



1 **Abstract**

2 Frontal alpha asymmetry has been proposed to underlie the balance between approach and  
3 withdrawal motivation associated to each individual's affective style. Neurofeedback of EEG frontal  
4 alpha asymmetry represents a promising tool to reduce negative affect, although its specific effects  
5 on left/right frontal activity and approach/withdrawal motivation are still unclear. The present study  
6 employed a neurofeedback training to increase frontal alpha asymmetry (right - left), in order to  
7 evaluate discrete changes in alpha power at left and right sites, as well as in positive and negative  
8 affect, anxiety and depression. Thirty-two right-handed females were randomly assigned to receive  
9 either the neurofeedback on frontal alpha asymmetry, or an active control training (N = 16 in each  
10 group). The asymmetry group showed an increase in alpha asymmetry driven by higher alpha at the  
11 right site ( $p < .001$ ), as well as a coherent reduction in both negative affect and anxiety symptoms ( $p$   
12  $< .05$ ), from pre- to post-training. No training-specific modulation emerged for positive affect and  
13 depressive symptoms. These findings provide a strong rationale for the use of frontal alpha  
14 asymmetry neurofeedback for the reduction of negative affect and anxiety in clinical settings.

15

16 **Keywords**

17 Neurofeedback; Frontal alpha asymmetry; Right prefrontal cortex; Negative affect; Anxiety; EEG.

18

## 1 **Introduction**

2           Several research lines converge in indicating the existence of two fundamental motivational  
3 systems in the mammalian brain (Davidson, 1992; Dickinson & Dearing, 1979; Gray & McNaughton,  
4 1982; Konorski, 1967; Lang, 2010; Lang & Bradley, 2013; Lang, Bradley, & Cuthbert, 1997): 1) an  
5 *appetitive/approach* system, that drives approach behaviors toward rewarding stimuli, and 2) a  
6 *defensive/withdrawal* system, associated with avoidance from aversive stimuli. The balance between  
7 appetitive and defensive dispositions has been referred to as the *affective style* of the individual  
8 (Davidson, 1998a, 1998b, 2004; Davidson, Jackson, & Kalin, 2000), which prompts responses to  
9 emotional stimuli, dispositional mood and vulnerability to psychopathology. On one hand, the  
10 motivational systems are embedded in evolutionary ancient brain structures which subserve similar  
11 functions in humans and in other mammals. On the other hand, humans further developed control  
12 over primary motivational impulses, mostly subtended by the prefrontal cortex (Damasio et al., 2000;  
13 Damasio & Carvalho, 2013; Ochsner & Gross, 2005).

14           In this sense, the dorsolateral prefrontal cortex acts as a moderator of the primary  
15 motivational and emotional responses, through its anatomical and functional connections with core  
16 limbic structures such as the amygdala, the basal ganglia, the anterior cingulate and the orbitofrontal  
17 cortex (Spielberg et al., 2012). Furthermore, an hemispherical specialization for the prefrontal cortex  
18 in motivation and affect has been reported: prevalent activity in the right compared to the left  
19 prefrontal areas has been related to withdrawal behaviors and to the experience of negative  
20 emotions, while the opposite pattern (i.e., greater left vs. right activity) accompanies approach  
21 behaviors and positive affect (Davidson, 1988, 1998b; Harmon-Jones, Gable, & Peterson, 2010;  
22 Papousek et al., 2014; Papousek, Reiser, Weber, Freudenthaler, & Schulter, 2012). Accordingly, it has

1 been advocated that 1) the left prefrontal cortex has a role in organizing limited resources toward  
2 goal-oriented behaviors, sustaining approach and positive affect; 2) the right prefrontal cortex  
3 mediates vigilance for threat and sensitivity to punishment, thus promoting avoidance and  
4 withdrawal (Gray & McNaughton, 1982; Sutton & Davidson, 1997). Therefore, the differential activity  
5 between the right and left prefrontal lobes is commonly considered a measure of affective style (Coan  
6 & Allen, 2004; Davidson, 1992).

