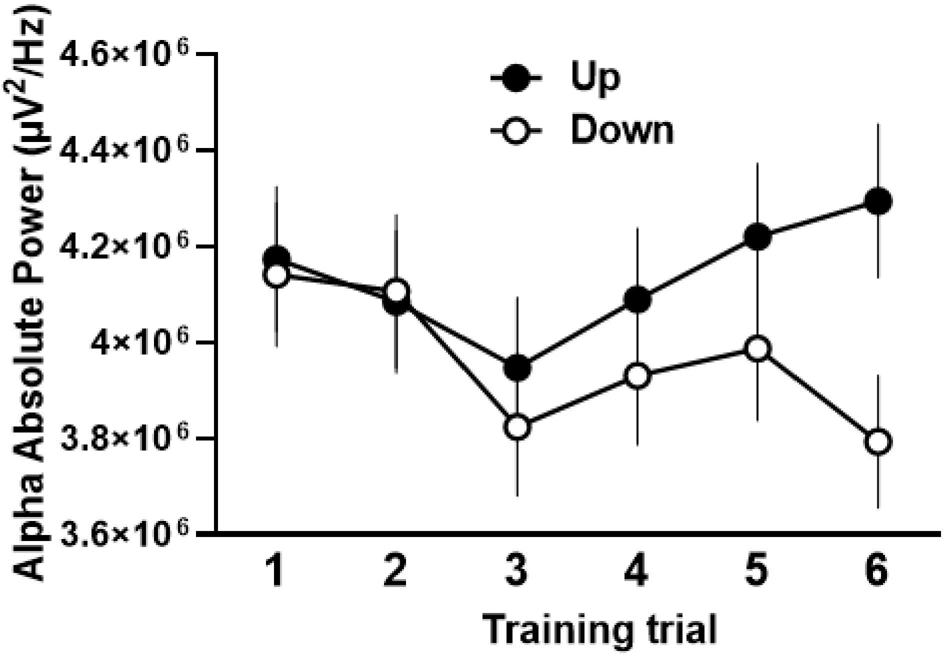

Figure 1

Change in alpha absolute power during neurofeedback training. Average global alpha absolute power recorded during neurofeedback training is visualized separately for each of the 6 training trials, across the two runs, and separately per training condition (white: down-regulation training; black: up-regulation training). Vertical bars denote +- standard errors.

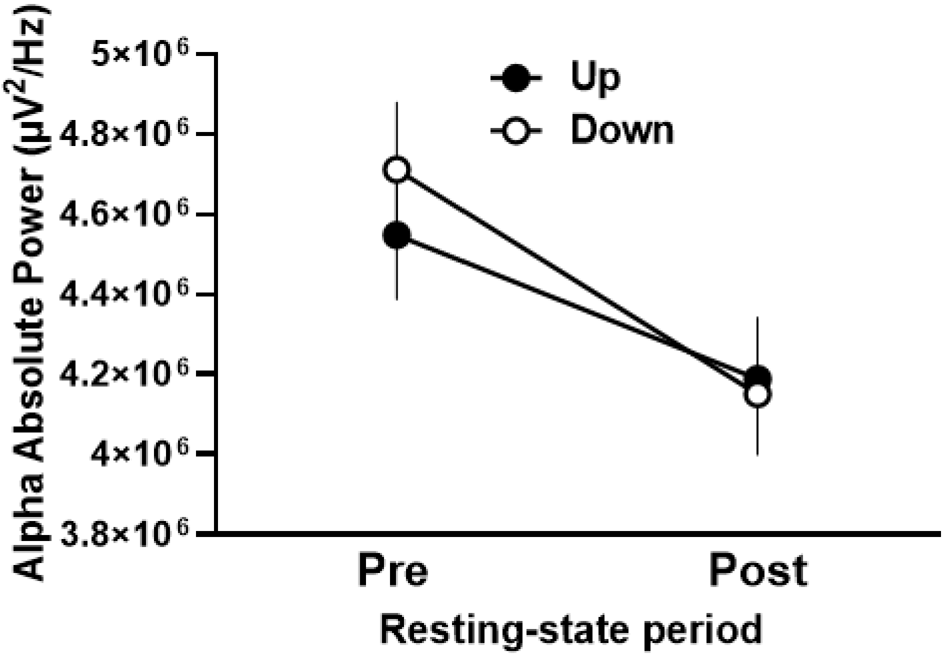

Figure 2

Alpha absolute power recorded during a resting-state period, pre- and post-neurofeedback training. Average global alpha absolute power is visualized separately for the resting state period recorded pre- and post-neurofeedback training, across the two runs, and separately per training condition (white: down-regulation training; black: up-regulation training). Vertical bars denote +- standard errors.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- alphaneurofeedbacksupplementarymaterialAPB.docx