

RESEARCH ARTICLE

Neurofeedback training with a low-priced EEG device leads to faster alpha enhancement but shows no effect on cognitive performance: A single-blind, sham-feedback study

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Abstract

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Introduction

Findings of recent studies indicate that it is possible to enhance cognitive capacities of healthy individuals by means of individual upper alpha neurofeedback training (NFT). Although these results are promising, most of this research was conducted based on high-priced EEG systems developed for clinical and research purposes. This study addresses the question whether such effects can also be shown with an easy to use and comparably low-priced Emotiv EPOC EEG headset available for the average consumer. In addition, critical voices were raised regarding the control group designs of studies addressing the link between neurofeedback training and cognitive performance. Based on an extensive literature review revealing considerable methodological issues in an important part of the existing research, the present study addressed the question whether individual upper alpha neurofeedback has a positive effect on alpha amplitudes (i.e. increases alpha amplitudes) and short-term memory performance focussing on a methodologically sound, single-blinded, sham controlled design.

Method

Participants (N = 33) took part in four test sessions over four consecutive days of either neurofeedback training (NFT group) or sham feedback (SF group). In the NFT group, five three-minute periods of visual neurofeedback training were administered each day whereas in the SF group (control group), the same amount of sham feedback was presented. Performance on eight digit-span tests as well as participants' affective states were assessed before and after each of the daily training sessions.

Results

NFT did not show an effect on individual upper alpha and cognitive performance. While performance increased in both groups over the course of time, this effect could not be explained by changes in individual upper alpha. Additional analyses however revealed that participants in the NFT group showed faster and larger increase in alpha compared to the SF group. Surprisingly, exploratory analyses showed a significant correlation between the initial alpha level and the alpha improvement during the course of the study. This finding suggests that participants with high initial alpha levels benefit more from alpha NFT interventions. In the discussion, the appearance of the alpha enhancement in the SF group and possible reasons for the absence of a connection between NFT and short-term memory are addressed.

Introduction

The growing number of college students using drugs like Methylphenidate (MPH, Ritalin) or Modafinil to enhance concentration, memory performance and wakefulness (16% on some college campuses, see e.g. [1–3]) can be considered an alarming indicator for the need of cognitive enhancement in our society. Rather than deploring this trend, the aim of this piece of research is to examine the usefulness of alternative methods for cognitive enhancement such as the non-invasive technique of neurofeedback training (NFT). Previous research addressing this topic has reported some evidence for a positive effect of NFT on cognitive performance. However, to our knowledge, no study has tested the effectiveness of NFT with a not-medical grade EEG. This gap in current research leaves the average consumer torn between the glorious slogans of a booming brain computer interface (BCI) industry with their easy-to-use and low-priced devices and a common sense which tries to disentangle advertising from possibility and innovation. The task is further exacerbated by the scientific field which suffers from the problem of publication bias (e.g. [4]), with methodologically problematic designs (e.g. no-intervention control groups) which make it difficult to give a clear statement about the usefulness of NFT for cognitive performance.

This study focuses on two aspects. Firstly, it aims at the investigation of the effectiveness of alpha NFT with an easy to use and low-priced EEG Headset and its corresponding software. Secondly, it provides an overview regarding methodological aspects in the field of alpha NFT and cognitive enhancement. Or, to put it differently, the authors try to help the average consumers when they are faced with questions like “can I improve my short-term memory capacity by using a low-priced EEG device for NFT?”

NFT can be considered a non-invasive technique to alter brain activity. Unlike for example transcranial magnetic stimulation, NFT does not interfere actively with the brain but serves merely as a mirror of the current amplitude of the target frequency band. NFT is a process during which subjects learn to influence their EEG pattern, for example by enhancing their individual upper alpha (IUA) amplitude [5]. In combination with a mental strategy (e.g. thinking about friends, [6]) and by receiving a feedback about their brain activity (which can be provided as e.g. bar graph [7], colour code [8] or as a function of different sounds [9]), subjects try to shape their cerebral activity in a certain given direction (e.g. enhance alpha activity). In the case of alpha enhancement, NFT is considered to be beneficial for cognitive performance [5,10–12]. While there exist a rather large number of publications supporting the assumption of a direct link between NFT and cognitive performance, several authors have questioned the

experimental designs of some of these studies and highlighted the need for additional empirical research adopting experimentally sound study designs, carefully considering methodological aspects such as blindfolding and expectancy effects (e.g. [13,14])

In this context, the goal of this study is twofold. First, we aim at presenting a proof of concept for the use of a low cost non-clinical EEG device in an individual upper alpha NFT paradigm for the enhancement of cognitive performance [5,15]. Second, we aim to emphasize a methodologically sound and reliable experimental procedure based on an exhaustive review of publications in the field of alpha NFT and cognitive performance.

The origin of neurofeedback training and its effect on cognitive performance in healthy participants

The use of NFT in medical and therapeutic contexts has gained increasing interest in research and practice over the past 50 years (e.g. [16–19]). Various studies indicate that NFT shows positive effects in the treatment of diseases like Attention Deficit Hyperactive Disorder, Autism Spectrum Disorder, Substance Use Disorder and Epilepsy (e.g. [14–24]). Also with regard to other disorders (e.g. General Anxiety Disorder, see [25]), there are some studies suggesting positive effects of NFT. Recently, a first pilot study investigating the usefulness of NFT as intervention technique for patients suffering from Alzheimer Disease (AD) revealed that “neurofeedback, in combination with treatment with cholinesterase inhibitors, may be a potential treatment by which the progressive deterioration in patients with AD can be stabilized” [26]. Finally, NFT seems to facilitate effectively the lives of people affected by Amyotrophic Lateral Sclerosis or the so-called Locked-in Syndrome [27].

Because of its positive effects in clinical practice, there has been increasing interest in the question whether NFT can influence the capacities of healthy individuals positively. Some studies seem to support this hypothesis [28] and according to Klimesch [12], especially the individual upper alpha band is of major importance for cognitive performance.

The individual upper alpha band is generally calculated based on EEG data. By means of Fast Fourier Transformation (FFT) the rhythmic EEG components delta (about 0.5–4 Hz), theta (about 4–8 Hz), alpha (about 8–13 Hz) beta (about 13–30 Hz) and gamma (about 30–100 Hz) can be extracted. The IUA constitutes a sub-band of the alpha component and is located between the individual alpha peak (IAP, between 7.5 and 12.5 Hz) and IAP + 2 Hz [12].

The ‘amount’ of alpha activity can be expressed in terms of amplitude or power. Working with amplitude instead of power values has the advantage that it prevents excessive skewing and improves the validity of the statistical analysis [7]. Sometimes (e.g. [29]), instead of amplitude values, relative alpha values are calculated by dividing the mean amplitude of the individual upper alpha band by the mean amplitude of the whole EEG. This normalization avoids variance in the absolute alpha amplitude caused by changes between trials due to changes in impedance between the electrodes and the scalp. By normalizing, the frequency band of interest is relativized, which mitigates the issue of attenuations caused by external factors, which affect all frequency bands equally [7].

Alpha is an especially interesting oscillation that the human brain exhibits. It’s the predominant rhythm in the human brain in a resting state, especially when eyes are closed [30]. Until the 80’s, Alpha NFT was considered as a simple relaxation training, located within the theoretical framework of unitary arousal models. Only during the 90’s, new interest arose and from then on many different research questions circulated around the alpha frequency band [31], which will be outlined in the following paragraphs.

One property of alpha is the association between individual alpha peak position and cognitive performance and neurological disorders, respectively. After conducting a FFT, the data

can be plotted in a frequency spectrum map. In resting state recordings, the alpha peak is clearly visible between 7.5 and 12.5 Hz and constitutes one of the strongest components of the FFT. Higher alpha peak frequencies (e.g. 12 Hz in comparison to 10 Hz) have been shown to correlate negatively with neurological disorders and with low age and high age, while higher alpha peak frequencies correlate positively with high memory performance [32,33] and IQ [34].

Another property of the alpha activity is the connection between alpha amplitude/power and cognitive performance. For example Neubauer and colleagues [35] found a positive correlation between individual upper alpha amplitude and IQ. More specifically, high alpha power during a resting state and low alpha power during the execution of a task was associated with good performance in semantic long-term memory tasks [12]. According to Klimesch [12], alpha shows a task-related desynchronization, it increases during resting states (especially when eyes are closed) and decreases during performance of a cognitive task (e.g. mental calculations). Therefore, it seems to be a promising approach to mimic the phenomena observed in good performers by means of NFT (enhanced alpha power during a resting period shortly before the short-term memory task) in order to enhance cognitive performance.

Interestingly, past studies [12] observed the connection between alpha desynchronization and cognitive performance only when the alpha band was divided into two sub-bands: upper and lower alpha. Klimesch located the upper alpha band between the individual alpha peak (IAP, between 7.5 and 12.5 Hz) and IAP + 2 Hz and stated that the lower alpha band is connected to a “variety of non-task and non-stimulus specific factors which may be subsumed under the term ‘attention’ [...] and reflect general task demands” [12]. This author located the lower alpha band between IAP−4 and IAP. Therefore, in most of the studies, the individual upper alpha (IUA) band was used for NFT and some researchers go as far as assessing the alpha band each test session anew.

A study of high importance for the development of IUA feedback addressed the topic by means of transcranial magnetic stimulation in a within-subject design [28]. In line with the correlational findings between alpha desynchronization and cognitive performance, the participants were stimulated to produce more IUA activity (individual alpha peak + 1 Hz) at P6 and Fz before the execution of a task. In this way, the natural desynchronization process which can be found in participants showing high cognitive performance (i.e. mental rotation and short-term memory performance) was mimicked. In the control condition, participants also ‘underwent’ transcranial magnetic stimulation, but the coil was rotated by 90° so the participants did not receive any stimulation. The results show a significant increase of IUA during transcranial magnetic stimulation in the experimental condition, as well as decreased test power, resulting in a large event-related desynchronization. None of these changes were observed in the control condition. Cognitive performance was assessed in terms of success in a Mental Rotation Task. Results showed that mental rotation performance in the experimental condition was higher compared to the control condition. The authors interpreted these findings as an indicator for a causal relationship between IUA activity and cognitive performance in healthy subjects.

