

The Effects of a Single Session of Upper Alpha Neurofeedback for Cognitive Enhancement: A Sham-Controlled Study

C. Escolano · M. Navarro-Gil · J. Garcia-Campayo · J. Minguez

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Abstract The minimization of the non-specific factors of neurofeedback (NF) is an important aspect to further advance in the understanding of the effects of these types of procedures. This paper investigates the NF effects of a single session (25 minutes) of individual upper alpha enhancement following a sham-controlled experimental design (19 healthy participants). We measured immediate effects after the training and one-day lasting EEG effects (eyes closed resting state and task-related activity), as well as the event-locked EEG effects during the execution of a mental rotation task. These metrics were computed in trained (upper alpha) and non-trained EEG parameters (lower alpha and lower beta). Several cognitive functions were assessed such as working memory and mental rotation abilities. The NF group showed increased upper alpha power after training in task-related activity (not significantly sustained one day after) and higher pre-stimulus power during the mental rotation task. Both groups improved cognitive performance, with a more prominent improvement for the NF group, however a single session seems to be insufficient to yield significant differences between groups. A higher number of training sessions seems necessary to achieve long-lasting effects on the electrophysiology and to enhance the behavioral effects.

Keywords neurofeedback · electroencephalogram (EEG) · individual upper alpha · cognitive performance · single session · sham feedback

Introduction

Neurofeedback (NF) promotes the self-regulation of brain activity by means of an operant conditioning paradigm. NF consists in measuring the brain activity (e.g., via electroencephalogram, EEG) and providing the subjects with real-time feedback covarying with the brain patterns of interest. Several EEG-based NF studies have reported its efficacy in the treatment of neurological and psychological disorders such as attention deficit hyperactivity disorder (ADHD) and depression, among others (Niv 2013; Başar and Güntekin 2008). NF research on healthy users has focussed on cognitive enhancement, in many cases by regulating the alpha rhythm (see Gruzelier 2013, for a review).

Alpha is the dominant rhythm in the human EEG, which is characterized by a ‘peak’ in the (7-13) Hz power spectra, and seems to be related to cognitive functions such as cognition (Palva and Palva 2007) and working memory (Freunberger et al 2011; Klimesch et al 2007; Klimesch 1999; Sauseng et al 2009). The cognitive effects of regulating this rhythm by means of NF have been already explored (Gruzelier 2013; Vernon 2005). Despite the accumulated evidence on this procedure, the reliability and specificity of the effects at both behavioral and electrophysiological level remain a common limitation (Gruzelier 2014; Vernon 2005). Some authors point out that such a limitation could be due to the high inter-subject variability of the alpha frequency band and the unspecific behavioral effects of regulating the entire band (Klimesch 1999).

C. Escolano
Aragon Institute of Engineering Research (I3A), Zaragoza,
Spain. E-mail: cescolano@gmail.com

M. Navarro-Gil
Bit&Brain Technologies SL, Zaragoza, Spain

J. Garcia-Campayo
Aragon Health Sciences Institute (IACS), Zaragoza, Spain

J. Minguez
Aragon Institute of Engineering Research (I3A), Zaragoza,
Spain; Bit&Brain Technologies SL, Zaragoza, Spain

Recent alpha-based NF studies have tried to overcome these limitations by adjusting the alpha band individually (i.e., per subject) using the Individual Alpha Frequency (IAF) as an anchor point (Klimesch 1999) instead of using a fixed band, and focusing on the upper section of the alpha band, (IAF, IAF+2) Hz range, as it is hypothesized to selectively respond to cognitive demands (Klimesch 1999). For instance, in a single-session NF study (Hanslmayr et al 2005) the subjects performed combined trials of theta suppression and upper alpha enhancement (within-subjects design) and those who succeeded in enhancing upper alpha activity improved performance in a mental rotation task. In other studies the subjects performed a series of training sessions and cognitive improvements were reported on working memory (Escolano et al 2011; Nan et al 2012), mental rotation abilities (Zoefel et al 2011) and a variety of cognitive functions (Alexeeva et al 2012).

This paper builds on the aforementioned evidence on NF training procedures with the main objective of minimizing the non-specific factors of the training to further advance in the understanding of the effects of these types of procedures (common limitation to NF studies, see a discussion on Brandeis 2011). An extensive evaluation of the effects on the electrophysiology was performed. Note that NF literature still lacks an extensive evaluation of the electrophysiological effects, especially on non-trained EEG parameters and during the execution of cognitive tasks, although some studies have partially addressed these issues (Zoefel et al 2011; Hanslmayr et al 2005).

