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Enhancing creative cognition with a rapid right-parietal neurofeedback procedure

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Abstract

The present article describes an innovative neurofeedback training (NFT) procedure aimed at increasing creative cognition through the enhancement of specific brain activities previously associated with divergent thinking. We designed and tested two NFT protocols based on training alpha and beta EEG oscillations selectively measured over the right parietal region. A total of 80 participants were involved, 40 in the alpha NFT protocol and 40 in the beta NFT protocol. The NFT loop was closed on a video stream that would advance only when oscillation power exceeded a normalized threshold. The total duration of the protocol was two hours in a single day, hence its classification as rapid. Changes in ideational fluency and originality, measured with a divergent thinking task, were compared between participants receiving real video feedback and participants receiving sham feedback. We controlled for individual differences in creative achievement level. Results showed that the protocols were effective at enhancing alpha and beta activities in the targeted area. Differences between the two protocols emerged in their effectiveness at promoting divergent thinking. While no significant changes in originality resulted from the rapid alpha NFT, increases in both originality and fluency emerged as a consequence of the rapid beta NFT. These results were particularly evident in participants starting with a low creative achievement level. Possible interpretations and future directions are proposed and discussed.

Keywords: neurofeedback; creativity; EEG oscillations; originality; fluency

1. Introduction

Creativity is undeniably one of the most complex and elusive human behaviors. Notwithstanding the long debate on the most appropriate definition of creativity, it is commonly accepted that it reflects the capacity to produce works that are potentially original and effective (Runco & Jaeger, 2012; Corazza, 2016). The concept of originality includes both novelty and nonobviousness, whereas effectiveness refers to the value or appropriateness of the outcomes of the creative process (Corazza, 2016). The study of creativity at the neuroscientific level has pursued two main aims. On the one hand, research mainly based on electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) has focused on understanding the neural correlates of creative behavior (Arden et al., 2010; Beaty et al., 2016; Dietrich & Kanso, 2010; Jauk et al., 2012; Jung et al., 2010). These techniques have been important for highlighting the brain networks that are associated with creativity. However, fMRI and EEG provide correlational evidence, and cannot establish which brain regions or neural dynamics are critical for creative behavior. On the other hand, a growing body of studies has applied brain stimulation to directly interact with neuronal activity and show causal links between brain structures and creative behavior (e.g., Kleinmintz et al., 2017; Luft et al., 2014). Similarly, since the pioneering work of Green and colleagues (1971) and of Sterman and Friar (1972), psychophysiologists have developed EEG-based neurofeedback approaches to enhance creative performance by non-invasively modulating specific EEG oscillations (Gruzelier, 2014a; Wei et al., 2014; Zmigrod et al., 2015). The present study is set within the latter context by proposing a new procedure designed to increase creative performance based on rapid EEG neurofeedback training (NFT).

Neurofeedback is a form of biofeedback that allows the user to take control over specific brain activities by means of operant conditioning (Lopez-Larraz et al., 2012; Gruzelier, 2014b; Marzbani et al., 2016). In this way, users acquire control over certain brain activity patterns (e.g., EEG oscillations), and can implement these skills in daily life (Gevensleben et al., 2009). Remarkably, NFT allows researchers to establish a causal link between modified brain activity and modified behavior (Watanabe et al. 2017) and has recently gained increased attention, since it represents a non-invasive way to modulate cognitive states in normal and pathological conditions (Marzbani et al., 2016). This is, for instance, shown by an increase in the number of publications about this technique in recent years (from 286 papers from 2008-2012 to 863 papers from 2013-2017; search on PubMed in January 2018, using "neurofeedback OR neuro-feedback" as query). NFT has been proposed as an enjoyable way to increase relaxation and cope with work-related stress (van Boxtel et al., 2012) and as a practical method for improving affective and cognitive functions (Egner & Gruzelier, 2004; Gruzelier, 2014b; Guez et al., 2015; Hosseini et al., 2016), mostly in clinical settings (Coghill, 2010).

Previous NFT studies on creative performance have shown promising results (Egner & Gruzelier, 2003; Gruzelier et al., 2013), although they required training windows extending over several days or weeks. These studies were guided by the idea that reaching a state of deep relaxation would increase participants' creative potential, as, in such a state, their creative performance would be best expressed (see Gruzelier, 2014a for a review). Accordingly, previous NFT studies have commonly focused on relatively slow EEG oscillations associated with closed-eye states of deep relaxation, i.e., theta (4-8 Hz) and alpha (8-14 Hz) oscillations, particularly over central parietal electrodes (Egner et al., 2002; Gruzelier, 2014b). Gruzelier and collaborators repeatedly demonstrated the efficacy of alpha and alpha/theta NFT protocols in increasing creative performance, especially in the artistic domain (Egner & Gruzelier, 2003; Raymond et al., 2005; Gruzelier et al., 2010; Gruzelier, 2012; Gruzelier, 2014b; Gruzelier et al., 2014; see also Gruzelier, Thomson, al., 2014).

Beyond enhancing relaxation, NFT protocols can be used to enhance EEG patterns associated with specific cognitive processes. Interestingly, prior EEG studies have often reported that creative performance can be associated not only with a power increase in relatively slow oscillations (e.g. alpha oscillations, which are generally associated with inhibited cortical states and relaxation) but also with beta oscillations, which commonly reflect active processes including cognitive control and attention (Bhattacharya & Petsche, 2005; Fink, Benedek, Grabner, Staudt, & Neubauer, 2007; Fink & Benedek, 2014; Molle et al., 1999). Thus, NFT procedures based on enhancing faster EEG oscillations appear to be a promising target for enhancing creativity.