Based on these findings, several studies examined the connection between IUA activity and cognitive performance. In those studies, different aspects of cognitive performance like short-term memory performance or working memory performance were assessed via a digit-span Task or a Conceptual Span Task (e.g. [5,36]), or Mental Rotation Task [37]. Mental flexibility and executive functions were assessed via the Trail Making Test [38], or creativity by the Unusual Uses Test [39]. Summarizing the results of these studies, imply a positive connection between individual upper alpha NFT and different aspects of cognitive performance like working memory/STM and visuospatial rotation. Whether the relationship between IUA and STM is of causal or correlational character, which underlying mechanisms lead to the enhancing

effect of individual upper alpha NFT on cognitive performance and whether unspecific environmental factors of the experimental setup play a key role in the process of NFT is still not fully understood at the moment. In the following section, some of these aspects are addressed by a comprehensive analysis of published studies addressing the link between IUA and cognitive performance.

Summary of experimental studies on neurofeedback training and cognitive performance

This section summarizes findings of studies addressing the link between IUA and cognitive performance. Inspired by Rogala and colleagues [14], Table 1 gives an overview of the existing experimental research addressing NFT training (Alpha and Alpha/Theta) and its effects on behavioural measurements of attention (column “A”) and memory (column “M”). Column “G” represents general success and subsumes general effects of the training obtained in any of the investigated measures other than memory and attention. Studies regarding Alpha NFT and Memory were highlighted grey and methodological aspects which deserve critical attention are marked bold. The overview contains studies that appear in [14] (marked with an asterisk *) as well as new research that has not been considered in the previous review. Inclusion criteria were that the studies used alpha as feedback frequency and the dependent variable was not a clinical outcome. The studies vary with regard to the feedback direction (upwards/increment or downwards/decrement, marked as + or -) and its effect on different behavioural outcomes. This overview does not claim to be complete but rather constitutes the result of our extensive literature search in this field of research.

As can be observed in Table 1, the interpretation of a large amount of study results in terms of whether IUA has an influence on cognitive performance is difficult. This is because a considerable proportion of published work on this topic do not report important aspects of the study design (e.g. information on blind-folding), do not use ideal control group designs, mix experimental manipulations, do not counterbalance intervention order or use very specific samples like old participants. Taking these limitations into consideration, there is only one study using a methodologically sound experimental design with regard to a control intervention and blindfolding, which found a significant effect of alpha-up-training on memory [15]. Because of this apparent lack of evidence, this piece of research aims to contribute to the existing body of literature to the literature regarding the relationship between alpha NFT on short-term memory performance emphasizing the methodological aspects of the at least single-blind control group design. Moreover, we want to approach the average consumer by using an easy to use and low-priced *Emotiv Epoc+* EEG headset.

The usefulness of low-cost EEG devices

Along with the increasing availability of low-cost devices for the assessment of brain activity, scientific research has also begun to systematically evaluate usefulness of these technological devices for practice and research. Various studies have been conducted using low cost EEG devices showing promising and useful results. It has been shown for example that the use of handy and easy to use mobile EEG devices in combination with P300 spelling devices and corresponding software is highly useful for locked-in patient [45]. In addition, off the shelf devices like the *Mindwave* can be used for NFT in combination with serious games for children with attention deficit hyperactivity disorder (ADHD), [46]. On a more general level, new portable low-priced and wireless EEG electrodes are being developed and the corresponding software, that processes EEG in real-time and for the use with tablets and smartphones is readily available [47]. In addition, studies investigating the question how arousal and prevalence of

Table 1. Overview of existing experimental research addressing alpha NFT and its effects on behavioural measurements.

N°	First Author Year	Citation	Protocol	EEG	Memory	Methodological considerations
1	Escolano 2011	[40]	Alpha+	1	1	Alpha NFT Group No-Intervention Control Group (took only part in the memory test)
						Random group assignment No blindfolding
2	Gil 2018	[41]	Alpha+	1	0	Alpha NFT Group No-Intervention Control Group
						Subject allocation according to a covariate-adaptive randomization procedure Single-blind
2	Guez 2015	[42]	Alpha+	0	1	Alpha NFT Group
						SMR NFT Group Sham Feedback Group
						Random group assignment Double-blind
3	Hsueh 2016	[43]	Alpha+	1	1	Alpha NFT Group, Random Frequency NFT Control Group
						Group assignment balanced for several variables, no information on blindfolding
5	Nan 2012	[5]	Alpha+	1	1	Alpha NFT Group No-Intervention Control Group
						Random group assignment No information on blindfolding
6*	Reis 2015	[44]	Alpha+	1	1	Alpha, Theta NFT Group (longitudinal conditions), Sham Feedback Group
						Random group assignment, single blind Interventions order not counterbalanced Only older participants, age > 55 years
7	Wei 2017	[15]	Alpha+	1	1	Alpha NFT Group Random Frequency NFT Group
						Random group assignment, single-blind

Success/Failure scores for studies (references in the second column) that qualified for analysis. Training results: 1, training success; 0, training failure. “EEG” column lists the results on the modulation of EEG features, the “Memory” column represents success/failure scores with regard to a dependent memory measure. The methodological considerations column gives information about the number of groups, interventions, random assignment and blindfolding. Abbreviations are defined as follows Theta = 4–7 Hz; Alpha also includes μ -rhythm (9–11 Hz) = 8–12 Hz. The studies vary with regard to the feedback direction (upwards/increment or downwards/decrement, marked as + or -) and its effect on the memory behavioural outcomes. The table contains studies that appear in [14] (marked with an asterisk *) as well as new research that has not been considered in the previous review.

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emotions can be measured and displayed with low-cost devices from the consumer goods sector (i.e. *Emotiv*) are conducted [48]. Even in combination with robotic prosthetics and movement classification, devices from *Emotiv* exhibit satisfying accuracy [49]. Other prototypes are being developed with the aim to promote muscular rehabilitation in patients suffering from paralyzed limbs as a result of severe strokes [50]. Beyond the clinical context, low-priced devices (*Muse*) seem to provide EEG correlates for user experience parameters like enjoyment [51]. Evaluating the devices mentioned in this section, there are promising results with regard to accuracy and data quality [52,53]. Empirical studies however revealed considerable differences between different devices, indicating for example that *Emotiv* showed better results compared to other off-the shelf products (e.g. *Mindwave*, [54]).

The present study

In line with the considerable progress of new hard- and software, EEG systems are available today which do not require conductive gel but use saline electrodes or operate with dry electrodes instead (e.g. *Quasar*, *Neurosky* or *Emotiv*). Along with this simplification of physiological measurements, EEG systems are becoming increasingly user-friendly and affordable. These new user-friendly and low-priced systems do not claim to compete with state of the art high-priced EEG systems. However, they measure valid EEG signals [52,53] and have their own niche: the average consumer [55].

That is why the study at hand combines the use of an easy to use and comparably low-priced EEG signal acquisition system (*Emotiv Epoc+* EEG headset) with the question regarding the connection between alpha NFT and cognitive enhancement by adopting a methodologically sound experimental design. The following research question was formulated.

Does individual upper alpha NFT with an easy in use, and comparably low-priced Emotiv Epoc EEG headset enhance cognitive performance in reasonably healthy participants?

In line with previous studies reporting increased individual upper alpha amplitude for NFT trainees, our first hypothesis (H1) predicts that relative IUA can be enhanced by means of IUA NFT, while no such increase is observed in the SF control group.

In our second hypothesis (H2), we expect this increase in relative IUA after NFT to result in an increased short-term memory performance, compared to the SF control group.

Our third hypothesis (H3) predicts in concordance with the theory of event related desynchronization [28], that there is an immediate positive effect of alpha-NFT on short-term memory performance. No such effect can be found in the SF control group.

Materials and method

Participants

Thirty-three psychology students were recruited at the *University of Fribourg* (Switzerland) via E-Mail and advertisement on the campus, ranging in age from 19 to 25 years ($M = 21.27$ years, $SD = 1.43$ years, 26 female).

After being duly informed about the protocol of the study, all participants agreed to written informed consent. The study at hand study was specifically approved by the internal review board of the ethical committee of the Department of Psychology, University of Fribourg. The project was evaluated under the Reference-N° IRB-e-375. As a compensation for their participation, they earned 5 credit points on a university-intern reward system. Participants were assigned randomly to either the experimental neurofeedback training group (NFT group, $n_1 = 17$, $M_{Age} = 21.29$, 12 female) or the control sham feedback group (SF group, $n_2 = 16$, $M_{Age} = 21.13$, 14 female). To assess whether subjects were aware of their condition, the last experimental task was to guess which group they were assigned to. The statement 'I was assigned to the control group' was answered on a 7-point Likert scale (ranging from 'I strongly disagree' to 'I strongly agree'). Analysis of the data showed that NFT and SF group did not differ, which indicates that participants in either group were unaware of their status ($M_{NFT} = 2.60$, $SD_{P1} = 1.45$; $M_{SF} = 3.18$, $SD_{SF} = 0.33$; $t(29) = 1.18$, $p = .249$).

Experimental protocol

In order to control for the influence of the circadian rhythm [12], each participant was scheduled to come to the laboratory at the same time-slot on 4 consecutive days (i.e. 4 sessions, e.g. from Monday to Friday always at 10 o'clock), see Fig 1.