This paper investigates the effects of a single-session NF procedure (25 minutes of training) for cognitive enhancement, which follows a double-blind sham-controlled experimental design with healthy subjects. Preliminary results were reported in Escolano et al (2012, 2013). The NF procedure focused on up-regulating the individual upper alpha power measured over the parieto-occipital area of the scalp. Non-specific factors were minimized by including a sham-feedback control group and by the short duration of the training. Note that a sham-controlled study provides a better consideration of non-specific factors such as motivation, expectancy and practice effects (Enriquez-Geppert et al 2013). A series of psychological tests and a cognitive task measured the effects on cognitive functions (working memory, attention, executive functions and mental rotation abilities). EEG analysis measured the effects on resting state and task-related activity immediately pre- and post- NF and one day after, as well as during training. Also, the effects on the event-locked EEG recorded during the pre- and post- executions of a mental rotation task were assessed. These effects were mea-

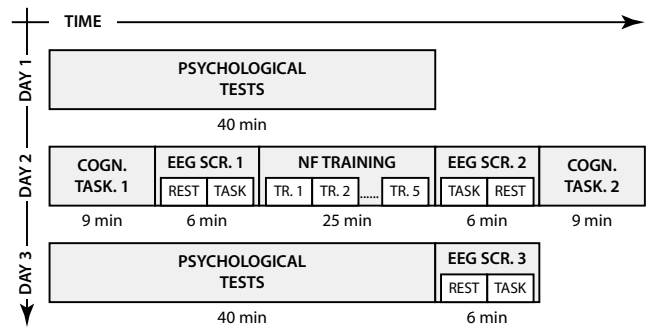


Fig. 1 Experimental design of the study, executed in three consecutive days. The NF training was performed on Day 2, with an EEG screening and a cognitive task executed immediately before and after NF training. An EEG screening was also executed on Day 3. Each EEG screening recorded eyes closed resting state activity and eyes open task-related activity. Psychological tests were executed on Day 1 and Day 3. Note that there is a numerical code for each EEG screening, cognitive task and training trial.

sured on the trained parameter (upper alpha), as well as in the surrounding frequency bands (lower alpha and lower beta).

Methods

Participants and experimental design

19 engineering students of the University of Zaragoza participated in the study. Participants were randomly assigned either to the NF group ($n = 10$, 3 females, mean \pm SD age: 25.8 ± 4.1 years) or control group ($n = 9$, 2 females, 24.3 ± 3.7 years). Participants were informed about the protocol of the study before signing the informed consent forms. They were told that all participants would perform a single session NF training to investigate the effects on cognitive performance. Participants were not informed about the existence of two groups to avoid biases (lack of motivation or effort since NF requires the active engagement of participants). Both groups performed the same experimental design with the only difference that the control group received sham feedback. Finally, participants were debriefed at the end of the study. The study was approved by the regional Ethics Board.

The design of the study is shown in Figure 1. In the first and third days, the psychological tests were carried out. In the second day, the NF training was performed with a pre- and post- EEG screening, and a pre- and post- execution of the cognitive task (EEG was recorded during the cognitive task). Finally, an EEG screening was also performed on the third day to assess one-day lasting effects on the EEG.

Psychological tests and cognitive task

Psychological data collection comprised four tests: (i) Paced Auditory Serial Addition Task (PASAT, Gronwall 1977) evaluated working memory and processing speed. This test is sensitive to minimal changes in neurocognitive performance and presents high levels of internal consistency and test-retest reliability (Tombaugh 2006). The test scores were the number of errors and elapsed time. (ii) Rey Auditory Verbal Learning Test (RAVLT, Rey 1964), Spanish version (Miranda and Valencia 1997), evaluated retention and immediate evocation, verbal learning, remembering items after an interference task, and recognition (Lezak 2004). The test score was the number of recognized words. (iii) Trail Making Test (TMT, Reitan 1958) evaluated the information on visual search, scanning, processing speed, mental flexibility and executive functions. The test is composed of two parts: part A measured attention and concentration, and part B measured executive functions such as planning and mental flexibility. The scores were the elapsed time to complete each part of the test. (iv) Stroop Color-Word Test (STROOP, Stroop 1992) evaluated attention, concentration, resistance to interference, and individual capacity to solve cognitive stress, inhibit interferences and process complex data (Lezak 2004). The test score was the interference.

The cognitive task was adapted from a visuospatial Spanish test (Yela 1969) and EEG was recorded during its execution. In each trial, a target and a test figure were presented one above the other, and the subjects had to indicate (by pushing a button) whether the test figure corresponded to a rotated version of the target. Subjects were instructed to answer as quickly and accurately as possible. The test consisted of two phases of 25 trials each, with an inter-trial interval of 2.5 s. Each trial lasted 7.5 s and was composed of two time intervals: rest interval (-1.5, 0) s, in which a fixation cross was displayed on the center of the screen, and task interval (0, 6) s, in which the figures were presented for 6 s. Note that (t=0) s denotes figures onset. The test scores were the number of correct responses and reaction time. Responses within the task interval plus the inter-trial interval were taken into account and reaction times were computed for the correct responses.

Two-way repeated-measures ANOVA was separately conducted for each score with the between-subject factor Group (NF, Control) and the within-subject factor Time (Pre, Post). Paired samples *t*-tests were performed for within-group (pre vs post) comparisons.

EEG recording and neurofeedback procedure

EEG data was recorded from 16 electrodes placed at FP1, FP2, F3, Fz, F4, C3, Cz, C4, P7, P3, Pz, P4, P8, O1, Oz and O2 (subset of the 10/10 system), with the ground and reference electrodes on FPz and on the left earlobe, respectively. EEG was amplified and digitized using a g.tec amplifier (Guger Technologies, Graz, Austria) at a sampling rate of 256 Hz, power-line notch-filtered at 50 Hz and (0.5-60) Hz band-pass filtered. EEG recording and the NF procedure were developed using software of *Bit&Brain Technologies, SL*.