7         Since electroencephalographic (EEG) alpha power is an inverse index of cortical activity (Cook,  
8 O'Hara, Uijtdehaage, Mandelkern, & Leuchter, 1998; Davidson, Chapman, Chapman, & Henriques,  
9 1990), the asymmetry in frontal alpha power is thought to reflect the balance between the activation  
10 of the right and left prefrontal lobes (Allen, Coan, & Nazarian, 2004). Accordingly, reduced alpha at  
11 right compared to left frontal sites (i.e., greater right-sided activation) has been associated with  
12 withdrawal motivation (Sutton & Davidson, 1997), negative affect (Jacobs & Snyder, 1996; Schaffer,  
13 Davidson, & Saron, 1983; Tomarken, Davidson, Wheeler, & Doss, 1992), as well as reports of more  
14 intense negative emotions after unpleasant film viewing (Papousek et al., 2014; Wheeler, Davidson, &  
15 Tomarken, 1993). On the other hand, reduced alpha at left compared to right frontal sites (i.e.,  
16 greater left-sided activation) has been related to approach motivation (Harmon-Jones & Allen, 1997,  
17 1998; Sutton & Davidson, 1997), trait positive affect (Tomarken et al., 1992), rates of pleasantness  
18 after positive film viewing (Wheeler et al., 1993), reward responsiveness (De Pascalis, Varriale, &  
19 D'Antuono, 2010), dispositional optimism (De Pascalis, Cozzuto, Caprara, & Alessandri, 2013), greater  
20 emotional flexibility (Papousek et al., 2012) and better emotional regulation (Jackson et al., 2003).

21         Electroencephalographic (EEG) biofeedback (*neurofeedback*) has been proposed as a tool to  
22 modulate the hemispherical asymmetry in prefrontal activity, in order to regulate affect (Rosenfeld,

1 Cha, Blair, & Gotlib, 1995). More in general, biofeedback is a bio-behavioral technique which aims at  
2 modifying physiological activity and, in turn, improving health and/or performance. In line with the  
3 biofeedback principles, neurofeedback relies on the assumption that, by providing real-time  
4 information on brain's activity, individuals can extend their conscious control and learn how to  
5 regulate their own brain activity (Thibault, Lifshitz, & Raz, 2016). Operant conditioning is a possible  
6 mechanism of action, since the positive feedback can be conceived as a reinforcement for the desired  
7 bio-behavioral pattern (Miller & DiCara, 1967). As a preliminary step, neurofeedback studies tested  
8 whether or not it was possible to modulate frontal alpha asymmetry, as well as the effects of this  
9 modulation on reported affect. Through five sessions of frontal alpha asymmetry neurofeedback  
10 using rewarding and non-rewarding tones, Allen and colleagues (2001) trained two groups of healthy  
11 participants either to increase or decrease their alpha asymmetry score, computed by subtracting left  
12 (F3) from right (F4) alpha power; therefore higher scores corresponded to reduced right compared to  
13 left frontal activity. Only participants trained to decrease alpha asymmetry succeeded and neither  
14 training modified current affect, as measured by the Positive and Negative Affect Scale, state version  
15 (PANAS; Watson, Clark, & Tellegen, 1988). Recently, one comprehensive study on a sample of 60  
16 individuals replicated Allen and colleagues' results, providing a visual feedback and adding a random-  
17 feedback control group (Quaedflieg et al., 2015); accordingly, this study showed that after 6 sessions  
18 participants were able to increase left compared to right alpha at frontal sites, but not vice versa.  
19 Further studies supported the efficacy of neurofeedback for the modulation of frontal alpha  
20 asymmetry in both directions (i.e., increasing or decreasing the asymmetry score) after three sessions  
21 of acoustic neurofeedback, with a similar design as the one from Allen and colleagues (Harmon-Jones,  
22 Harmon-Jones, Fearn, Sigelman, & Johnson, 2008), or even after one session of visual feedback

1 (Peeters, Ronner, Bodar, van Os, & Lousberg, 2014). Again, neither positive nor negative affect were  
2 influenced by the training.