In the present study, we used NFT to investigate creative potential, i.e., the potential to produce ideas that are both original and effective (Corazza, 2016). Specifically, we explored divergent thinking, i.e., the ability to generate alternative responses by exploring many possible solutions. Divergent thinking represents the best characterization of creative potential (Runco & Acar, 2012) and previous research has already demonstrated that it can be effectively trained (e.g., Scott et al., 2004). We designed our NFT protocol based on previous EEG studies that used divergent thinking tasks to investigate brain dynamics involved in creative cognition (Fink & Benedek, 2014; Runco & Yoruk, 2014). Those studies highlighted an association between creative performance and different brain oscillations, particularly in the alpha and beta bands, both during active tasks and in a resting state (Bhattacharya & Petsche, 2005; Fink, Benedek, Grabner, Staudt, & Neubauer, 2007; Shemyakina et al. 2007; Fink & Benedek, 2014; Molle et al., 1999). They detected such activity mainly over right parietal regions (Benedek et al., 2011, 2014, 2016; Fink et al., 2007, 2010; Wu et al., 2015). However, those EEG studies could not answer the critical question of whether an enhancement of alpha and/or beta oscillations might cause an increase in creativity. Answering this outstanding question is the goal of the present NFT study.

1.1 Aims of the current study

Using NFT, we sought to test the functional relevance of alpha and beta activity to divergent thinking. Building on previous EEG studies, we developed a novel NFT procedure to increase participants' creative performance, as measured through the fluency and originality of ideas produced in a divergent thinking task (i.e., the classic Alternative Uses Task, AU task; Guilford, 1967), by monitoring the EEG signal specifically over the right parietal region (Benedek et al., 2011, 2014, 2016; Fink et al., 2007, 2010; Wu et al., 2015) and providing visual feedback when the activity in this region increased above a normalized threshold. We developed two distinct NFT protocols, i.e., Alpha and Beta NFT protocols, in order to separately explore the efficacy of NFT based on alpha and beta EEG oscillations. Importantly, we aimed to develop a rapid procedure, in order to deliver improvement within a single day.

1.2 Hypotheses

The change in brain activity over the right parietal region, as well as the change in creative performance in the divergent thinking task, were analyzed and contrasted during three NFT sessions delivered in a single day in four groups of participants. Two experimental groups (alpha and beta NFT) received visual feedback when the alpha or beta activity in the selected brain region exceeded a normalized threshold. Each experimental group was matched to a corresponding control group (alpha and beta sham) that received sham feedback unrelated to brain activity. Specifically, to validate the efficacy of the alpha and beta NFT protocols, a two-step experimental approach was implemented, based on the following hypotheses.

In the first step, we tested whether the alpha and beta NFT protocols effectively changed brain oscillations, hypothesizing that the time during which alpha/beta activity in the right parietal region exceed the normalized threshold value should progressively increase in the training condition compared to the corresponding sham condition.

As a second step, we tested the effect of NFT on participants' creative performance, reflected by ideational fluency and originality in the AU task. Importantly, if alpha and/or beta oscillations are not just epiphenomenally associated with creativity, but play a causal role in creative thinking, we would expect that alpha and/or beta NFT protocols would improve AU task performance, thus demonstrating a casual involvement of enhanced oscillatory activity in improved creative behaviour.

In addition, we measured participants' lifetime creative achievement, using the Creative Activity and Accomplishment Checklist (Hocevar, 1981; Milgram & Hong, 1999; Paek, Park, Runco, & Choe, 2016; Runco, Noble, & Luptak, 1990). This measure was necessary to control for individual differences in terms of creative success in real life, and to explore whether a median split over this variable (i.e., low vs. high creative achievers) could explain differential outcomes of the NFT procedures. A number of studies on the effectiveness of cognitive training have indeed shown the importance of considering the moderating role of higher order individual differences on the effect of training (e.g., Jaeggi, Buschkuehl, Shah, & Jonides, 2014). Following this reasoning, we assumed that participants with lower creative abilities should particularly benefit from NFT, i.e., the increase in creative performance should emerge more prominently in participants characterized by a low lifetime creative achievement level.

2. Method

2.1 Participants

A total of 80 female students from the University of Bologna took part in the experiment. Two separate protocols were performed to train oscillations in the alpha and beta bands. Forty participants were randomly assigned to the alpha NFT protocol (mean age = 21.10 years, *SD* = 2.12; age range from 19 to 27 years), and 40 to the beta NFT protocol (mean age = 20.64 years, *SD* = 2.38; age range from 18 to 27 years). Within each protocol, 20 participants were assigned to the experimental (training) condition, and 20 to the control (sham) condition. All participants had normal or corrected-to-normal vision, and none of them reported current or past neurological or psychopathological problems on a medical history screening questionnaire, adapted from one that is routinely used in non-invasive brain stimulation studies (see Rossi et al., 2009, 2011). They gave written informed consent and were paid for their participation. The experimental protocol conformed to the Declaration of Helsinki and was approved by the Bioethics committee of the University of Bologna.