EEG screenings

EEG screenings were carried out immediately before and after the NF training on Day 2, as well as on Day 3. For each EEG screening we recorded three-min of eyes closed resting state activity and three-min of eyes open task-related activity. In the latter, subjects faced a computer screen showing a square that changed saturation color randomly from gray to red or blue (gradually). Participants were instructed to count the number of saturation changes from gray to red as a cognitive challenge (Zoefel et al 2011).

Neurofeedback procedure

The NF training focused on the increase of upper alpha (UA) power averaged over parieto-occipital locations (P3, Pz, P4, O1 and O2, referred to as feedback electrodes). The procedure consisted of two steps: calibration to individualize the training for each subject, and online training (5 trials of 5 min each). In both steps, EEG power was calculated through a short-term FFT with 1 s hamming window, 30 ms of overlapping, and zero-padded to 1024 points (0.25 Hz resolution).

In the calibration step, the pre-NF task-related EEG screening (Day 2) was filtered from artifacts: we automatically filtered out the blinking component by Independent Component Analysis (ICA) using the FastICA algorithm (Hyvarinen 1999) and removed the epochs with amplitude larger than $200\mu V$ at any electrode. UA band was defined as the (IAF, IAF+2) Hz frequency range, where the Individual Alpha Frequency (IAF) was computed on the power spectra of the filtered EEG data as the frequency bin with the maximum power value in the (7-13) Hz alpha range (Klimesch 1999). Note that when no clear alpha peak was found, the UA band was computed on resting state activity instead. Finally, the baseline was computed as the mean UA power averaged across the feedback electrodes, and (5th-95th) percentiles established the lower and upper

limits, respectively. After the calibration, the subjects performed the training trials. During training, EEG data was online filtered from blinking artifacts (through the aforementioned ICA filter) and a visual feedback was then displayed every 30 ms on a computer screen in the form of a square with changing saturation colors. UA power values above the baseline were displayed in a red color scale with increasing saturation. Similarly, power values below the baseline were displayed in a blue color scale. The color scales ranged from 0% saturation (baseline in gray color) to 100% saturation in both blue and red color scales set by the lower and upper limits, respectively.

Before the beginning of the study we recorded the EEG of a healthy subject performing the same NF procedure. In our study, the NF group and the control group performed the same NF procedure except for the fact that all participants of the control group received feedback according to the aforementioned EEG recording, thus receiving the same feedback.

EEG analysis

Offline EEG pre-processing

The EEG data of each Day was cleaned from artifacts using a three-step procedure: filtering of the blinking component by FastICA (Hyvarinen 1999), epoch rejection by a time-domain threshold ($> 150\mu V$) at any electrode, and epoch rejection by a frequency-domain threshold. In the latter step, we computed the power values for each epoch in the bands (1-4) Hz and (20-30) Hz, commonly affected by ocular and muscular artifacts (Delorme et al 2007), and outliers (z -score > 2) at any electrode were removed. In the case of the EEG collected during the cognitive task, we applied an ICA filter, and we further applied epoch rejection in both time and frequency domains on a trial basis (instead of on an epoch basis).

Analysis of EEG screenings and NF trials

Immediate and one-day lasting effects were assessed in resting state and task-related activity. Immediate effects were measured as the power comparison between the pre- vs post- EEG screening of Day 2 (SCR.1 vs SCR.2, Figure 1). One-day lasting effects were measured as the power comparison between the pre-NF EEG screening vs EEG screening of Day 3 (SCR.1 vs SCR.3). In addition, training progress evaluated the power enhancement during training, measured as the power comparison between the baseline (task-related activity in pre-NF EEG screening) vs training trial five.

We performed the analysis in the trained parameter (i.e., UA power) and an exploratory analysis in the following bands, based on Klimesch (1999): lower alpha 1, $LA_1 = (IAF-4, IAF-2)$; lower alpha 2, $LA_2 = (IAF-2, IAF)$; and lower beta, $LB = (IAF+2, IAF+4)$.

Analysis of event-locked EEG during the cognitive task

The power in the pre- and post- executions of the cognitive task was computed in rest interval (-1.5, 0) s, and task interval (0, 6) s. Note that ($t=0$) s represents the figures onset. Power was computed for each trial and averaged across trials. In addition, we computed the power desynchronization between rest and task intervals using two metrics: (i) absolute power desynchronization, computed as the power in task interval minus the power in rest interval, and (ii) event-related desynchronization (ERD), computed as the power in task interval minus the power in rest interval, normalized by the power in rest interval (Pfurtscheller and Lopes da Silva 1999). Thus, the NF effects on the event-locked EEG were assessed by the pre- vs post- power comparison in rest and task intervals, and by the pre- vs post-power desynchronization comparison measured using the absolute metric and the relative metric (ERD). We performed the analysis in the trained parameter and an exploratory analysis in LA_1 , LA_2 and LB bands.