3 Although there is evidence for neurofeedback to be effective in modulating frontal alpha  
4 asymmetry, previous studies did not address whether observed modifications were mostly driven by  
5 changes in alpha power at right, left, or both frontal sites. From a clinical perspective, this is of  
6 particular relevance, given that similarly altered patterns of frontal alpha asymmetry have been found  
7 in different conditions characterized by affect dysregulation, such as anxiety and depression (Beaton  
8 et al., 2008; Mennella, Messerotti Benvenuti, Buodo, & Palomba, 2015; Moscovitch et al., 2011;  
9 Stewart, Coan, Towers, & Allen, 2011, 2014). In particular, even though both anxiety and depressive  
10 symptoms have been associated with reduced frontal alpha asymmetry (right - left), in anxiety this is  
11 subtended by a dominance in withdrawal motivation and negative affect (increased right compared to  
12 left frontal activation); on the other hand, in depression the asymmetry dysregulation has been  
13 related to a reduction in approach motivation and positive affect (reduced left compared to right  
14 frontal activation) (Davidson, 1998a; Shankman & Klein, 2003). For this reason, it seems crucial  
15 establishing the specific effect of frontal alpha asymmetry neurofeedback on left and right activation,  
16 in order to provide a strong rationale for its clinical application.

17 The present study evaluated the effectiveness of frontal alpha asymmetry neurofeedback in  
18 *increasing* the alpha asymmetry index (F4 - F3). Furthermore, it was tested whether variations in  
19 asymmetry are subtended by relative changes in left (F3) and/or right (F4) frontal alpha power.  
20 Finally, the effects of the training on affect were assessed using a comprehensive battery, including  
21 the PANAS, for the evaluation of both positive and negative affect, as well as measures of anxiety and  
22 depressive symptoms.

1           It was hypothesized that 1) the frontal alpha asymmetry training would be effective in  
2 increasing alpha asymmetry (F4 - F3); 2) in case higher alpha asymmetry was subtended by an  
3 increase in alpha power at the right site (less dominant right-sided activation) this would be  
4 associated with a decrease in negative affect and anxiety scores; 3) if higher alpha asymmetry was  
5 driven by decreased alpha power at the left site (more prominent left-sided activation), higher  
6 positive affect scores and a reduction in depressive symptoms was expected.

## 1 **Methods**

### 2 **Participants**

3 Thirty-two healthy and free from medication undergraduate students (M age = 23.1, SD = 1.2)  
4 from the University of Padova were enrolled. The present study included only right-handed females,  
5 since asymmetrical alpha activity is influenced by handedness (Davidson, 1988), and previous studies  
6 have primarily examined female participants (Allen et al., 2001; Harmon-Jones et al., 2008; Peeters,  
7 Ronner, et al., 2014). Exclusion criteria were: previous head injury, chronic mental or neurological  
8 diseases and treatment with medications known to influence EEG, such as tranquilizers or  
9 antidepressants. Participants were randomly assigned to receive a biofeedback training designed  
10 either to increase frontal alpha asymmetry (i.e., F4 - F3; *asymmetry group*; N = 16), or to increase mid-  
11 frontal (Fz) alpha activity (*active control*; N =16). Neurofeedback aimed at increasing alpha activity has  
12 been previously employed in order to reduce stress and anxious symptoms (Brown, 1970; Hammond,  
13 2005; Hardt & Kamiya, 1978), due to the positive association of alpha power with states of relaxation  
14 and low arousal. Usually, this training is carried out at posterior sites, since the alpha rhythm is  
15 predominant in the occipital and parietal regions. On the contrary, in the present study the training  
16 targeted the mid-frontal site, to serve as a specific control condition for the frontal alpha asymmetry  
17 neurofeedback.

18 The groups were comparable with respect to sociodemographic variables (Table 1).  
19 Participants were told that at the end of the seven sessions they would receive a monetary payment  
20 proportional to their performance during training sessions (total payment ranged from 10 to 25  
21 euros). The present study was carried out with the adequate understanding and written consent of



1 the participants in accordance with the Declaration of Helsinki. The study was approved by the Ethics  
2 Committee of the Department of General Psychology, University of Padova (Italy).