2.2 Procedure and instruments

On arrival, participants were seated in a sound-attenuated room. They were introduced to the whole procedure and prepared for EEG recording. The experimental procedure was the same for all participants, and was performed in a single day (see Figure 1). In the pre-training phase, participants' EEG activity was recorded in two 3-min EEG recordings at rest, the first with eyes closed (EC block) and the second with eyes open (EO block, baseline). Subsequently, participants completed the first 10-min block (AU_{pre}) of the Alternative Uses (AU) task, which consisted of producing unusual/original uses for conventional, everyday objects. In the NFT phase, participants performed three 8-min NFT sessions, each followed by an AU block. The whole procedure, including a short post-training debriefing, took about 2 hours.

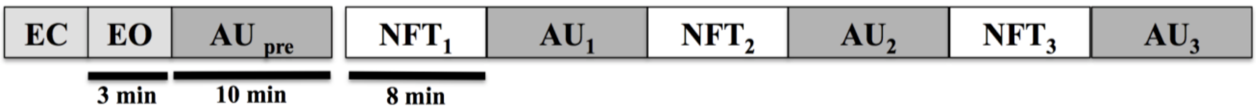

Figure 1. Schematic structure of the experimental protocol. The protocol started with a 3-min EEG recording with eyes closed (EC), a 3-min baseline EEG recording with eyes open (EO) and the first 10-min block of the Alternative Uses task (AU_{pre}). The NFT consisted of three 8-min neurofeedback sessions (NFT_1, NFT_2, and NFT_3), each followed by a 10-min block of the Alternative Uses task (AU_1, AU_2, and AU_3).

2.3 Neurofeedback apparatus and procedure

EEG signals were recorded using a G.tec g.HIamp amplifier (Guger Technologies OG, Austria) with 34 scalp sensors mounted on an elastic cap (EASYCAP GmbH, Germany) according to the 10/20 system: Fpz, AFz, Fz, FCz, Cz, CPz, Pz, POz, Oz, Fp1, F3, FC3, C3, CP3, P3, O1, F7, FT7, T7, TP7, P7, Fp2, F4, FC4, C4, CP2, CP4, CP6, P4, O2, F8, FT8, T8, TP8. AFz and the right cheek were used as reference and ground, respectively. The neurofeedback procedure (including baseline recording, online EEG data analysis, visual feedback presentation and data storing) was controlled by custom software developed in Simulink and Matlab (R2015a, MathWorks Inc., USA).

EEG signals were sampled at 512 Hz and band-pass filtered (0.1-60 Hz). An additional 50 Hz notch filter was also applied. The electrodes CP2, CP4, CP6 and P4 were chosen as representative of the EEG oscillation level over the right parietal region (see, for instance, Koessler et al., 2009). In fact, previous EEG studies have specifically implicated right-lateralized parietal activity in AU tasks (Fink & Benedek, 2014; Benedek et al., 2011, 2014; Fink et al., 2007), and fMRI studies have pointed to the right inferior parietal lobe as a key component of a fronto-parietal network involved in divergent thinking (Aberg, 2017; Beaty et al., 2014; Fink et al., 2010; Wu et al., 2015). The signal averaged over these four electrodes was analyzed online and visual feedback was provided to participants if the power in the frequency band of interest (i.e., the alpha or beta band) exceeded the mean power measured in the baseline EO block by 30% (normalization). The low and high cut-off frequencies of a band-pass filter (Butterworth filter) were set specifically for each NFT protocol, such that the 8-12 Hz and 16-24 Hz ranges were passed in the alpha and the beta NFT protocols, respectively. The signal was then squared, and band-specific frequency power was measured online in a 250-ms sliding window and compared to the alpha/beta power averaged over the entire 3-min EO baseline period. If the power was 30% greater than the mean baseline power (threshold), then feedback was delivered.

The visual feedback consisted of a video stream characterized by a dynamic sequence of different pictures of natural scenarios. The pictures were selected from a set of public-domain pictures available on the Internet (depicting people in daily contexts and landscapes), and connected in a video sequence through a zoom effect. Participants were told that they should make the video advance, although no explicit instructions were given by the experimenter on how to achieve control over EEG activity. Participants were told to immerse themselves in the video and try to imagine which scenario would come up. If the EEG power level was under the selected threshold, participants saw a static frame of the video stream; otherwise, the video stream went forward. The visual feedback was presented on a 19″ LCD monitor with 800 × 600 pixel-resolution and a 60 Hz refresh rate.

To evaluate whether NFT effectively modulated brain oscillations in the alpha/beta band, and whether this modulation had an effect on behavioral performance, a sham neurofeedback procedure was administered to a control group. In the sham condition, participants were tested with the same experimental procedure as in the training condition. Crucially, control participants were prepared for the EEG recording and received the same instructions to take control over the video stream. However, in the sham condition, the visual feedback was totally unrelated to participants' brain activity (Hosseini et al., 2016; Ros et al., 2013; Egner et al., 2002). Specifically, each sham participant was exposed to the video stream obtained from a corresponding training participant (i.e., from the alpha training group for alpha sham and from the beta training group for beta sham). The presentation order of video stream experiences obtained from the training group was pseudorandomized.

2.4 Creative performance: Alternative Uses (AU) task

All participants performed four blocks of the Alternative Uses (AU) task (see Figure 1), in which they were instructed to think of and write down alternative uses for common objects (e.g., a brick, a knife). We administered the paper-and-pencil version of the task. The first block was completed in the pre-training phase, and the other three in the NFT phase, each after a neurofeedback session. Each AU block consisted of 5 objects; participants were required to produce as many alternative uses as they could think of for each object in 2 minutes, for a total of 10 minutes per block. A total of 20 objects (five per session) were randomly presented to the participants.