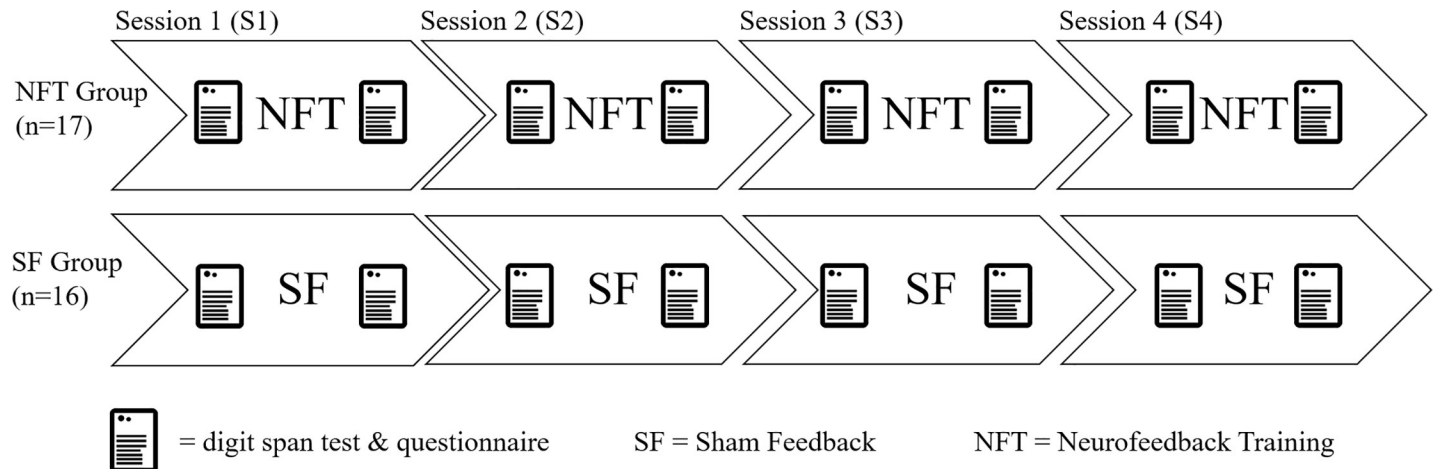


Fig 1. Procedure over four sessions. Experimental procedure in NFT group (neurofeedback training, experimental group) and SF group (sham feedback, SF group) over four sessions on four consecutive days.

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A more detailed description of the experimental session undergone from session 1 (S1) to session 4 (S4) ensues. If not indicated differently, all of the following details apply for both, the NFT group (receiving NFT) and for the SF group (receiving a control sham feedback intervention).

After being equipped with the EEG headset, participants filled out the German version of the multidimensional mood state questionnaire (mehrdimensionaler Befindlichkeitsfragebogen, MDBF) [56] and a series of questionnaires concerning their daily physical activities and use of substances like caffeine, alcohol and cannabis, variables that have possible implications on alpha activity [57–59]. Participants then performed a short-term memory test followed by two 2-min resting state EEG recording epochs, one with eyes closed and another with eyes open. These baseline recordings were used to assess the individual upper alpha peak for the NFT group (see next section for details).

NFT or Sham feedback (SF) started immediately after the baseline recordings and consisted of five 3-min periods with a 30 second break in-between. For S1, participants first received verbal and written information about alpha activity and were encouraged to be creative and come up with five personal strategies for the five periods of NFT (or SF). A list with five strategies (positive thinking, evoking emotions, visualizing activities, love and physiological calm) based on [5] was offered to participants who had difficulty coming up with their own ideas. Participants were asked to use only one strategy during each period, write it down during the break and to use every strategy only once over the course of the five periods. This procedure allowed to determine the most-successful alpha-enhancing strategy (one strategy, which produced the highest relative IUA for each participant). The participants were instructed to use their most successful strategy during the following sessions of S2 to S4.

At the end of each session, participants repeated the digit span test and the MDBF. For a schematic overview of the procedure during each of the sessions S1 to S4 see Fig 2.

Neurofeedback training

Feedback sites P7, O1, O2 and P8 were chosen for their connection to visual and attentional processes (see e.g. [59,60]). Using a simple channel spectra procedure in EEGLAB (*pop_four-ieeg*), each session's baseline recordings was analysed to determine the IUA frequency band, which was then used in that session. More specifically, the individual alpha peak (IAP)

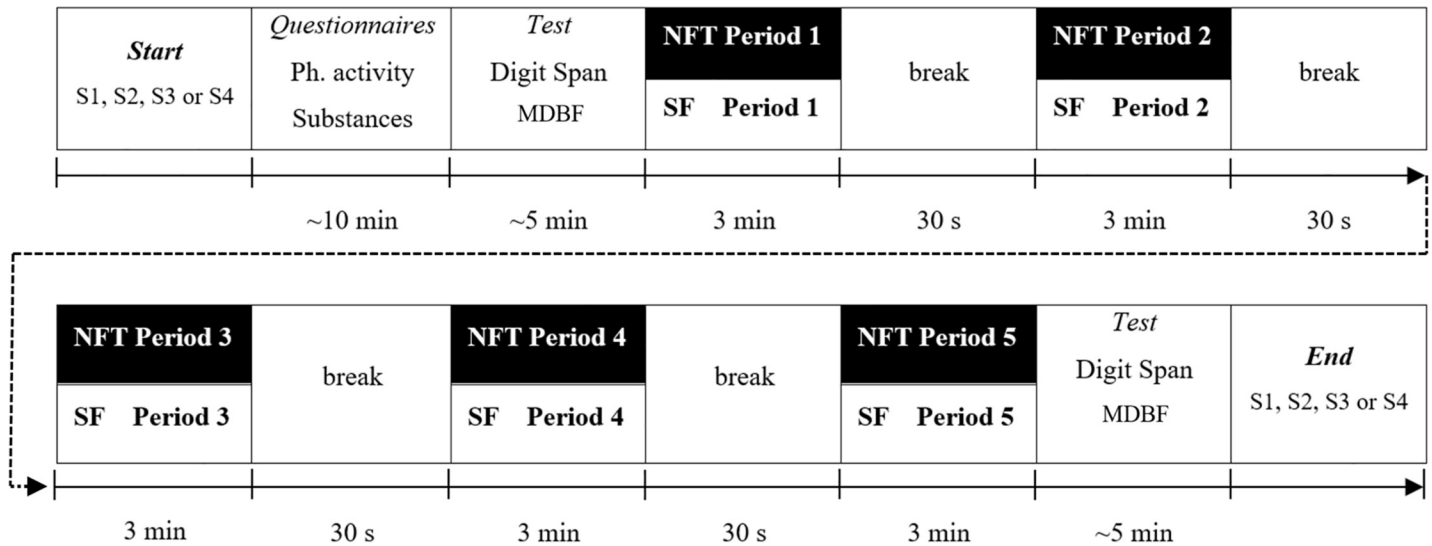


Fig 2. Procedure within sessions S1 to S4. Procedure during each of the sessions S1 to S4 in the NFT group (neurofeedback training, experimental group) and SF group (sham feedback, control group).

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between 7.5 and 12.5 Hz [12] was assessed from the eyes closed resting condition and the lower and upper border of the IUA frequency band were defined as IAP and IAP + 2, respectively. We used the *Emotiv 3D Brain Activity Map* standalone software to provide IUA feedback with a colour spectrum ranging from grey (low IUA amplitude) over green to red (high IUA amplitude). The *3D Brain Activity Map* application was tested in a pilot study by three participants before the onset of data collection and was perceived to be of intuitive character and to provide colour changes in an adequate frequency and with appropriate sensitivity. During each session’s period, participants watched their real-time IUA activity at occipital and parietal sites (P7, O1, O2, and P8) colour-coded on the surface of an animated head (see Fig 3) and were advised to produce as much red activity as possible. Participants in the NFT group (experimental group) performed IUA NFT always with a real-time IUA band feedback. The SF group (control group) received SF by watching recordings of NFT sessions from another subject not included in this sample.

EEG recording and processing

An *Emotiv Epoc+* EEG headset was used for EEG baseline recordings and NFT. It has 14 channels (AF3, AF4, F7, F3, F4, F8, FC5, FC6, T7, T8, P7, P8, O1 and O2, international 10–20 system) and uses passive saline sensors. The device is wireless and transmits data via Bluetooth through the 2.4 GHz band, has a battery autonomy of 12 hours and uses a built-in amplifier, as well as a CMS-DRL circuit for the reduction of external electrical noise. It has a sampling rate of 128 bit/s, a bandwidth ranging from 0 to 64 Hz, automatic digital notch filters at 50 Hz and 60 Hz and the dynamic range referred to the input is 8400µV(pp). Moreover, a digital 5th order Sinc filter is built-in and impedance can be measured in real-time. EEG was recorded using the software *Emotiv TestBench*, ground-reference was M1 and sampling method was by default sequential sampling.