Statistical analysis

Between-group statistical significance was assessed by independent samples t -tests on change scores. Paired samples t -tests were performed for within-group (pre vs post) comparisons. Power values were log-transformed prior statistical testing. Regarding the exploratory analysis in LA_1 , LA_2 , UA and LB bands, a non-parametric randomization method using the t -max statistic was used to correct for the number of bands, i.e., to control the familywise type I error rate (FWER, Holmes et al 1996). Following this method, the null distribution of the maximum absolute t -value across all bands was estimated by 5000 random permutations. Then the absolute observed t -value for each band was tested against the $(1 - \alpha)th$ percentile of the null distribution. The FWER was set at $\alpha = .05$.

EEG results

This section analyzes the NF effects on the EEG: the effects in the EEG screenings and NF trials, and the event-locked EEG effects during the execution of the cognitive task. Groups did not differ statistically in baseline IAF. Mean \pm SD IAF in resting state was

9.8 ± 0.2 Hz for the NF group and 10.3 ± 0.3 Hz for the control group (independent samples t -test: $t_{17} = -1.50, p = .15$); and in task-related activity it was 10.2 ± 0.2 Hz for the NF group and 10.6 ± 0.3 Hz for the control group ($t_{17} = -1.05, p = .3$).

Analysis of EEG screenings and NF trials

We first assessed the NF effects in the trained parameter (UA power). Regarding the resting state, no significant difference appeared between groups (on change scores) either immediately after the training or the following day. Figure 2A displays the UA power in task-related activity and during training. Task-related activity showed a between-group difference at statistical trend immediately after the training ($t_{17} = 1.88, p = .077$). Post-hoc t -tests showed a significant increase for the NF group ($t_9 = 3.42, p < .01$), with an average increase of 13.08%. These effects were not significantly sustained the following day. Training progress showed a between-group difference at statistical trend ($t_{17} = 1.81, p = .089$). Post-hoc t -tests showed a statistical trend for the NF group ($t_9 = 1.94, p = .084$), with an average increase of 51.22%. The higher effects in the latter metrics were found in posterior areas of the scalp. In addition to that, we measured the training progress as the trend (slope of a fitted regression line) of the power values of the baseline and five NF trials (see Figure 2A). The average slope was 0.11 for the NF group (significantly higher than zero, $t_9 = 1.86, p = .048$) and 0.02 for the control group (non significant, n.s.).

We assessed the EEG effects in three alpha subbands and lower beta (LA₁, LA₂, UA, LB). Figure 2B displays the pre- and post- EEG power spectra in immediate and one-day lasting effects, as well as the training progress. Note that the statistical results below reported were corrected for the multiple bands using a t -max randomization procedure (Holmes et al 1996). No significant between-group differences (on change scores) appeared in resting state either immediately after training or the following day. Regarding the immediate effects in task-related activity, we found a significant between-group difference in LA₂ band (threshold $t = 2.80^1, t = 3.69, p = .01$). Post-hoc t -tests showed a significant increase for the NF group (threshold $t = 2.98, t = 4.06, p < .01$), with an average increase of 50.93%. No significant one-day lasting effects appeared in task-related activity. Finally, a between-group difference in training progress appeared in LA₂ band at statistical trend (threshold $t = 2.74, t = 2.45, p = .085$). Post-hoc

t -tests showed a significant increase for the NF group (threshold $t = 2.69, t = 4.14, p < .005$), with an average increase of 74.55%. No significant pre- vs post- changes appeared for the control group.

Analysis of event-locked EEG during the cognitive task

We first assessed the NF effects in UA power. Figure 3A depicts the UA power time-course: absolute power time-course and ERD metric. Note that the absolute power time-course allows to observe the pre- and post- power changes in each trial interval (rest, task). The UA power in rest interval showed a between-group difference (on change scores) at statistical trend ($t_{17} = 1.96, p = .067$). Post-hoc t -tests showed a significant increase for the NF group ($t_9 = 3.97, p < .005$), with an average increase of 16.61%. The higher effects were found in posterior areas of the scalp. No significant effects appeared for the task interval. A desynchronization pattern was apparent, showing an UA power decrease after the figures onset for both groups and pre- and post- executions (Figure 3A). This pattern is in line with other studies performing similar mental rotation tasks (Hanslmayr et al 2005; Klimesch et al 2003). A between-group difference at statistical trend was found in absolute power desynchronization ($t_{17} = -1.99, p = .063$). Post-hoc t -tests showed a significant increase for the NF group ($t_9 = -2.53, p = .032$), with an average increase of $2.2\mu V^2$. Note that a positive difference denotes an increase in desynchronization.