### 3 **Procedure**

4 The whole procedure was run by two psychologists expert in biofeedback, clinical assessment  
5 and EEG procedures, with the help of two trained undergraduates for data collection. The procedure  
6 consisted of 7 biweekly sessions (completed within two weeks). Each session lasted about 45 min,  
7 starting within the same 3-hr time window. During the first session, upon arrival at the laboratory,  
8 participants received general information about the experiment and read and signed an informed  
9 consent form. A brief semi-structured interview for the collection of sociodemographic status  
10 information and exclusion criteria was conducted. Then, individuals sat on a semi-reclined  
11 comfortable armchair in a sound dampened dimly lit recording room, where a psychophysiological  
12 assessment was carried out, including psychological questionnaires administration and  
13 electrophysiological recordings in resting conditions. After the initial session (*pre-training*  
14 *assessment*), participants were randomly assigned to the *asymmetry* or to the *active control* groups,  
15 and underwent 5 neurofeedback sessions. In the final session the initial assessment was repeated  
16 (*post-training assessment*), in order to evaluate the effects of the training.

17

### 18 **Psychological assessment**

19 Participants completed the following questionnaires:

20 1) The Positive and Negative Affect Schedule (PANAS; Watson et al., 1988) consists of two subscales  
21 of 10 items each (i.e., negative affect (NA) and positive affect (PA)). In the version of the test used for  
22 the present study, for each item, participants are asked to rate (from 1 to 5) the extent to which they

1 have experienced a particular emotion during the present day. The two subscales reflect dispositional  
2 dimensions, with high-NA scores characterizing subjective feelings of distress and unpleasurable  
3 engagement, and high-PA scores reflecting the extent to which an individual experiences pleasurable  
4 engagement with the environment. Reliability and validity of the PANAS as a measure of positive and  
5 negative affect are high in non-clinical samples (Crawford & Henry, 2004).

6 2) The Beck Anxiety Inventory (BAI; Beck, Epstein, Brown, & Steer, 1988) is composed of 21 items,  
7 which the participant has to evaluate on a four-point (0–3) Likert scale. The total score ranges from 0  
8 to 63, with higher scores corresponding to higher levels of anxiety. Reliability and validity of the BAI as  
9 a measure of anxiety symptoms are high in both community samples (Beck et al., 1988) and college  
10 populations (Creamer, Foran, & Bell, 1995).

11 3) The Beck Depression Inventory-II (BDI-II; Beck et al., 1996; Italian version by Ghisi et al., 2006). The  
12 BDI-II is a valid and reliable self-report questionnaire that evaluates the severity of depressive  
13 symptoms in the past two weeks and is composed of 21 items, which the participant has to evaluate  
14 on a four-point (0–3) Likert scale. Higher BDI-II scores correspond to more severe depressive  
15 symptoms. Importantly, reliability and validity of the BDI-II as a measure of depressive symptoms are  
16 high in both community samples (Lasa, Ayuso-Mateos, Vázquez-Barquero, Díez-Manrique, & Dowrick,  
17 2000) and college populations (Sprinkle et al., 2002).

18

### 19 **Electrophysiological recordings**

20 EEG and vertical electro-oculogram (VEOG) were recorded in a standardized fashion using a  
21 computerized recording system (ProComp Infiniti, Thought Technology; Montreal, Canada).

22 Electrophysiological signals were recorded for 5 min, while participants were required to fixate a

1 white cross on a gray background, in order to reduce eye-movements. EEG was collected from three  
2 active scalp positions using golden electrodes with a bipolar montage. The EEG sites were F3, Fz and  
3 F4, referenced online to Cz, consistently with previous neurofeedback studies (Allen et al., 2001).  
4 Using a bipolar montage, VEOG was recorded in order to detect eye-movements and eye-blinks.  
5 Electrodes were placed at the supra- and suborbit of the right eye.

6 All electrodes impedances were kept below 5 k $\Omega$ . Each physiological signal was amplified,  
7 band-pass filtered (1–100 Hz) and digitized at 2048 Hz with ProComp Infiniti Encoder.