All analyses were carried out with MATLAB and EEGLAB [61]. The data was pre-processed using the following methods: re-referencing to channel M1, automatic removal of bad epochs using the command *pop_autorej*, calculation of IC weights with the *runica* algorithm. Following [29], the relative alpha values for both, NFT and SF were calculated from the pre-processed

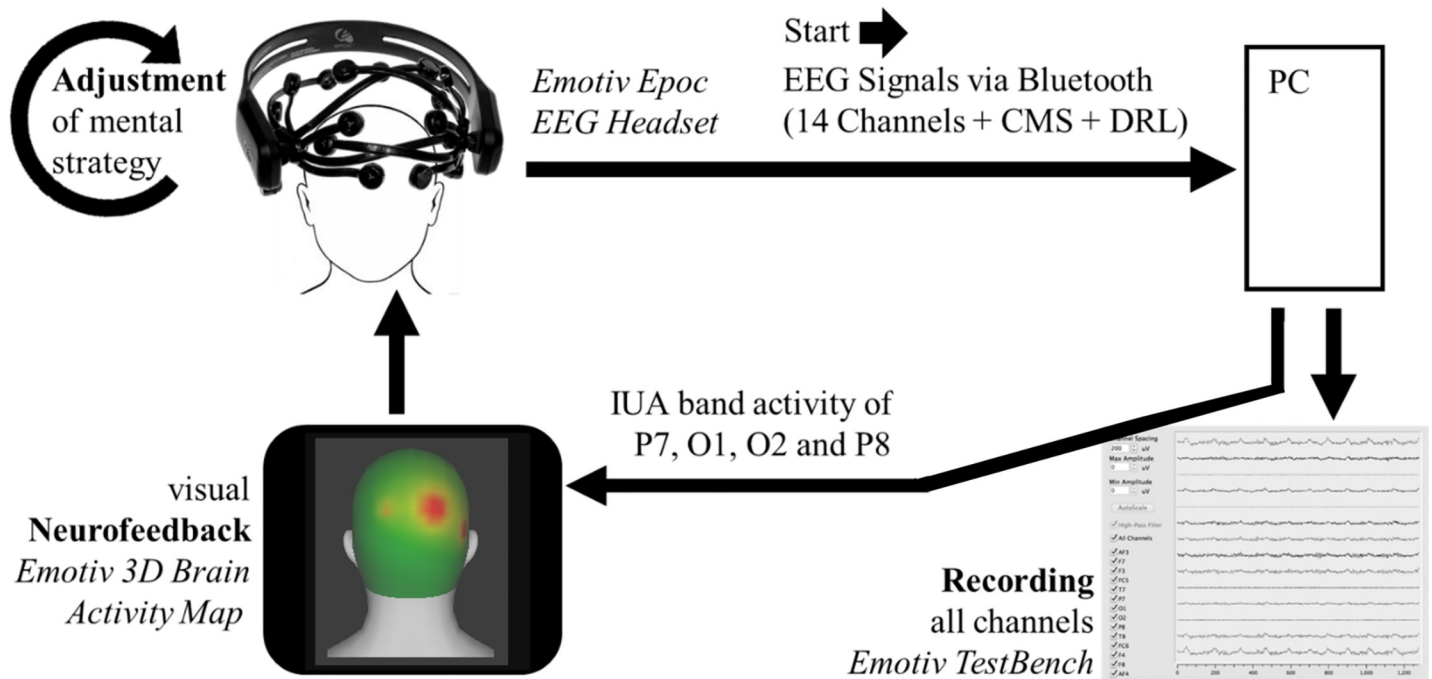


Fig 3. Neurofeedback loop and EEG recording.

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EEG by dividing the mean amplitude of the IUA band (defined individually in the same way as in the NFT, between the IAP and IAP + 2 Hz) by the mean amplitude of the entire EEG bandwidth (Eq 1).

$$Relative\ Alpha = \frac{IndividualUpperAlphaAmplitude}{EEGAmplitude_{0.5-64Hz}} \quad (1)$$

This normalization was applied to avoid variability in the absolute amplitude between trials and sessions due to changes in impedance between electrodes and scalp. This way, attenuations caused by external factors that affect all frequency bands are mitigated. Furthermore, we worked with amplitude instead of power values to prevent excessive skewing and improve the validity of the statistical analysis [7].

Subjective and objective measures

Questions about physical activities, substance intake and sleep were assessed with a self-made questionnaire. Information about the mental alpha enhancement strategies were collected systematically. The self-reported strategy descriptions were first classified individually by two assessors. Afterwards, the rating was discussed, until consensus with regard to the keywords was found. Short-term memory performance was assessed by means of a forward digit span test taken from the PEBL test battery [62]. During this test, digits appeared on the screen and participants were advised to memorize them. On first trial, three digits appeared one after another and the participant typed them into an input field in the same order as they had appeared. In case of a correct answer, a positive feedback was given and the trial was repeated with the same number of digits. If the participant succeeded again, the number of digit was increased by one. The test continued until the participant typed in a wrong answer on two consecutive trials. Two performance indicators were assessed. One is the digit span itself, defined

as the highest amount of digits the participants remembered correctly. Another measure is the total correct value, representing the total number of correct answers. For example, a digit span of 9 indicates that the participant was able to remember 9 digits correctly. The total correct value in this example however can vary between 7 and 16 because participants were allowed to continue with the test if they made an error in one trial (e.g. they remembered 8 digits only once). In the statistical analysis of the present study, only total correct values are reported.

Statistical analyses

All analyses were carried out with the IBM Statistical Package for Social Sciences (SPSS version 24) and R [63]. Except for *Mauchly's test* of sphericity the chosen level of significance for all analyses was $\alpha = .05$ (5%). Data were analysed with several mixed-measures design ANOVAs and corresponding contrast analyses using either a *polynomial* or a *simple* algorithm. Concerning the mixed design ANOVAs, *Mauchly's Test of Sphericity* was taken into account. If *Mauchly's Test* was not significant ($p \geq .20$, sphericity was assumed. When *Mauchly's Test* was significant ($p < .20$) and *Greenhouse-Geisser Epsilon* was smaller than .75, *Greenhouse-Geisser* corrected results were reported. When *Mauchly's Test* was significant ($p < .20$) and *Greenhouse-Geisser Epsilon* was higher .75, *Huynh-Feldt* corrected results were reported. Regarding *Mauchly's test*, setting alpha = .20 leads to a lower chance of granting the sphericity assumption, the according corrections are more likely applied, resulting in a lower chance of committing type 1 errors (rejection of the null hypothesis although it is true) [64–66].

The general connection between alpha and digit-span was assessed with linear regressions. Additionally, for a more detailed picture, paired-samples *t*-tests with Bonferroni adjustment were conducted. More specifically, during each analysis (e.g. the 20x2 mixed designs ANOVA), Bonferroni correction was applied by multiplying the *p*-value of all associated *t*-tests by the number performed *t*-tests.

For the present study, only the change of alpha and digit-span and not their general level was of interest. Hence, all alpha measurements were standardized by subtracting the mean value of the first measurement. By applying this standardisation to NFT group and SF group separately, it was assured both groups had the same initial value of alpha and digit-span, respectively. Digit-span values were not standardized because they did not differ during the first measurement ($M_{\text{NFT}} = 8.76$, $SD_{\text{NFT}} = 1.82$; $M_{\text{SF}} = 7.94$, $SD_{\text{SF}} = 1.81$; $t(31) = 1.31$, $p = .20$).

Complementary analyses for selected extraneous variables. During the analyses of session related changes in mood, thirteen extraneous variables related to mood and effort were collected before and after each experimental session. We computed session related changes for each one of these variables and used principal component analysis (PCA) for feature extraction. The number of principal components (PCs) was chosen by interpreting the *scree* plot, and choosing the number of components until when diminishing returns would be obtained, guaranteed that at least 60% of variance could be explained. Each PC was then used as the response variable of a linear mixed effects model, resulting in one linear model for each PC. Each model had two random variables: subject as the random intercept and session number as the random slope. The fixed effect term was a triple interaction between period, NFT group and changes in relative alpha. Changes in relative alpha at each period were computed using an area under the curve with respect to increase (AUC_i) formula described in [67], and these values were averaged for each session. Satterthwaite approximation for the degrees of freedom was used to compute *p*-values with the *lmerTest* package in the R programming environment [68].

By performing the analysis of the extraneous variable pre-session relaxation, we aimed at investigating if the inclusion of pre-session relaxation increases the predictive validity of the

NFT group in changes for relative alpha for each session. A mixed effects model was used to predict the session average relative alpha AUC_i , using each subject as the random intercept and session number as the random slope. The fixed effect term was the moderation between NFT group and pre-session relaxation. The moderation was introduced to understand if pre-session relaxation increases in alpha would be specific to one of the NFT groups. If the interaction term was not significant, we would test the additive model. For the latter, pre-session alpha would be tested as a suppressor variable. Satterthwaite approximation for the degrees of freedom was used to compute p -values with the *lmerTest* package in the R programming environment.

Results

Alpha

Regarding the temporal development of individual upper alpha (Fig 4), visual inspection of the data indicates that both groups increased in alpha. However, this impression was not confirmed by the results of a mixed measures design 20×2 , $TIME_{\alpha} \times GROUP$ ANOVA, where no main-effect of $TIME_{\alpha}$ was found ($F(5.24, 162.36) = 1.79, p = .114, \eta_p^2 = .06$). Moreover, neither