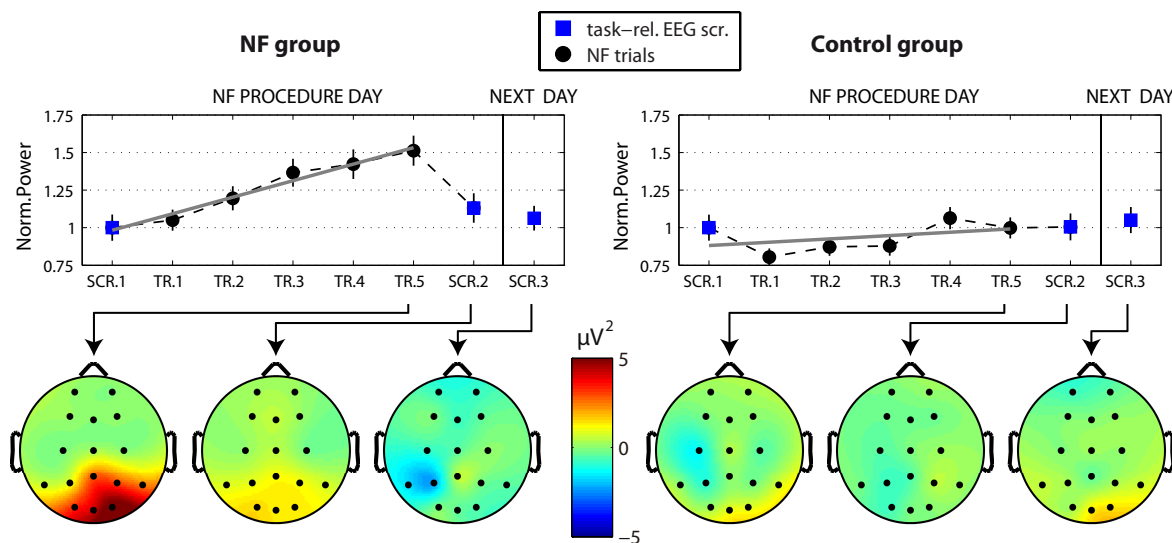
We assessed the EEG effects in three alpha subbands and lower beta (LA₁, LA₂, UA, LB). Figure 3B displays the time-frequency analysis in the (IAF-4, IAF+4) Hz range, showing the initial and change (pre vs post) absolute power values for each group. Note that the statistical results below reported were corrected for the multiple bands (Holmes et al 1996). We did not find significant differences between groups (on change scores) in any band and metric. We further conducted pre- vs post- t -tests within each group. A significant increase appeared in LA₂ band for the NF group in rest interval (threshold $t = 3.17, t = 4.52, p = .006$), with an average increase of 29.9%; as well as in task interval (threshold $t = 3.01, t = 4.10, p = .007$), with an average increase of 12.1%. These effects in LA₂ power can be observed in Figure 3B. No significant pre- vs post-changes appeared for the control group.

Behavioral results

This section analyzes the NF effects on cognitive performance measured by a battery of psychological tests

¹ The t thresholds reported throughout this paper (for the t -max randomization procedure) were computed at ($\alpha = .05$).