Two measures of participants' creative performance were derived from the AU task: originality and fluency. Participants generated a total of 3180 uses in the alpha NFT protocol, and a total of 3728 uses in the beta NFT protocol for the 20 objects presented across the four sessions. Two judges independently rated the originality of each response separately for the alpha and beta NFT protocols (Silvia et al., 2008). For each object, the responses were transcribed onto a spreadsheet and alphabetically ordered. This method ensured that the ratings were not biased by the serial position of the response, the total number of responses in the set, and the preceding and subsequent responses. The judges were required to read all responses before scoring them.

Response originality was rated on a 1 (not at all original) to 5 (highly original) scale, using the scoring procedure of Silvia et al. (2008). This scoring procedure was originally proposed by Wilson, Guilford, and Christensen (1953), to assess individual differences in originality. According to their model, responses must be uncommon, remote, and clever to be judged as creative. Judges were asked to include these three criteria into their evaluation with the understanding that a strength on one criterion could balance a weakness on another criterion (Silvia et al., 2008). Inter-rater reliability calculated on the total number of uses was good in both the alpha- (Cohen's $\kappa = 0.61$) and beta-neurofeedback protocols (Cohen's $\kappa = 0.65$). In case of large discrepancies between ratings, the judges were asked to review their responses and to assign a score by consensus. Mean originality scores were finally derived from the ratings of the two judges.

In order to measure the change in participants' creative potential as a consequence of the experimental session, three delta scores were computed. Namely, separately for each dependent variable (originality and fluency), the average score obtained during the first AU block (AU_{pre}) was subtracted from the scores obtained during each of the other three AU sessions (i.e., AU_1, AU_2, and AU_3).

2.5. Creative Activity and Accomplishment Checklist (CAAC)

CAAC is a self-report measure of creative achievement in different life domains. It was delivered while the neurofeedback apparatus was being prepared. It was first used by Hocevar (1981) and, since then, it has been frequently used in creativity research (e.g., Milgram & Hong, 1999; Runco et al., 1990; Paek et al., 2016) and included in the Runco Creativity Assessment Battery (rCAB). The original version of the scale measures creative accomplishments in many domains. The present study used a short 45-item version of the instrument referring to the artistic, scientific, and everyday creative domains. Each item represents an activity performed in one of these three domains. The checklist uses a four-point ordinal response scale. Participants are asked to answer each item using the following scale: A = Never did this, B = Did this once or twice, C = Did this 3–5 times, or D = Did this more than 5 times. To account for the influence of context on creative activities, each item also asks how many times they performed an activity both within and outside their scholastic environment, with reference to their entire education. For each item, participants had to check two responses (A-D) that best described the frequency of the activity performed, respectively, inside school and outside school. Finally, a total creative achievement score for each participant was derived from the average of the artistic, scientific, and everyday creative achievement scores inside and outside of school.

2.6. Data analysis

As suggested by past literature (Angelakis, 2007; Dempster & Vernon, 2009), neurofeedback efficacy was evaluated by extracting the percentage of time (time%) frequency power in the trained bands (i.e., 8-12 Hz and 16-24 Hz frequency bands for the alpha and beta NFT protocols, respectively) was above the threshold in the targeted area. Specifically, average signals from the four electrodes considered for the NFT (i.e., CP2, CP4, CP6, and P4) were band-pass filtered (Hamming windowed Sinc FIR filter) and squared (power, in μV^2) to isolate the rhythmic activity of interest. An 8-12 Hz band-pass filter was applied on EEG data recorded during the alpha NFT protocol, whereas a 16-24 Hz band-pass filter was applied in the beta NFT protocol. The percentage of time above threshold was measured by comparing, for each time point in a recording block (i.e., EO, NFT_1, NFT_2, and NFT_3), the mean power in the NFT-specific band in the preceding 250-ms interval with the mean power in the EO block: time% was computed as the percentage of time points in the block that exceeded the power (in the respective band) averaged over the baseline EO block by 30%. To note that this procedure totally reflects the procedure used online during NFT to deliver feedback. Even if no real feedback was delivered in the sham condition, the percentage of time participants spent above the threshold was computed offline both for training and sham conditions, considering the corresponding frequency band of interest. In other words, time% for the alpha NFT and the alpha sham groups accounted for the time in which alpha power was above threshold, whereas time% for the beta NFT and the beta sham groups accounted for the time in which beta power was above threshold. EEGlab (v12.0.2.6b; Delorme & Makeig, 2004) functions were used for EEG data preprocessing. A repeated-measures analysis of variance (ANOVA) was conducted with SESSION (4 levels: EO, NFT_1, NFT_2, NFT_3) as a within-subjects factor, and CONDITION (2 levels: Training, Sham) and PROTOCOL (2 levels: Alpha, Beta) as between-subjects variables.