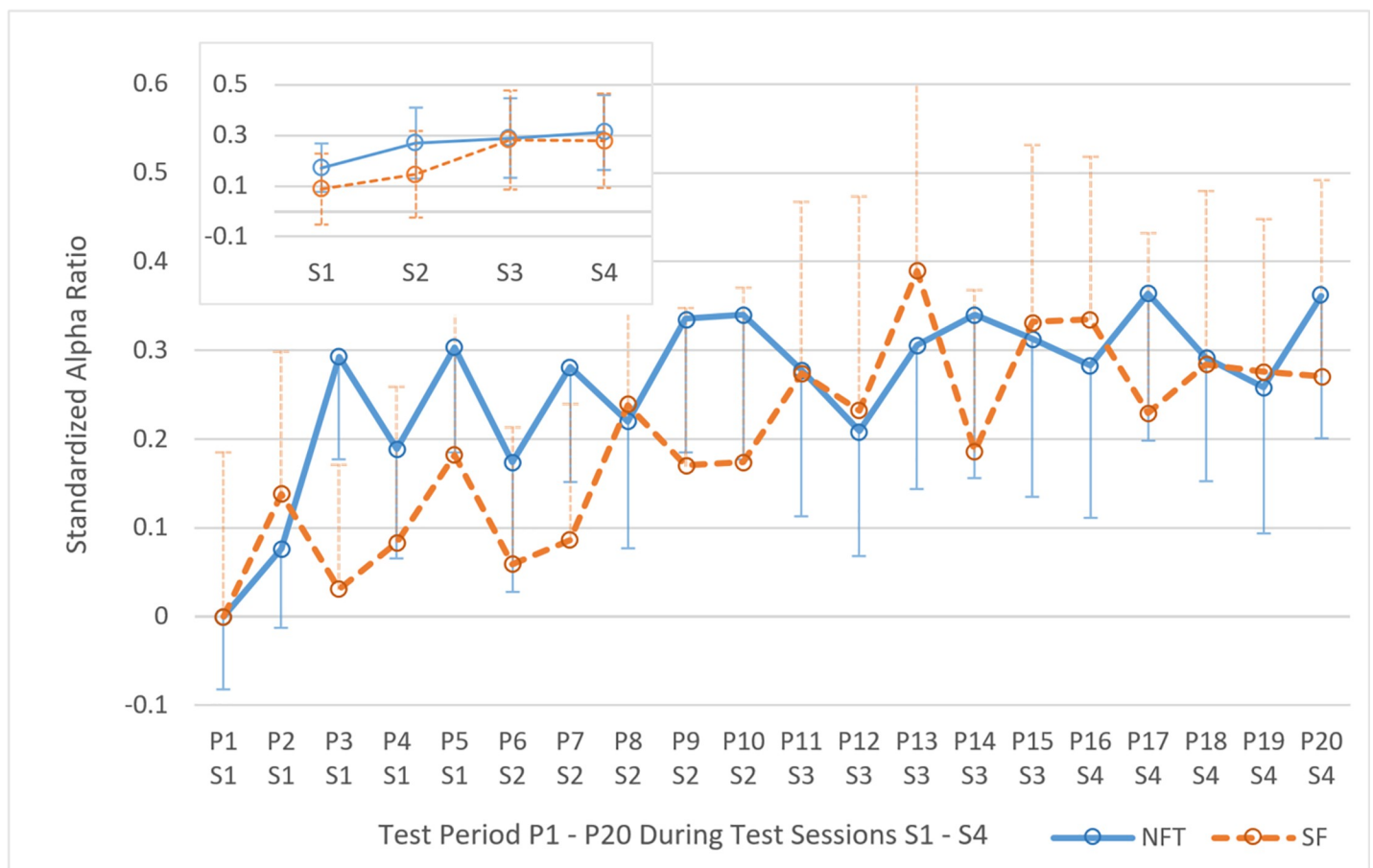


Fig 4. Temporal development of individual upper alpha. Temporal development of relative individual upper alpha over twenty 3-min periods of Neurofeedback Training (NFT, blue line) and sham feedback (SF, orange dashed line) during the four test sessions on four consecutive days. Relative alpha was obtained by dividing the average amplitude of the individual upper alpha band (around 10 to 13.5 Hz) by the average amplitude of the entire EEG band (i.e. 0.5 to 64 Hz). Moreover, relative alpha values was standardized with the first measurement (i.e. period 1). Error bars indicate standard error of the mean (SEM).

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the interaction $\text{TIME}_{\alpha} * \text{GROUP}$, $F(5.24, 162.36) = 0.58$, $p = .363$, $\eta_p^2 = .02$ nor the effect of GROUP were significant, $F(1, 31) = 0.10$, $p = .757$, $\eta_p^2 = .00$.

However, Fig 4 shows descriptively stronger increase between P1 and P20 for the NFT group compared to the SF group. T -tests with Bonferroni adjustment showed significant differences from P1 to P20 for the NFT group ($M_{P1} = 0.00$, $SD_{P1} = 0.34$; $M_{P20} = 0.36$, $SD_{P20} = 0.66$), $t(16) = 2.63$, $p = .018$, but not for the SF group ($M_{P1} = 0.00$, $SD_{P1} = 0.74$; $M_{P20} = 0.27$, $SD_{P20} = 0.88$), $t(15) = 1.33$, $p = .204$. The same results were obtained comparing the average of the first 2 periods with the average of the last 2 periods, when no correction was applied; NFT group ($M_{P1P2} = 0.04$, $SD_{P1P2} = 0.33$; $M_{P19P20} = 0.31$, $SD_{P19P20} = 0.64$), $t(16) = 2.33$, $p = .029$; SF group ($M_{P1P2} = 0.07$, $SD_{P1P2} = 0.64$; $M_{P19P20} = 0.27$, $SD_{P19P20} = 0.77$), $t(15) = 1.10$, $p = .145$. This additional analysis was conducted as the mean of two repeated measurements might be less affected by random effects.

Applying contrast analysis (simple), the first significant amplitude difference in the SF group appeared between P1 and P11, $F(1, 15) = 5.08$, $p = .04$, $\eta_p^2 = .25$. The NFT group showed its first significant differences already between measurements P1 and P3, $F(1, 16) = 12.67$, $p = .003$, $\eta_p^2 = .44$. Contrast analyses indicate hence a faster increase of relative alpha in the NFT group.

Moreover, in the NFT group t -tests with Bonferroni adjustment showed significant improvements from P1 ($M_{P1} = 0.00$, $SD_{P1} = 0.34$) to P3 ($M_{P3} = 0.29$, $SD_{P3} = 0.48$), $t(16) = 3.56$, $p = .006$, and from P1 to P5 ($M_{P5} = 0.30$, $SD_{P5} = 0.49$), $t(16) = 3.69$, $p = .004$. The significant increase in alpha from P1 to P3 and from P1 to P5 could not be observed in the SF group ($M_{P1} = 0.00$, $SD_{P1} = 0.74$; $M_{P3} = 0.03$, $SD_{P3} = 0.56$; $M_{P5} = 0.18$, $SD_{P5} = 0.73$), $t(15) = 0.28$, $p = 1$; $t(15) = 1.08$, $p = .594$, indicating a faster increase in relative alpha in the NFT group as well.

Interestingly, regardless of group and on an exploratory note, a significant positive correlation between the unstandardized initial relative alpha (P1) and the alpha improvement during the course of the experiment (P20 minus P1) was observed, $r(31) = .44$, $p = .011$. This finding was supported when the same analysis was performed on the level of test days (sessions). Relative alpha during Period 1 (i.e. the first 3 min period during the first test-day) correlated with the mean improvement over the course of the experiment (S4), $r(31) = .52$, $p = .002$. In other words, participants who exhibited a high relative alpha in the beginning of the experiment had a higher gain in alpha during the training compared to participants who started with a low alpha level.

The findings examined so far are partially in concordance with hypothesis H1, stating a positive effect of NFT on relative IUA. The IUA increase in the NFT group is observed earlier and the difference between P1 and P20 shows significance only in the NFT group. Interestingly and contrary to our expectation, alpha enhancement could be observed in the SF group as well, when contrast analyses are taken into consideration.

Neurofeedback training and short-term memory performance

Regarding the temporal development of STM performance (see Fig 5), a significant main effect of TIME_{STM} was observed, $F(7, 217) = 4.90$, $p < .001$, $\eta_p^2 = .14$, but the interaction $\text{TIME}_{\text{STM}} * \text{GROUP}$ did not reach significance level, $F(7, 217) = 1.24$, $p = .280$, $\eta_p^2 = .04$. No effect of factor GROUP was observed, $F(1, 31) < 0.01$, $p = .963$, $\eta_p^2 < .01$. Contrasts showed a linear trend of TIME_{STM} with $F(1, 31) = 6.36$, $p = .017$, $\eta_p^2 = .17$. No linear trend of the interaction $\text{TIME}_{\text{STM}} * \text{GROUP}$ was observed $F(1, 31) = 0.02$, $p = .887$, $\eta_p^2 < .01$.

Paired-samples t -tests with Bonferroni adjustment revealed no significant differences between first and last measurement of STM in the NFT group ($M_{T1} = 8.77$, $SD_{T1} = 1.82$; $M_{T8} = 10.06$, $SD_{T9} = 2.49$), $t(16) = 1.85$, $p = .083$, but for the SF group ($M_{T1} = 7.94$, $SD_{T1} = 1.81$; $M_{T8} = 9.69$, $SD_{T8} = 1.96$), $t(15) = 2.78$, $p = .014$. All results examined in this section contradict hypothesis H2 postulating a general effect of NFT on STM.