(A) EEG SCREENINGS AND NF TRIALS: UA POWER



(B) EEG SCREENINGS AND NF TRIALS: POWER SPECTRA

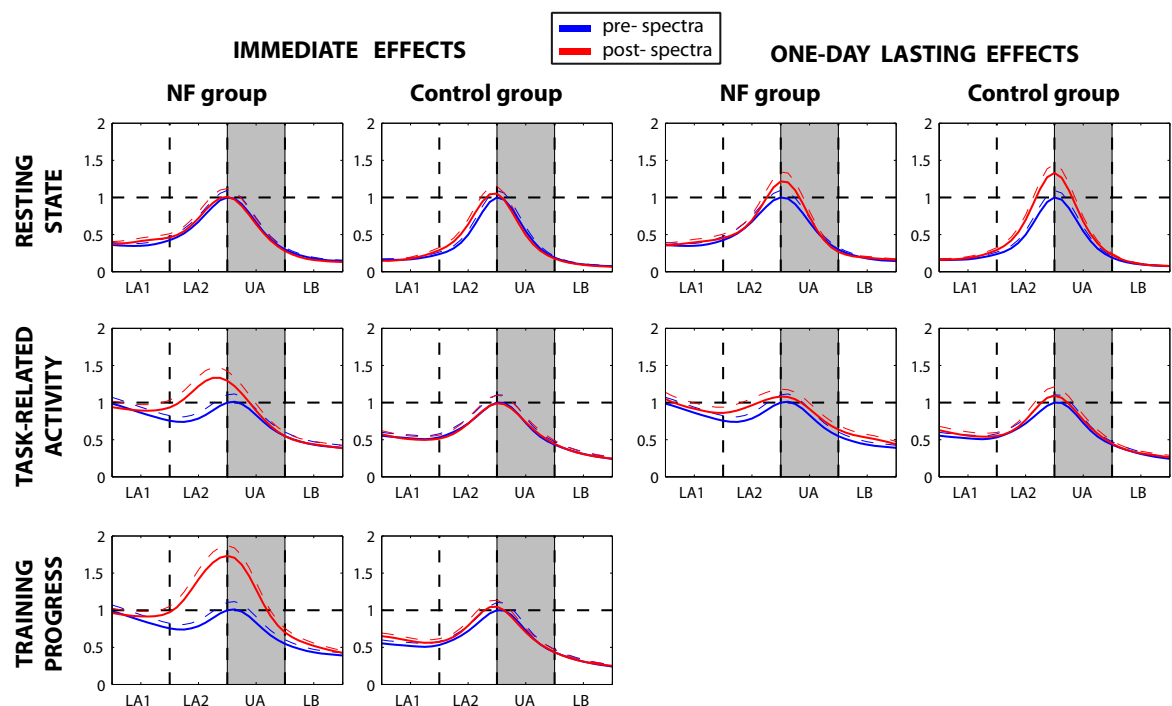
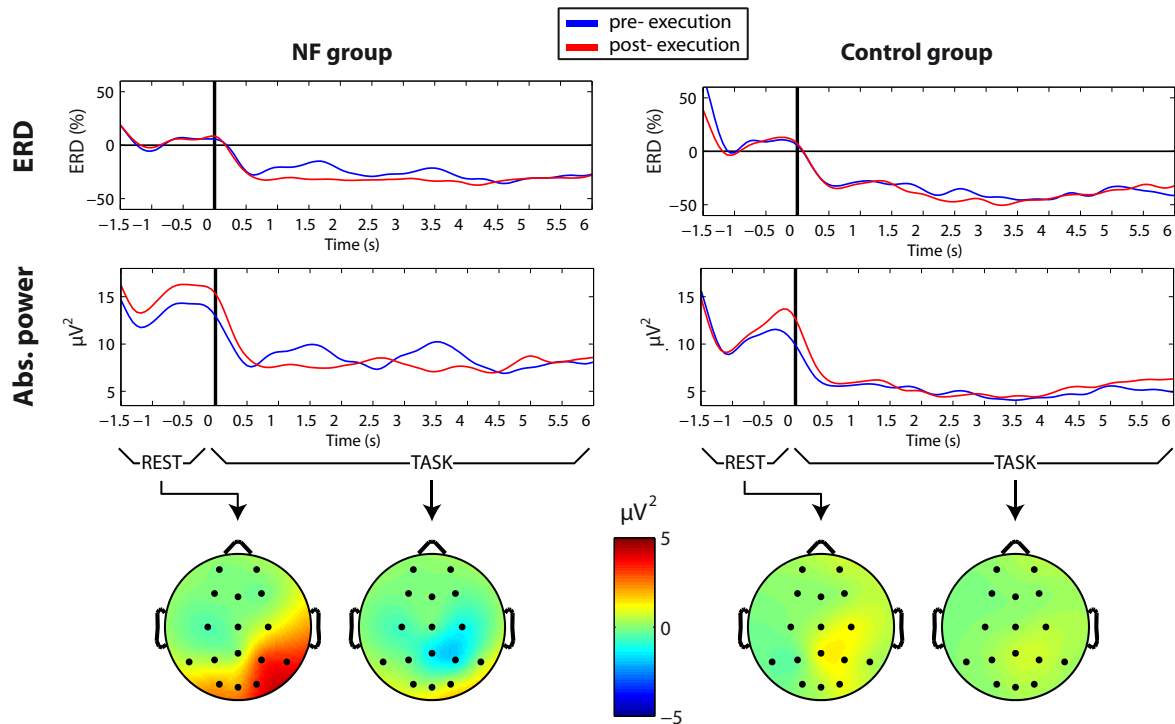


Fig. 2 NF effects on the EEG screenings and NF trials. (A) displays the UA power in the task-related EEG screenings (blue squares) and training trials (black dots). Values are normalized per subject to the power in the pre-NF EEG screening. Vertical bars indicate SEM. The gray line represents the training progress. Topoplots display the power difference (μV^2) with regard to the pre-NF EEG screening. (B) displays the pre- and post- EEG power spectra for the immediate and one-day lasting effects on both resting state and task-related activity, as well as the training progress. Average and SEM power values are displayed (solid and dashed lines, respectively). Note that for illustration purposes, the pre- and post- power spectra were normalized per subject to the power in the pre-spectra IAF bin, and averaged across subjects. The (IAF-4, IAF+4) Hz frequency range is displayed (covering LA₁, LA₂, UA, and LB frequency bands). UA band is shaded in gray color.