Finally, in order to investigate the effect of the alpha neurofeedback protocol on creative potential, changes in originality and fluency (measured by subtracting the baseline average score, AU_{pre}, from the average scores in AU_1, AU_2, and AU_3) were explored in two separate generalized linear mixed models (AR1 covariance structure) and treated as repeated dependent variables. Robust error estimation was used to control for the effect of outliers (Wu, 2009). SESSION (3 levels: NFT_1, NFT_2, NFT_3) was entered in the models as a within-subjects factor, while CONDITION (2 levels: Training, Sham) and CREATIVE ACHIEVEMENT (2 levels: Low, High) were entered as between-subjects factors. Finally, two-way and three-way interactions between the previous variables were added to the models.

3. Results

3.1 EEG data: neurofeedback efficacy

The analysis showed significant main effects of SESSION ($F_{3,288}$ = 4.847, p = .003, η_p^2 = .060) and CONDITION ($F_{1,76}$ = 8.081, p = .006, η_p^2 = .096), and a significant SESSION x CONDITION interaction ($F_{3,288}$ = 3.086, p = .028, η_p^2 = .039), highlighting a constant increase in the percentage of time participants spent above the threshold in the Training condition, as compared to the Sham condition, for both alpha and beta NFT protocols. Figure 2 depicts the mean time% values (± SE) separately for the different protocols (Alpha and Beta) and conditions (Training and Sham).

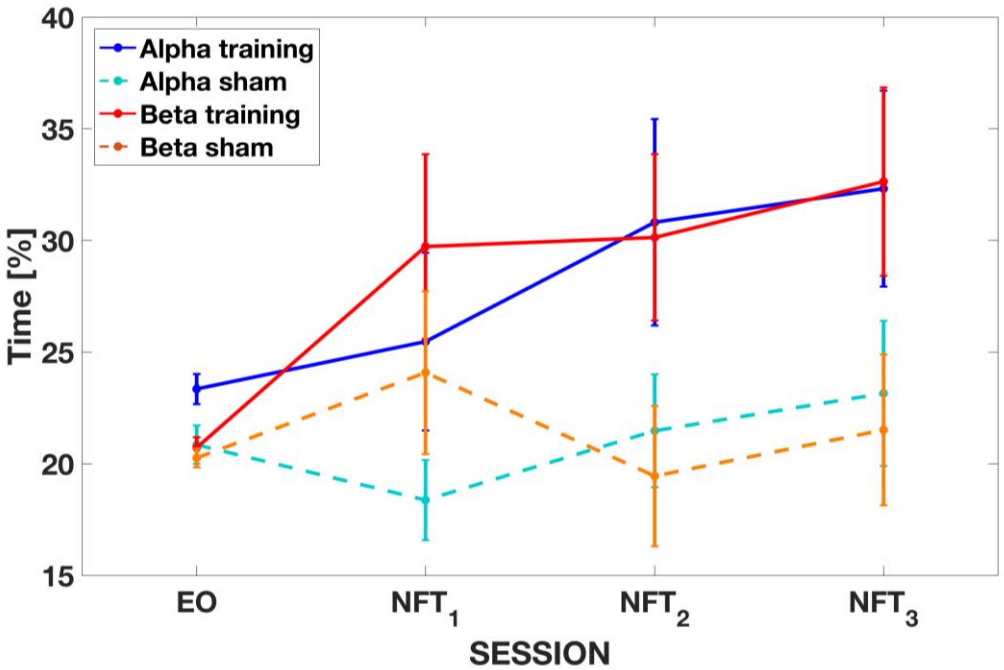

Figure 2. Mean percentage of time above threshold. Time [%] was computed separately for the two protocols (Alpha and Beta) as a function of SESSION (EO, NFT $_1$, NFT$_2$, and NFT$_3$), and CONDITION (Training and Sham). Error bars represent standard errors of the mean (SEM).

3.2 Behavioral data

3.2.1 Alpha protocol

A significant main effect of CONDITION emerged on fluency ($F_{1,108}$ = 11.46, p = .001, 95% CI = [-10.282, -.1.536]), highlighting an overall difference in fluency scores between the Training and the Sham conditions, with a decrease in fluency in the former and a slight increase in the latter (Figure 3). No other main or interactions effects on fluency were significant (all *p*s > .114). Furthermore, no significant effects emerged on originality scores (all *p*s > .205).

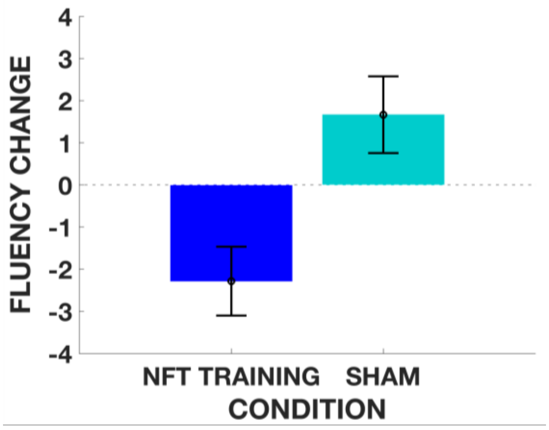

Figure 3. Alpha NFT protocol: Mean change in fluency in the NFT Training (blue bar) and the Sham (cyan bar) conditions. Error bars represent SEM.