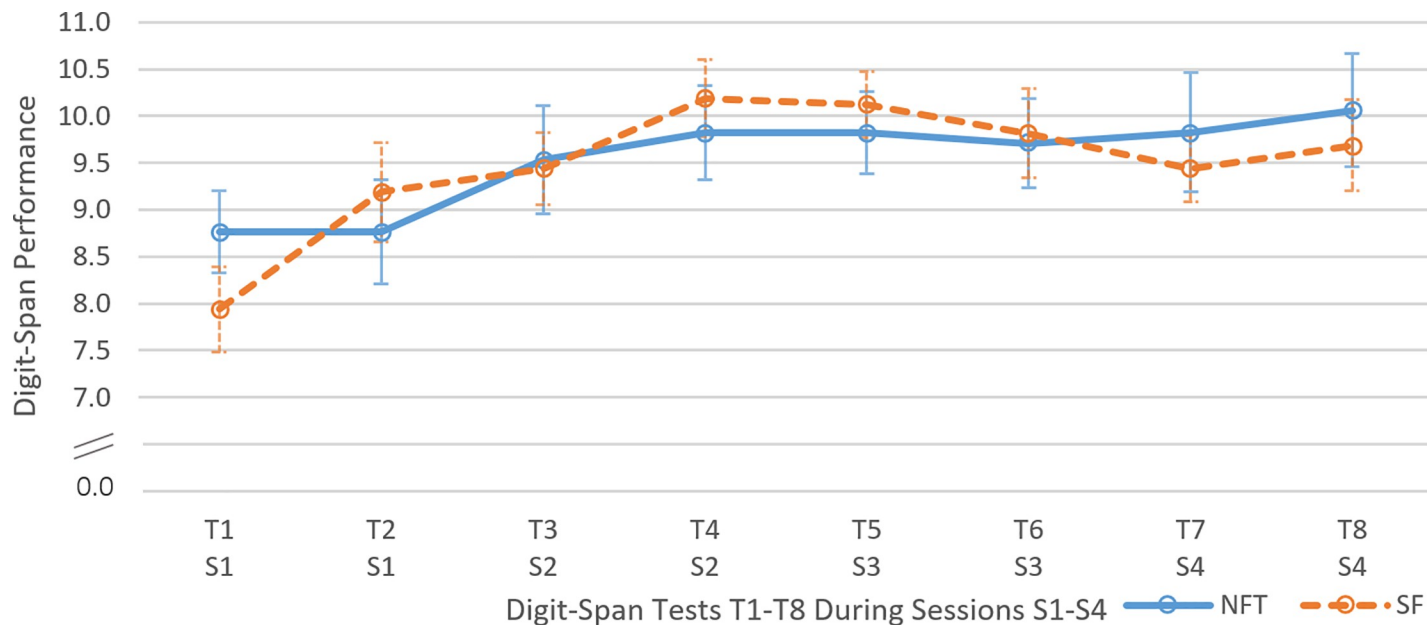


Fig 5. Temporal development of short-term memory performance. Temporal development of short-term memory (digit-span) performance over 8 tests (T1 to T8) in a neurofeedback (NFT, blue line) and a sham feedback (SF, orange dashed line) group. Subjects participated in four consecutive test days (S1-S4) containing two tests each. Uneven test numbers (T1, T3, T5 and T7) were conducted before the intervention (NFT or SF), even test number (T2, T4, T6 and T8) were conducted after the intervention. Error bars indicate SEM.

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To evaluate the immediate effect of NFT on STM performance, a 2*2 mixed-model ANOVA with the within factor PRE/POST and the between-groups factor GROUP was conducted. Factor PRE/POST had two levels: averaged digit span performance values conducted before the intervention vs. averaged digit span performance values conducted after the intervention (see Fig 6). Participants did not improve in STM performance during NFT/SF, $F(1, 31) = 2.98, p = .094, \eta_p^2 = .09$. Test of within subjects effects did not reveal an interaction effect, $F(1, 31) = 1.26, p = .271, \eta_p^2 = .04$. No effect of GROUP was observed, $F(1, 31) = 0.02, p = .907, \eta_p^2 < .01$. These findings do not support hypothesis H3 postulating an immediate positive effect of NFT on STM.

Alpha and short-term memory

To assess the connection between alpha and STM, a multiple regression analysis was conducted. The dependent variable was STM improvement defined as performance delta-value of test 8 (T8) minus test 1 (T1). Relative alpha values were averaged over sessions (see upper-left corner Fig 4) and served as predictors. Explained variance R^2 was 0.10 and the corresponding ANOVA was not significant, $F(4, 32) = 0.79, p = .540$. This finding contradicts hypothesis H2, assuming a general connection between alpha and STM performance.

Analyses for selected extraneous variables

Session related changes in mood. In order to infer how NFT affected mood changes during the experiment, we calculated the differences in mood from the beginning to the end of each session. We also calculated the total amount of change in relative alpha at each period using an area under the curve with respect to increase (AUC_i) formula described in [67]. The 12 mood change variables, and one variable representing effort, were compressed using principle component analysis (PCA) into 5 principal components (PCs) explaining 60.2% of the

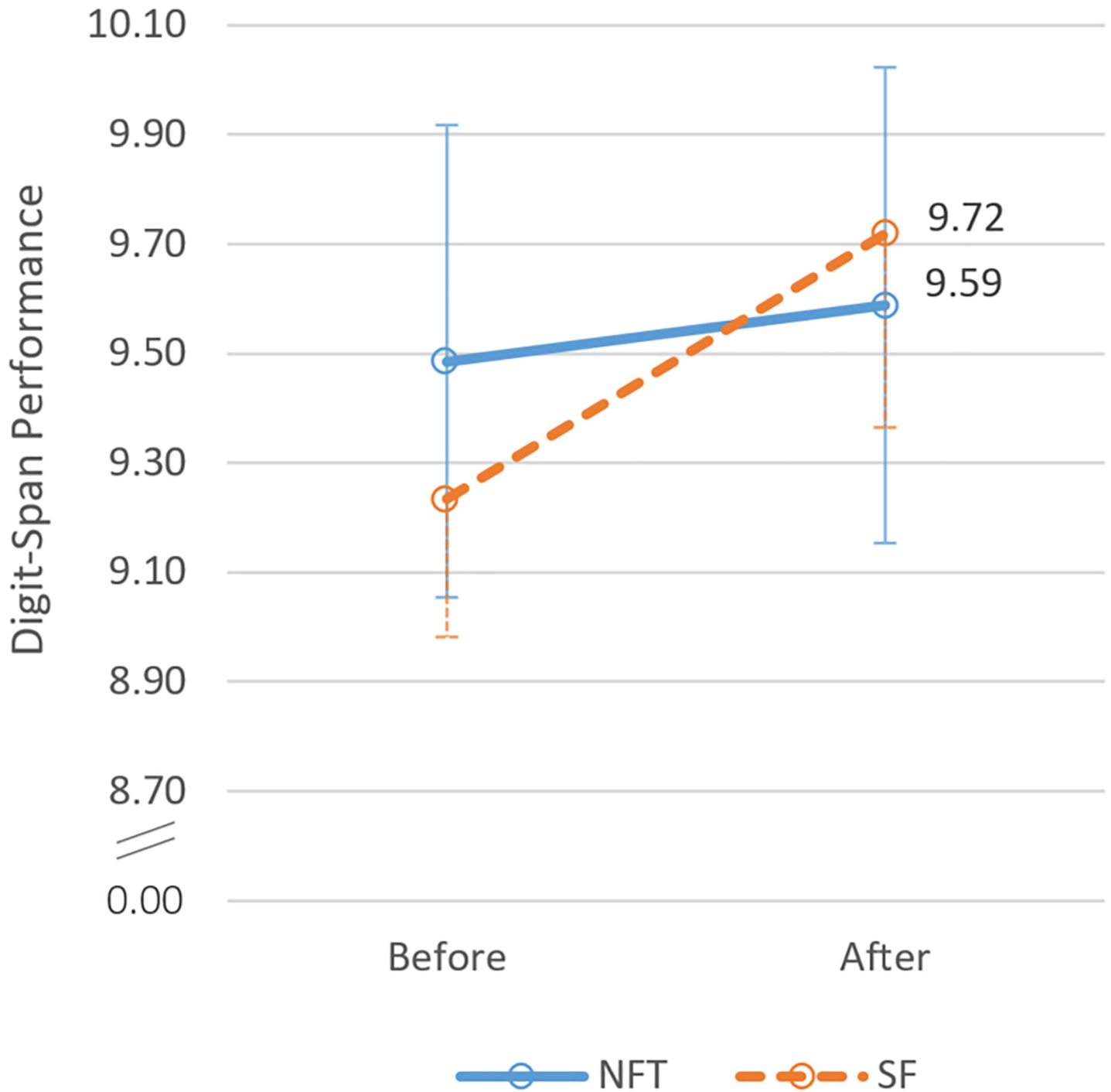


Fig 6. STM performance before vs. after the intervention. Short-term memory performance, measured by digit-span tests before and after neurofeedback training (NFT, blue line) and sham feedback (SF, orange dashed line). Error bars indicate SEM.

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variability in the original variables (See Fig 7A). *Varimax* rotation was used to facilitate interpretation of each PC, resulting in the loading matrix in Fig 7B. Each PC was used as the response variable in a linear mixed effects model (see Fig 7C for the model with PC5 as the response variable) with each subject as the random intercept, session number as the random