(A) EVENT-LOCKED EEG EFFECTS: UA POWER



(B) EVENT-LOCKED EEG EFFECTS: ABS. POWER TIME-FREQUENCY MAPS

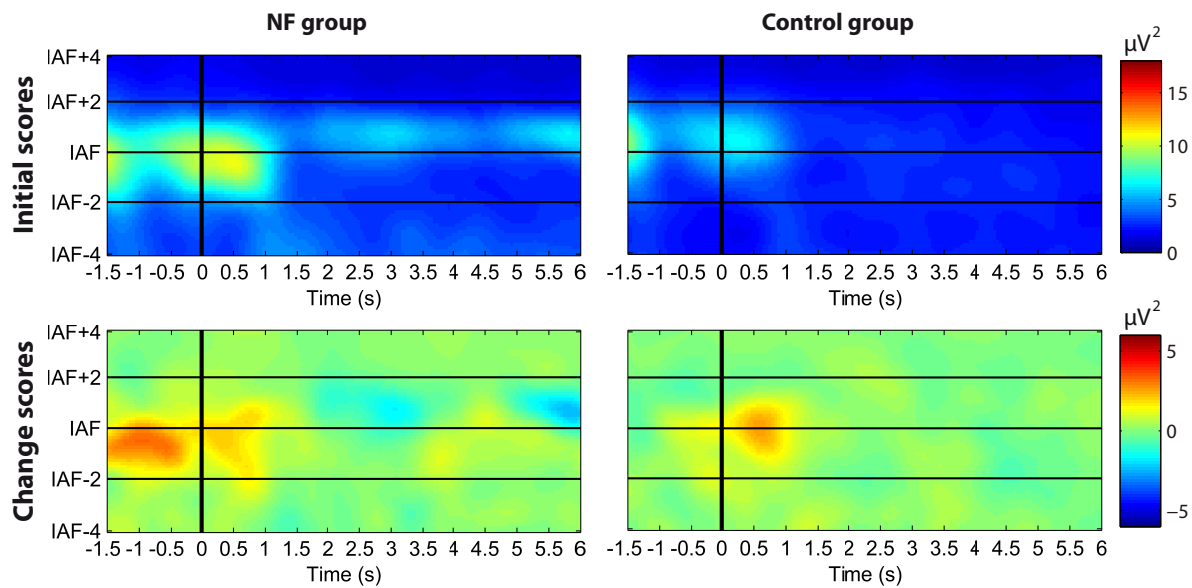


Fig. 3 NF effects on event-locked EEG during the pre- and post- executions of a cognitive task. (A) displays the UA power time-course. Upper figures show the ERD measurement (Pfurtscheller and Lopes da Silva 1999): UA power in each time instant was normalized to the power in rest interval. Bottom figures show the absolute UA power. Topoplots display the averaged pre- and post- power difference (μV^2) in both rest and task intervals. (B) displays the absolute power time-frequency maps in the initial (pre- execution) and change scores (pre- vs post- execution) for each group. The (IAF-4, IAF+4) Hz frequency range is displayed (covering LA₁, LA₂, UA, and LB frequency bands).

Table 1 Pre- and change scores (mean \pm SEM) on the behavioral results for each group. The t - and p -values of the paired-samples t -tests are shown for each group (pre vs post changes), as well as the F - and p -values of the $Group \times Time$ interaction in the ANOVAs. Significant effects are marked bold ($p < .05$)

Test scores	NF		Control		Paired-samples t -test				ANOVA	
	Pre	Change	Pre	Change	NF		Control		$G \times T$	
	mean (SEM)	mean (SEM)	mean (SEM)	mean (SEM)	t -val	p -val	t -val	p -val	F -val	p -val
PASAT										
# errors	6.70(1.03)	-3.10(1.02)	4.11(1.03)	-1.33(0.90)	-3.05	.014	-1.49	.176	1.67	.214
time (s)	199.93(18.12)	-42.09(7.97)	174.24(19.83)	-33.47(8.72)	-5.28	<.001	-3.84	.005	0.53	.475
RAVLT										
# recognized words	13.90(0.41)	0.90(0.35)	13.67(0.53)	0.89(0.54)	2.59	.029	1.65	.137	0.00	.986
TMT										
part A, time (s)	27.16(3.59)	-6.15(3.03)	27.07(3.92)	-6.64(2.69)	-2.03	.073	-2.47	.039	0.01	.905
part B, time (s)	53.98(4.11)	-17.24(4.04)	36.10(3.54)	-7.27(2.07)	-4.26	.002	-3.52	.008	4.51	.049
STROOP										
interference	3.17(1.94)	3.60(3.66)	10.54(3.07)	2.69(1.38)	0.98	.351	1.95	.088	0.05	.826
COGN.TASK										
# correct responses	41.20(1.40)	4.00(1.20)	39.00(0.99)	2.33(0.65)	3.33	.009	3.61	.007	1.40	.253
reaction time (s)	4.49(0.32)	-0.68(0.13)	4.14(0.22)	-0.44(0.22)	-5.18	<.001	-2.02	.078	0.93	.349

(targeting functions such as working memory, episodic memory, attention, concentration, and executive functions) and the cognitive task (mental rotation abilities). Table 1 summarizes the scores in the psychological tests and cognitive task.

We assessed the between-group differences by the $Group \times Time$ interaction in the ANOVAs. A significant effect appeared in part B of TMT test ($F_{1,17} = 4.51$, $p = .049$). Post-hoc t -tests showed that both groups improved performance (NF: $t_9 = -4.26$, $p < .005$; Control: $t_8 = -3.52$, $p < .01$), with a higher improvement for the NF group. No significant between-groups differences appeared for the other scores. We further conducted pre- vs post- t -tests within each group as an exploratory analysis. PASAT test showed a decrease in the number of errors for the NF group only ($t_9 = -3.05$, $p = .014$), whereas the time elapsed decreased for both the NF ($t_9 = -5.28$, $p < .001$) and control group ($t_8 = -3.84$, $p = .005$). The number of recognized words in the RAVLT test increased for the NF group only ($t_9 = 2.59$, $p = .029$). Part A of the TMT test improved for the control group only ($t_8 = -2.47$, $p = .039$). The interference score in the STROOP test did not significantly change for any group. Regarding the cognitive task, the number of correct responses increased for both the NF ($t_9 = 3.33$, $p < .01$) and the control group ($t_8 = 3.61$, $p < .01$). The reaction time decreased for the NF group only ($t_9 = -5.18$, $p < .001$).