3.2.2 Beta protocol

The same statistical approach as in the alpha neurofeedback protocol was used to explore the change in creative potential as a consequence of the beta protocol. First, the analysis performed on fluency scores showed a significant SESSION X CONDITION X CREATIVE ACHIEVEMENT interaction ($F_{2,108} = 5.74$, $p = .004$). No other interactions or main effects were significant. In order to further explore the three-way interaction, separate analyses for the two creative achievement levels were performed. These analyses showed a significant interaction between SESSION and CONDITION only in low creative achievers ($F_{2,54} = 3.78$, $p = .029$ for low creative achievers, $F_{2,54} = 2.09$, $p = .134$ for high creative achievers). In particular, as shown in Figure 4 (upper left panel), the Training and Sham conditions were characterized by two different trends in low creative achievers: in comparison to the Sham condition (which was the reference point for the comparison), an increase in fluency was found in the Training condition, which was significant between the first and the third sessions (AU_1 vs. AU_3, $b = 6.15$, $t_{54} = 2.65$, $p = .010$, 95% CI = [1.506, 10.797]), and almost significant between the second and the third sessions (AU_2 vs. AU_3, $b = 5.17$, $t_{54} = 1.99$, $p = .051$, 95% CI = [-0.019, 10.362]), while there was no significant change in fluency between the first and the second sessions (AU_1 vs. AU_2, $b = 0.98$, $t_{54} = 0.41$, $p = .686$, 95% CI = [-3.856, 5.816]).

Similarly to the analysis of fluency, the analysis performed on originality scores showed a significant SESSION X CONDITION X CREATIVE ACHIEVEMENT interaction ($F_{2,108} = 4.66$, $p = .011$). No other main effects or interactions were significant. In order to further explore the three-way interaction, separate analyses for the two creative achievement levels were performed. These analyses showed a significant interaction between SESSION and CONDITION only at a low creative achievement level ($F_{2,54} = 3.39$, $p = .041$ for low creative achievers; $F_{2,54} = 1.75$, $p = .184$ for high creative achievers). As shown in Figure 4 (bottom left panel), low creative achievers in the Sham condition were characterized by originality scores which were slightly, even if not significantly, below the baseline level; instead, in the Training condition originality emerged above the baseline level and higher than in the Sham condition, particularly in the first block ($AU_{1training}$ vs. AU_{1sham}, $b = -0.31$, $t_{54} = 2.38$, $p = .021$, 95% CI = [0.049, 0.568]).