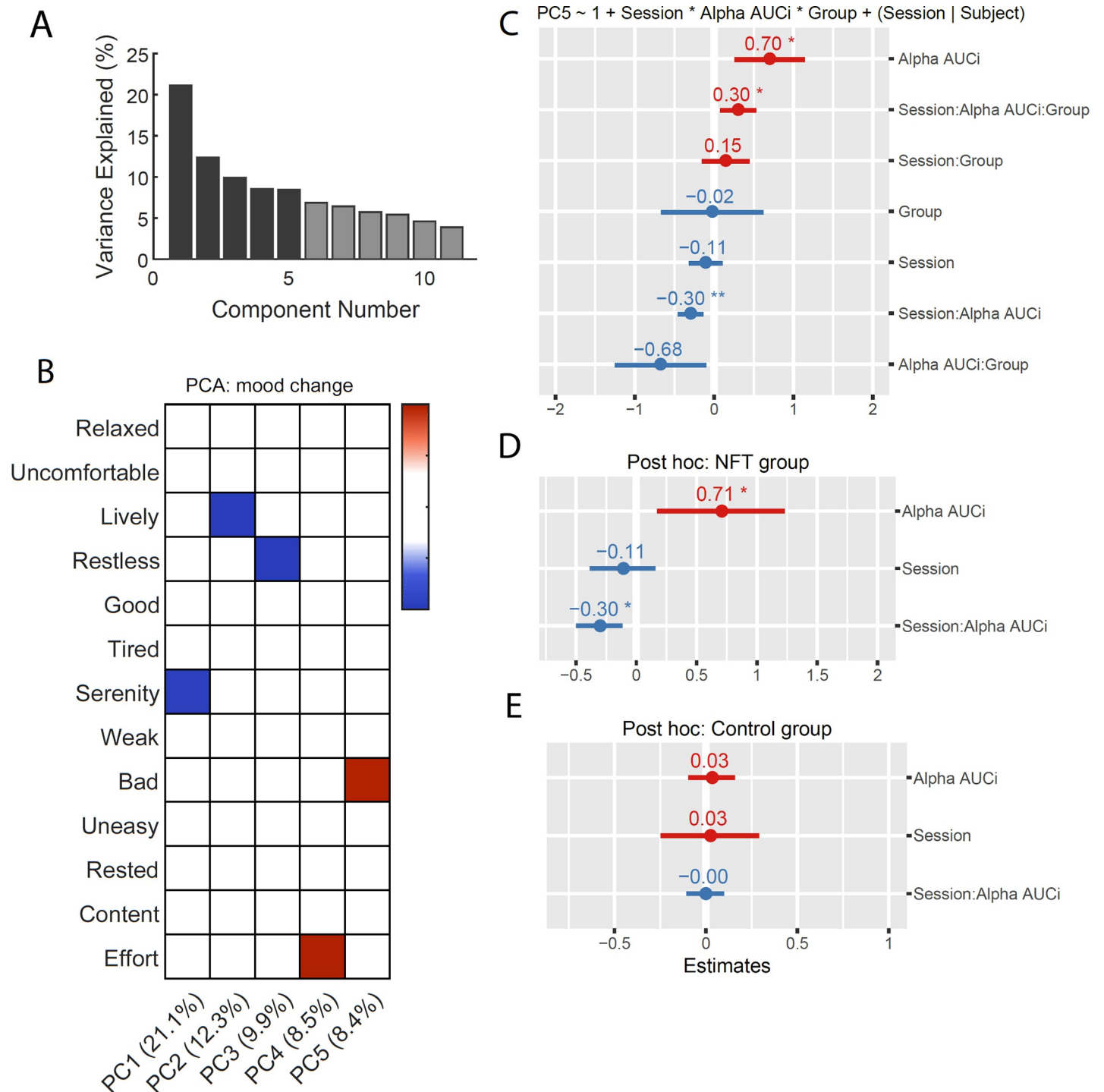


Fig 7. Effects of neurofeedback training (NFT) on mood change. A) Percentage of variance explained for each principal component (PC). The 5 PCs used result in a total of 60.2% of variance explained (dark-shaded bars). B) Loading matrix for each PC after *Varimax* rotation. Loadings smaller than 0.4 are not shown. C) Linear mixed effect model for PC5 as the response variable and the triple interaction between session, relative alpha an area under the curve with respect to increase (AUCi) and NFT group (neurofeedback training, experimental group) as predictors. D) Simple effects model for the NFT group. E) Simple effects model for the SF group (sham feedback, control group). For panels C), D) and E) coefficient estimates and standard errors (SE) depicted as dot and line respectively. Red and blue colors represent positive and negative coefficient estimates, respectively. Significance levels: ** $p < .01$, * $p < .05$. Significance levels are presented for uncorrected p -values. When *Bonferroni* correction is applied, to control for Type I errors due to the comparing models for five PCs, the triple interaction term in panel C is no longer significant ($p_{corrected} = 0.152$). For panels D and E, when applied, *Bonferroni* correction controls for two comparisons made in the simple main effects analysis resulting in a significant interaction effect 'Session x relative alpha' AUCi ($p_{corrected} = 0.028$).

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slope and a triple interaction between period, NFT group and relative alpha AUCi. The only PC with a significant ($p = 0.030$, however when applying Bonferroni correction for 5 comparisons $p_{\text{corrected}} = 0.152$) triple interaction predictor was PC5, a component that loads positively on the variable changes in the bad mood (positive values of PC5 represent an increase in bad mood). This model had a total explanatory power (conditional R^2) of 48.06%. The triple interaction between session, relative alpha AUCi and NFT group (see Fig 7C; $\beta = 0.30$, $SE = 0.14$, 95% CI [0.035, 0.57], $t(105) = 2.20$, $p = .030$, $p_{\text{corrected}} = 0.152$) could be considered a small effect (std. $\beta = 0.33$, std. $SE = 0.15$). Simple main effects for each NFT group were analyzed in order to evaluate whether the interaction of session and relative alpha AUCi was significant only for the NFT group (after correcting for these two comparisons). For this group, the interaction effect between Session and relative alpha AUCi was significant ($\beta = -0.30$, $SE = 0.12$, 95% CI [-0.53, -0.070], $t(52) = -2.56$, $p = .014$, $p_{\text{corrected}} = 0.028$) and could be considered as small (std. $\beta = -0.25$, std. $SE = 0.097$). Since no effects were found for the SF group ($p = 0.997$, $p_{\text{corrected}} = 1$), these results suggest that in the NFT group, learning to progressively increase the relative alpha band lead to small but significant reductions in bad mood.

Analysis of the extraneous variable pre-session relaxation. One hypothesis to explain the similar alpha production between the NFT and control group is, that participants in the SF group, although not receiving real feedback, were also trying relaxation strategies (since this was one of the cognitive strategies recommended to participants). Therefore, we decided to investigate if the NFT group variable would be capable to predict higher relative alpha AUCi values in the NFT group by accounting for the moderation between NFT group and pre-session relaxation. Fitting the model described in Fig 8 to the data, the effect of NFT Group was significant ($\beta = -1.89$, $SE = 0.72$, 95% CI [-3.30, -0.47], $t(94) = -2.63$, $p < .010$) and could be considered small (std. $\beta = -0.20$, std. $SE = 0.17$). The negative value of the estimated coefficient points to a lower overall relative alpha AUCi for the SF Group. The effect of the interaction between level of relaxation at the beginning of the session and NFT Group ($\beta = 0.47$, $SE = 0.19$, 95% CI [0.088, 0.84], $t(99) = 2.45$, $p = .016$) and could be considered small (std. $\beta = 0.44$, std. $SE = 0.18$). This indicates either the NFT or the SF group could show an effect of level of relaxation on the production of relative alpha. A post hoc analysis revealed that this is not true for the NFT group: The effect of being relaxed was not significant ($\beta = -0.19$, $SE = 0.11$, $t(37) = -1.63$, $p = .112$). For the SF group there was a trend for being relaxed leading to more relative alpha increases ($\beta = 0.28$, $SE = 0.15$, 95% CI [-0.029, 0.58], $t(53) = 1.87$, $p = 0.068$) and the effect could be considered small (std. $\beta = 0.23$, std. $SE = 0.12$). These results suggest that if the level of relaxation before each Session is taken into consideration, then it is possible to observe an overall effect of NFT on the production of relative alpha. It also suggests that for the SF group, being relaxed might have been what lead to increases in relative alpha.

Analysis of mental alpha enhancement strategy. The following strategy categories were extracted in descending order with regard to appearance frequency (frequency displayed in brackets followed by an exemplary sentence). “Love” (9, “I tried to think about my grandparents and how I was at their place when I was younger”), “positive emotion” (7, “positive emotion by remembering beautiful moments”), “physiological calm” (7, “physiological calm and slow breathing”), “activities” (5, “walking through the forest, swimming”), “art” (3, “creative thinking -> design of a poster”) and “negative emotion” (2, “fear, sadness and anger”).

With regard to alpha enhancement strategy efficiency (i.e. the corresponding produced relative alpha) we obtained the following order. “Activities” was descriptively the most efficient strategy followed by “love”, “physiological calm”, “positive emotion”, “art” and “negative emotion” being the least efficient strategy. Inference statistically, the efficiency with regard to alpha improvement, however, did not differ between strategies, $F(5, 27) = 0.67$, $p = .668$, $\eta_p^2 = .11$.