Discussion

This manuscript reports the results of a single-session NF procedure for cognitive enhancement in healthy

subjects. The NF training aimed at enhancing the individual upper alpha power measured over parieto-occipital locations. A double-blind sham-controlled study was designed within a short procedure (25 minutes of training) to minimize the non-specific factors of the training, which is a common claim to NF studies (Brandeis 2011). To the best of our knowledge, there is not a standard procedure to compute/provide sham feedback. In the current study, all participants in the control group received the same feedback based on the EEG signal of a single subject (not included in the study). The objective of the study was to investigate the NF effects on several cognitive functions (working memory, episodic memory, attention, concentration, executive functions and mental rotation abilities) and to perform an extensive evaluation of the effects on the electrophysiology. Note that the reliability and specificity of the NF effects at behavioral and electrophysiological level remain a common limitation (Gruzelić 2014; Vernon 2005).

EEG results

The EEG analysis of the EEG screenings and NF trials showed that upper alpha power was enhanced for the NF group only, measured immediately after training in task-related activity, and during training. The higher effects were found in posterior areas of the scalp. These effects were not restricted to the upper alpha band: lower alpha 2 showed a higher increase than the corresponding increase in upper alpha (in the same metrics). These effects may be due to a 0.1 Hz decrease in the IAF immediately after training (independent samples t -test: $t_{17} = -2.33$, $p = .03$), which reduced the effects on up-

per alpha while increasing the effects on the lower sections (see Figure 2B). Note that Escolano et al (2011) also reported an IAF decrease immediately after training. The IAF decrease was not sustained one day after, which is consistent with previous studies (Escolano et al 2011; Zoefel et al 2011). No significant one-day lasting effects appeared for any group. Eyes closed resting state activity was not significantly modified for any group, which suggests that this procedure presents lower effects on this type of activity. In relation to other works, upper alpha NF studies reported no modifications in lower alpha and lower beta (Escolano et al 2011; Zoefel et al 2011), however they followed a different definition for the frequency bands (herein the most common definition was adopted, Klimesch 1999).

The analysis of the event-locked EEG effects during the execution of the mental rotation task showed that the NF group enhanced upper alpha power in the rest interval (pre-stimulus) immediately after training. Power in task interval was not significantly modified for any group. As a consequence, the NF group increased upper alpha desynchronization measured using absolute power measurements. Note that this desynchronization increase was already suggested to be positively related to cognitive performance (Klimesch et al 2007). These results are in line with a previous study involving a mental rotation task (Hanslmayr et al 2005). Similarly to the effects in the EEG screenings and NF trials, lower alpha 2 power showed a significant increase for the NF group (no significant between groups) in both rest and task intervals (see Figure 3B).

Behavioral results

The NF group performed better than the control group in all the scores (except for part A of TMT test), but with no significant difference between groups (except for part B of TMT test, in which the NF group performed significantly better). In addition to that, some scores were improved for the NF group only such as the number of errors in the PASAT test (working memory is suggested to be related to alpha rhythm, Freunberger et al 2011; Klimesch et al 2007), the number of recognized words in the RAVLT test and the reaction time in the mental rotation task. However, the improvement in these scores was not significantly superior to the improvement observed in the control group.

These effects in cognitive performance might be explained by a strong learning effect due to repeated measurements (30 min between test-retest in the cognitive task, and one day in the psychological tests) and by the short duration of the training, which might be insufficient to yield significant differences between groups.

Note that NF effects on the EEG were not sustained at the post-NF administration of the psychological tests, which may have diminished the behavioral effects. In relation to other works, a previous study (Hanslmayr et al 2005) comprising a single-session training of combined trials of theta suppression and upper alpha enhancement (within-subjects design) led to improved performance in a mental rotation task for the subjects that responded to the upper alpha NF. The difference to the results herein presented may be due to the fact that a within-subject design could have better dealt with the between-group variability in baseline scores.

Limitations

Deception was used to blind the participants to the experimental condition. When debriefing the participants we could have asked them to “guess” the condition they were assigned. This point should be considered in future studies. A limitation of the behavioral analysis was the high baseline scores (e.g., the number of correct responses in the cognitive task was 41.2/50 and 39/50 for the NF and control group), which left little margin for improvement. The degree of difficulty of the psychological tests or cognitive tasks should be adapted to the participants in future studies, and cut-off scores could be established. Finally, a larger sample size would be desirable to increase the statistical power.

Conclusions

This paper showed that 25 minutes of NF training produced electrophysiological effects for the NF group only, showing an upper alpha power enhancement immediately after the training in task-related activity (not sustained one day after), and during training. The NF group presented higher pre-stimulus upper alpha power during the mental rotation task and consequently higher event-locked power desynchronization. Regarding the behavioral results, the NF group showed higher performance improvement than the control group, however no significant difference between groups was obtained. Thus, although the electrophysiological basis supporting the cognitive enhancement can be obtained in a single session, 25 minutes of NF training seem not enough to produce sustained effects on the EEG and to reach significance level (between groups) in cognitive performance. A higher number of training sessions is thus necessary to achieve long-lasting effects on the electrophysiology and enhance the behavioral results.

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