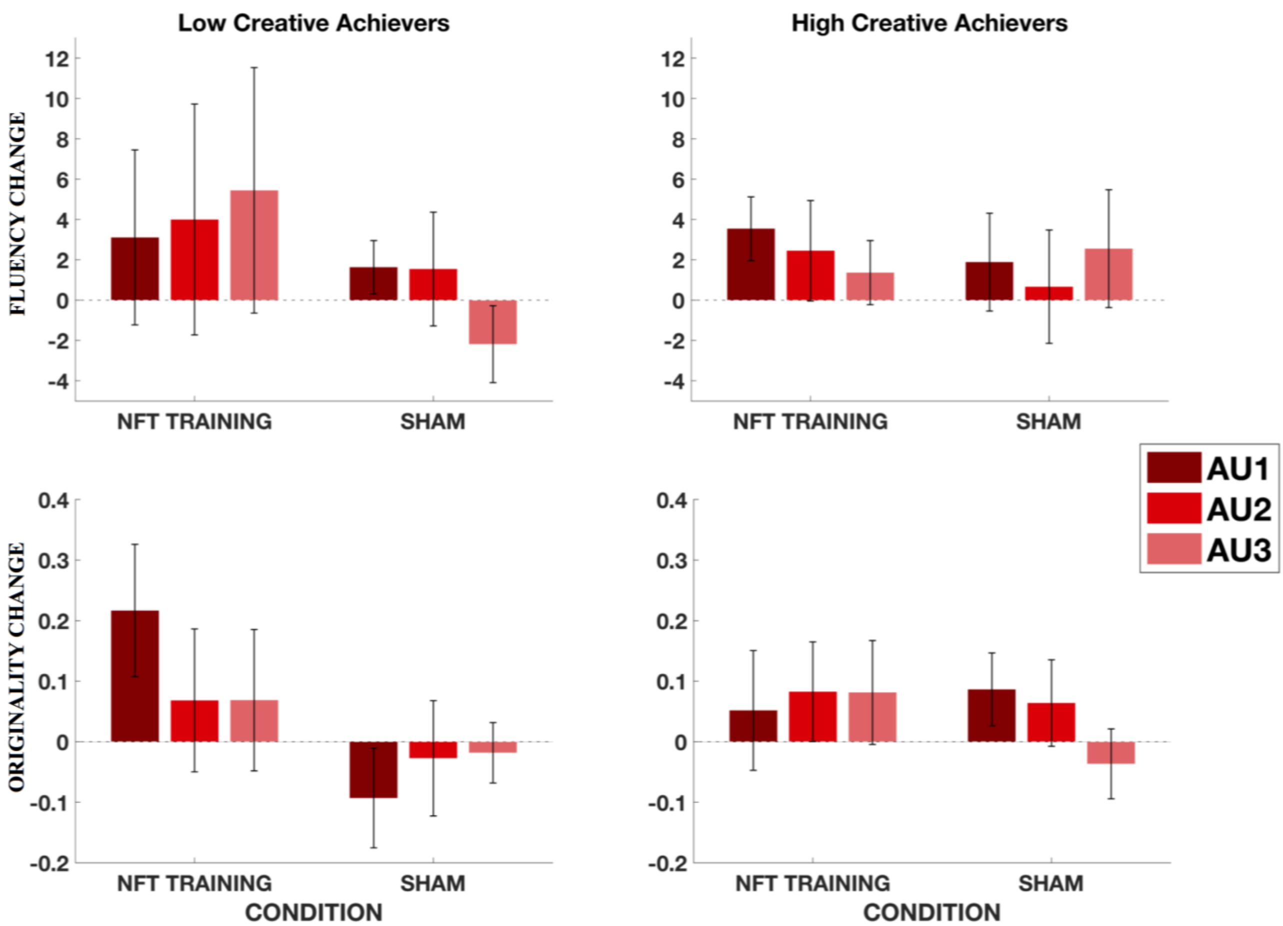

Figure 4. Beta NFT protocol: Mean difference in fluency (top panel) and originality (bottom panel) as a function of SESSION (AU_1, AU_2, AU_3) and CONDITION (NFT Training, Sham), shown separately for low and high creative achievers. Error bars represent SEM.

4. Discussion

The present study describes a rapid NFT procedure expressly designed to increase specific brain activities that were previously shown to be associated with creative thinking. In particular, two NFT protocols were tested, with the aim of increasing alpha or beta power over the right parietal region in a single day. The purpose of these procedures was to enhance participants' creative potential, as measured through ideational fluency and originality in a divergent thinking task. This way, we also test the functional role of alpha and beta activity on divergent thinking.

First, we demonstrated the effectiveness of the NFT procedure in increasing both alpha and beta activity in the right parietal region. Its effectiveness was shown by a progressive increase in the amount of time in which alpha and beta activity exceeded the mean oscillatory power recorded in the baseline period. Crucially, this effect emerged over three sessions of NFT in the training group, whereas no increase in the amount of time spent above the threshold emerged in the sham control group. Previous studies on neurofeedback often used control conditions in which participants simply sat and relaxed without NFT (for a discussion see Van Boxtel et al., 2012). In the current study, however, we used a more suitable control condition in which participants received the same instructions and visual stimulation as the training group did, except that the video stream was not linked to their brain activity (Hosseini et al., 2016; Ros et al., 2013; Egner et al., 2002). This strategy allowed us to assess the neurophysiological and behavioral effects of NFT, while removing confounding factors such as differences in the instructions, participants' expectations of training efficacy, and stimulus perception. Our result highlights, for the first time, the effectiveness of a NFT procedure specifically designed to modulate brain activity that is directly associated with creative behavior, in terms of divergent thinking abilities. In particular, our results support the hypothesis that participants could be trained to enhance their brain oscillations, in order to maintain high alpha and beta power for increasing amounts of time over the training sessions. Whereas it has been previously demonstrated that learning how to self-regulate a general state of relaxation increases creative performance (Gruzelier, 2014a), our procedure allowed participants to engage specific brain activities which have been demonstrated to be directly associated with creative cognition. In doing so, our study highlights the functional relevance of such brain activity.

We also explored the effects of alpha and beta NFT over the parietal region on AU performance. Surprisingly, the alpha NTF protocol did not yield any significant enhancement in participants' originality scores. The increase in alpha was instead associated with a decrease in ideational fluency in the training group, compared to the sham group. Contrary to our initial hypothesis, an enhancement of alpha oscillation power over the right parietal region was detrimental to AU performance. In other words, although the NFT procedure was designed on the basis of recent research showing a robust relation between alpha oscillations and creative performance (see Fink & Benedek, 2014), and it was indeed effective at enhancing alpha oscillations, it had no consistent incremental effect on the fluency dimension of divergent thinking performance. However, some considerations should be made when interpreting this surprising result. Firstly, most of the past research has focused on the originality dimension of creative behavior (Dietrich & Kanso, 2010 for a review) and has shown differences in originality between individuals with high and low levels of creativity, but no differences in ideational fluency (Fink, Grabner, et al., 2009). In this vein, an alpha power increase in the right parietal region has been associated with the qualitative aspects of divergent thinking (i.e., originality) rather than a mere difference in the number of responses (i.e., fluency; Fink, Graif, et al., 2009). On the other hand, it is possible that our alpha NTF protocol, by increasing alpha oscillations, might have induced relaxation in our participants, which in turn could have been detrimental to fluency.

It should be also noted that common experimental paradigms require participants to think of and report the single most original idea, and are specifically designed to separate the generative phase from the oral or written report of the idea. This procedure allows researchers to investigate EEG oscillations specifically during the ideational phase of divergent thinking tasks. Idea generation requires a shift from externally-directed attention to internally-directed attention. During this phase, an increase in alpha power is detected, especially in the right parietal region. Such an increase might reflect a shielding mechanism supporting internally-directed attention, which would prevent the interference of irrelevant external stimuli and facilitate the (re)combination of remotely associated semantic information (e.g., Benedek, et al., 2011; Fink et al., 2007; Fink, Grabner, et al., 2009; Benedek et al., 2014; Benedek et al., 2016). Unlike past EEG research, we analyzed the impact of previously trained brain activity on subsequent creative performance on a paper-and-pencil task. Thus, we could argue that the alpha power increase in the parietal region might be beneficial in a pure ideational phase, but its beneficial role might be interrupted or disturbed during our task. Indeed, participants in the current study performed a paper-and-pencil AU task that not only required to generate original and alternative ideas, but also to transcribe all (or some) of them, alternating an ideational phase characterized by internally-focused attention with an encoding phase characterized by externally-focused attention. We could assume that our paper-and-pencil task could have affected the beneficial shielding effect associated to the enhancement of alpha power in the parietal brain region, as it required a continuous shift between internal and external allocation of attention. Further studies are needed to investigate the relation between an increase in alpha power and the production of original ideas in paper-and-pencil divergent thinking tasks. At the same time, it is important to understand not only the duration of the training effect on subsequent creative performance, but also any possible interference of complex divergent thinking tasks on the trained brain activity. Moreover, while we considered the entire range of alpha oscillations (8-12 Hz), future NFT studies could target upper (10-12 Hz) vs. lower (8-10 Hz) bands of alpha oscillations, as the former appears more associated with creative performance (Fink & Benedek, 2014; Fink, Graif, et al., 2009; Fink et al., 2011).