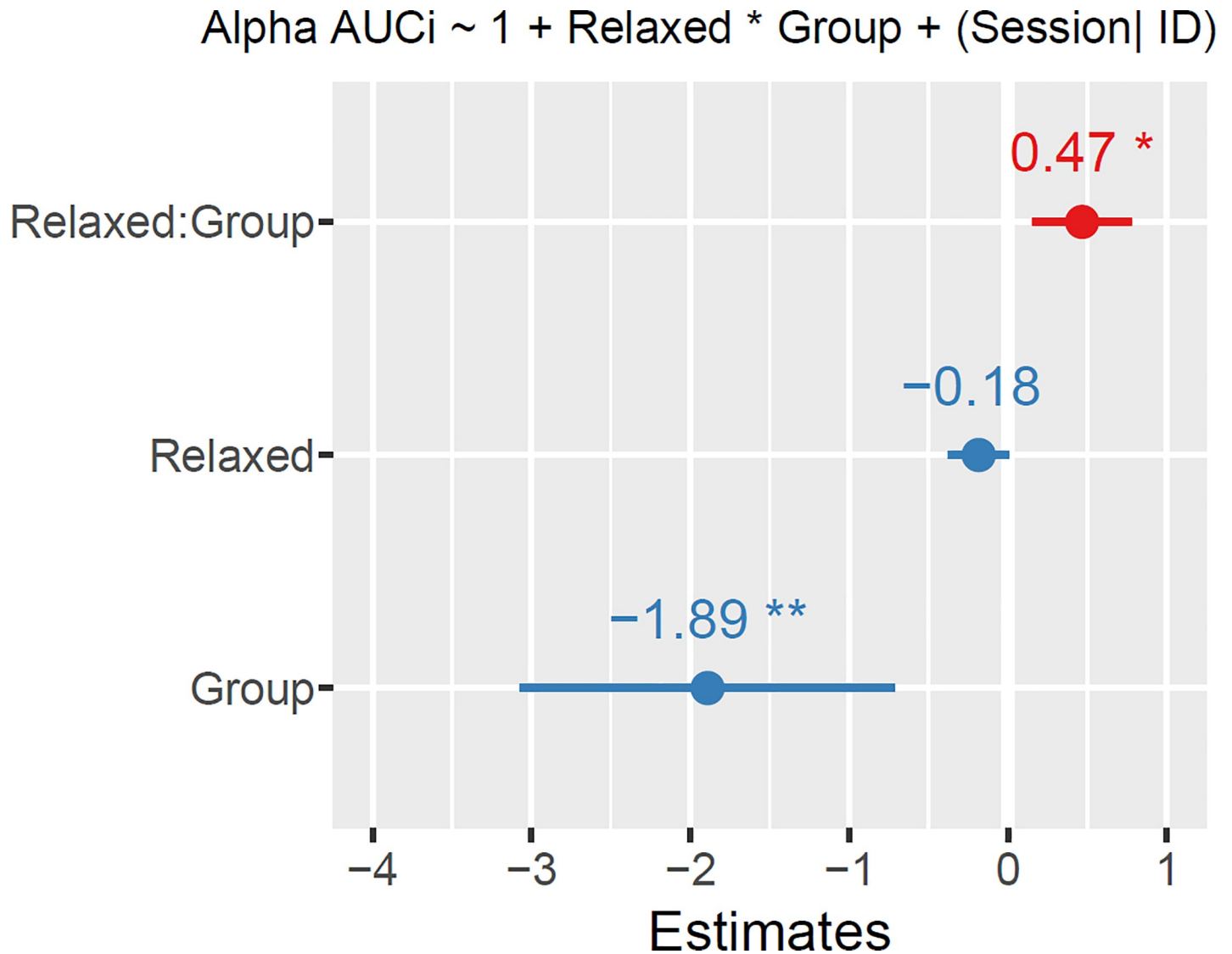


Fig 8. Linear mixed effect model for relative alpha area under the curve with respect to increase (AUC_i) as the response variable and the interaction between how relaxed participants were at the beginning of the Session and NFT group (neurofeedback training, experimental group) as predictors. Coefficient estimates and standard errors (SE) depicted as dot and line respectively. Red and blue colors represent positive and negative coefficient estimates, respectively. Significance levels: ** $p < .01$, * $p < .05$.

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We created a word cloud representing frequency of words used to describe the most successful strategy by word size (see Fig 9).

Discussion

The present study investigated if a commercially available BCI device (*Emotiv Epoc*) used as a NFT device enables volitional control and enhancement of EEG activity and reveals the connection between IUA alpha NFT, relative alpha and short-term memory performance using a commercially available BCI device (*Emotiv Epoc*) in a single-blind design. In line with previous results [5], an enhancing effect of the training on the relative alpha and on short-term memory performance (digit-span Task) was expected.



Fig 9. Appearance frequency of words used by participants to describe their mental alpha enhancement strategy. Frequency indicated by word size.

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Our analyses showed a significant improvement in relative alpha in the neurofeedback group between period 1 and period 20 which could not be observed in the sham feedback group. Moreover, contrasts showed that the increase in alpha was obtained much earlier (period 3) for participants who saw their real-time brain activity compared to participants who followed a sham-feedback intervention (period 11). Additionally, we also observed that if the level of relaxation before each session is taken into account, it is possible to observe a clear effect of NFT on the production of relative alpha. All in all, the results regarding relative alpha indicate that up-training alpha with a real-time NFT procedure facilitates the process of enhancing alpha activity. Thus, the results of the present study were in accordance with hypothesis H1.

Furthermore, we hypothesised the SF group would not show an enhancement in alpha activity. Interestingly though, contrast analyses showed the opposite was true and mixed measure longitudinal analysis indicated that the slope for both groups were equal. One possible explanation for this finding is that the SF group was given feedback during the first session. Although sham feedback was used for this group, by the end of this session they were informed of the most successful mental strategies for alpha upregulation. This would imply that it is possible to infer appropriate mental strategies within one session and that coherent visual feedback might not be necessary for ensuing sessions to upregulate alpha to a certain degree, provided the adequate mental strategy is used. This interpretation seems to be in line with studies showing an alpha enhancing effect of certain types of meditation (e.g. [42–44]). A replication study with an additional SF group that would not be informed about which strategies are generally linked to alpha enhancement might address this question. Another possible explanation resides in the framework of socio-physiological processes. Alpha is enhanced by

being in a calm and resting state and in the course of the current study, participants became more and more familiar with the experimental environment, as well as with the experimenter. It is likely that the participants became more and more relaxed, comfortable and calm during the later sessions of NFT/SF, which might have led to the observed enhanced level of alpha in the SF group. This interpretation finds some support in the analysis of extraneous variables, which suggests that being relaxed is an important factor for increases in relative alpha. In line with [13] it could be important to collect data from a control group advised with an inverse NFT paradigm.

No general connection between alpha and STM performance was observed in this study and thus, no evidence supported hypothesis H2. There was indeed a significant effect of time throughout the eight digit-span tests but no main or interaction effects due to NFT. There was also no immediate positive effect of NFT on STM performance. All in all, these findings contradicted our hypotheses and several explanations can be put forward.

For one, the quick improvement in the digit-span task observed in most participants is most likely due to practice and it seemed to be stronger than the more subtle positive impact of higher alpha amplitude. Electrode placement could also be responsible for the lack of effect of NFT on STM performance. Feedback signals were acquired from P7, O1, O2 and P8 because the occipital cortex is involved in every visual process and parietal sites are connected to attention (e.g. [39]). It is possible though, that the choice of electrodes influenced or impaired the effect of the NFT on STM performance. Many authors use electrode sites like Cz, Pz, Fz and C3 which differ from the sites used in the current study (see e.g. [9,13,52,53]). However parietal and occipital electrode sites are used commonly for IUA NFT as well (e.g. [10,30,54]). A further explanation for a missing effect could be the fact that there was also an increase in IUA in the SF group (see paragraph above). Hence it is possible that the disclosure of the best strategy in the first session also for the SF group led to a similar (but slower) increase in IUA and thus to a similar positive effect on cognitive performance as in the NFT group.

Finally, the possibility of the absence of an effect of IUA NFT on STM performance should be considered. Previous studies where this effect was reported have used no-intervention or waiting-list control groups (e.g. [5,10]), which deserve critical attention. Neither have they ruled out the expectancy effect on the side of the participants (placebo or Hawthorne effect, [69]), nor did such designs compensate for a potential experimenter bias. In the few studies using randomized sham feedback control groups, no significant results indicating an effect of alpha feedback on STM performance could be reported [70,45]. All these observations are in accordance with a review of Rogala [14], which excluded many alpha NFT studies for methodological considerations and could rate only one study [44] as success in regard of the effect of NFT on memory (i.e. digit-span task).

Nevertheless, some limitations in this study need to be pointed out which could have obscured this effect. Although it is used in various clinical test batteries and generally is considered a useful indicator for cognitive performance [46], the digit-span task used in this study showed rather low intra-individual variation and strong learning effects in the repeated measures design. Therefore, a different measure for cognitive performance (e.g. Mental Rotation Task, N-Back or a Trail Making Test) might have led to larger variances without concealing a potential NFT effect by learning.

It is also possible, that the conditioning paradigm was not efficient enough due to using a dimensional colour-code as feedback signal. Other authors worked with very specific reward symbols and sounds (e.g. beeps, counters, pleasant sounds or even applause, [70,71,47]). Future implementations should guarantee that NFT is done in an immersive environment with clear, categorical and intuitive rewards. This is particularly important in the perspective of NFT with commercially available devices since they most probably will be used outside

controlled laboratory settings. Although it is common practice to use colour maps for the feedback of the alpha amplitude (see e.g. [5,36,37,70,48]), we are aware of an ongoing debate about the colour maps used for feedback parameters [49,50]. Despite this discussion, to the authors' knowledge, at the moment these methods do not constitute the standard representation of real-time neurofeedback. Furthermore, e.g. bar graphs lack attractiveness for the user.

Finally, the study also has some limiting aspects regarding how mental strategies were employed to enhance individual upper alpha activity. Participants were asked to maintain the same strategy after the first training session. Interestingly, the corresponding gain in alpha activity on the first day was very high compared not only to the first measurement of NFT but also compared to the rest of the training course. In period 5 (P5), participants in the NFT group reached nearly the same relative alpha ($M_{IUA,P5} = 0.30$, $SD_{IUA,P5} = 0.49$) as in the last period, P20 ($M_{IUA,P20} = 0.36$, $SD_{IUA,P20} = 0.66$). Perhaps, choosing one successful strategy for alpha enhancement is not as effective as advising the participants "to be guided by the feedback process" itself [57] or to interchange between more than one strategies in order to avoid fatigue or, the effect of alpha NFT plateaus in general after a certain amount of training like Dekker states [72].

One of the main motivations for this study was to assess if a commercially available EEG device could offer the necessary means to achieve EEG self-regulation and, in turn, reap its benefits in cognitive improvement. We think this is an important question to answer given the promising benefits of NFT on mental health and well-being, its non-invasiveness, and the growing affordability of commercial EEG devices; NFT is no longer just important in the clinical setting, but also in real-life settings. Although our hypotheses for cognitive improvement were not verified, we observed promising results in our NFT group concerning alpha upregulation: this group achieved significant alpha increases faster and these increases were associated with decreases in negative mood. We expect this study to be a stepping stone in larger collection of works that aim for ecological validity and sound experimental design. Ultimately, it will be possible to collect data from a large number of participants following NFT at their homes, workplaces or any place of their choosing so, it is urgent to start defining appropriate protocols. While the NFT implementation of the present study might not be suitable for the daily use, NFT harbours great potential, especially, in our opinion, when combined with gamification strategies. This way, the enhancing effect of NFT could be combined with the immanent beneficial effect of computer games (see e.g. [58]) and immersive virtual environments. Future research should not only focus on theoretical aspects of the working mechanism behind NFT, but on the development of engaging NFT implementations with practical relevance.

Supporting information

S1 Dataset. Alpha_STM_Data. Minimal dataset.
(XLSX)

S1 Supporting Information. Annex. Original questionnaire.
(PDF)

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