Strikingly, our study showed beneficial effects of the beta neurofeedback protocol on divergent thinking performance, thus suggesting a key functional role of beta oscillations in creativity. In particular, beta NFT showed a consistent behavioral effect in participants characterized by low creative achievement. Indeed, both originality and fluency increased during the three beta NFT sessions, but only in low creative achievers belonging to the training group. Consistent with past research (e.g., Jaeggi et al., 2014; Rosen et al., 2016), this result once again highlights the importance of considering basic individual differences as moderating variables for training success (see below). In addition, even though originality and fluency are usually highly related (Runco, 2010), the intrinsic differences in these creative indexes should be highlighted. While originality was measured through the ratings of expert judges, fluency was a truly quantitative measure calculated from the total number of responses produced by participants. Our results showed that the beta NFT protocol affected both measures. Specifically, low creative achievers in the training group exhibited a progressive increase in ideational fluency during the training sessions, whereas originality was characterized by a significant initial increase, followed by a return to baseline values. Overall, these results suggest that fluency seemed to benefit from repetition of the training sessions, whereas originality did not. The qualitative aspect of divergent thinking indeed seemed less influenced by NFT repetition. This effect should, however, be taken with caution, as we used a small number of sessions during the training protocol. The limited number of training sessions might also explain the lack of effects in high creative achievers. Indeed, we cannot exclude the possibility that these participants would benefit from longer NFT protocols, including several sessions over different days (Marzbani et al., 2016 for a review).

Taken together, these results showed that rapid NFT training of beta activity over the right parietal region produced a significant increase in creative performance, whereas the rapid alpha NFT protocol did not. In other words, our beta NFT protocol, more so than alpha NFT, appears specifically capable of boosting divergent thinking. As already demonstrated by past research (Mölle et al., 2009), a significant increase of beta activity over the parietal region is associated with better performance in divergent thinking tasks, probably reflecting an enhancement in attentiveness and in binding capacity (Bhattacharya & Petsche, 2005; Razumnikova, 2007), which are the main functions required for divergent thinking. Extending previous findings, our study suggests that beta activity in the parietal region seems not only to favor thinking processes occurring during the recording of the brain activity, but also the performance in a following divergent thinking task, thus highlighting a key functional role of beta parietal oscillations in creative performance. Moreover, we can assume that the beneficial effects of the beta power increase over the parietal region may last over subsequent time intervals, as significant effects emerged over the 8-minute NFT training sessions used in the present study. Although our experimental procedure does not allow us to identify all the brain structures and functions modulated by NFT, our results demonstrate a role for right parietal activity in creative cognition. The posterior parietal cortex is a multimodal associative region involved in several higher-order functions such as multisensory integration, sensory-motor transformation, spatial coding and attention (Kaas et al., 2016; Whitlock, 2017). In the context of creativity, neuroimaging studies have shown that the inferior parietal lobule is implicated in creative production as part of the default-mode network (DMN; Beaty et al., 2015, 2016). For instance, more creative individuals (as evaluated by a divergent thinking task) showed increased resting-state functional connectivity between the inferior parietal lobule and other nodes of the DMN (Beaty et al., 2014) and this network seems to cooperate with areas of the executive system (such as the ventral anterior cingulate cortex and the dorsolateral prefrontal cortex) during the AU task (Beaty et al., 2015; Mayseless et al., 2015). Our study adds to the imaging evidence by suggesting that neural activity within the parietal node of the DMN is functionally relevant to AU performance.

Interestingly, functional connectivity studies have also shown that highly creative individuals are characterized by greater cooperation between the DMN and executive control areas at rest (Beaty et al., 2014; Takeuchi, 2012; Wei, 2014). This suggests that highly creative individuals already have an efficient and optimized system that enables them to outperform others on creative tasks such as the AU task. Thus, while the lack of improvement in our high creative achievers may be due to a ceiling effect and/or the relatively short duration of our NFT procedure, our data suggest that this procedure is particularly beneficial in individuals with less efficient systems. This result is consistent with prior research on NFT and other causal methods (i.e., brain stimulation) showing the moderating influence of individual differences on brain physiology, personality or the ability to perform the task (Rosenfeld et al., 1997; Hardman et al., 1997; Gruzelier, 2014c; Rosen et al. 2016; Paracampo et al. 2018; Valchev et al. 2017).

Although the effectiveness of the proposed NFT procedure on creative behavior deserves more investigation, understanding the impact of a short training procedure on real-world creativity is a particularly pertinent topic, which may have practical benefits in our daily lives. In this light, the present study is a first attempt demonstrating that training self-control over brain activities specifically related to creative thinking is effective in producing a significant enhancement of the individual creative potential.

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