8

### 9 **Neurofeedback training**

10 Each training session began with a 5-min baseline recording at rest with eyes open, in order to  
11 establish the baseline frontal alpha asymmetry score. Mean baseline values were used to calculate  
12 the threshold for the training session, defined as mean activity + 0.85 standard deviations (Allen et al.,  
13 2001). Five 5-min biofeedback training trials followed, with a 1-min inter-trial break. Each trial was  
14 segmented in 150 epochs of 2 sec. Alpha power (8–13 Hz) at right (F4) and left (F3) frontal leads was  
15 extracted online using a fast Fourier transform algorithm with a Hamming window function applied to  
16 the 2-sec epoch. The difference in alpha power between right and left (F4 - F3) was then computed  
17 and compared against the threshold value established during the baseline. Participants were provided  
18 with a visual feedback consisting of a histogram reflecting the current frontal alpha asymmetry score.  
19 If the alpha asymmetry score was below the threshold, the histogram was red; when the asymmetry  
20 score exceeded the threshold (i.e., desired state), the histogram instantly turned green. The feedback  
21 was inhibited if ocular activity exceeded  $\pm 50 \mu V$ .

1 In the control condition, participants had the same visual feedback, but it reflected the  
2 changes in alpha power recorded at Fz electrode, instead of the frontal alpha asymmetry score.  
3 Before starting the training, participants were told that biofeedback training involved modifying the  
4 activity of their brain, and that they should try to maintain the histogram green as long as they could.  
5 Every time they maintained the desired EEG state for 10 sec (consecutive or not), a point was scored.  
6 It was explained to the participants that each point would correspond to 0.1 euros to add to the  
7 minimum payment of 10 euros for the participation. Participants were never told that the  
8 biofeedback was contingent on frontal alpha asymmetry and/or mid-frontal alpha.

9

#### 10 **EEG data processing**

11 The signal was down-sampled offline at 256 Hz, and continuous EEG data correction for  
12 eyeblinks was performed through a regression-based correction algorithm (LMS regression; Gómez-  
13 Herrero, 2007). Epochs of 500 ms each were then obtained from the continuous signal and EEG  
14 chunks containing artifacts greater than  $\pm 70 \mu\text{V}$  were automatically rejected (using EEGLAB plugin  
15 Darbeliai). Each EEG segment was further inspected for residual artifacts. For each accepted epoch, a  
16 Hamming windowing was applied and chunks were then overlapped by 50% to minimize loss of data.  
17 A Fast Fourier Transform (FFT) method was used to derive estimates of spectral power ( $\mu\text{V}^2$ ) for each  
18 electrode site. Power density values ( $\mu\text{V}^2/\text{Hz}$ ) were calculated averaging spectral power within the  
19 alpha band (8-13 Hz) for each participant at each site.

20

#### 21 **Statistics**

1 Alpha power at right (F4), left (F3) and midline (Fz) sites was  $\log_{10}$  transformed. After  
2 transformation, data were normally distributed, as assessed with the Kolmogorov–Smirnov-test.  
3 Alpha asymmetry was calculated subtracting the logarithm of alpha power at F3 site from F4 (i.e., F4 -  
4 F3).

5 Analyses of variance (ANOVAs) with Group (Asymmetry, Active control) as a between-subjects  
6 factor were used to compare the two groups in terms of age, education, and alpha power at each site.

7 Changes in resting frontal alpha asymmetry were evaluated running an ANOVA with Group as  
8 a between-subjects factor and Time (pre-training assessment, post-training assessment) as a within-  
9 subjects factor.

10 Changes in absolute alpha power at left and right sites were evaluated running an ANOVA with  
11 Group as a between-subjects factor, Time and Lateralization (F4, F3) as within-subjects factors. An  
12 ANOVA with Group as a between-subjects factor and Time as a within-subjects factor was run to test  
13 changes in alpha power in Fz. Separate ANOVAs with Group as a between-subjects factor and Time as  
14 a within-subjects factor were conducted on each psychological measure, namely the PANAS NA and  
15 PA scores, BAI and BDI-II.

16 Whenever the sphericity assumption was violated, the Greenhouse-Geisser correction was  
17 applied. Corrected p-values,  $\epsilon$  estimates and uncorrected degrees of freedom are reported. Tukey  
18 HSD test was used for post-hoc analyses. Main effects and interactions were considered to be  
19 significant at  $p < .05$ . Partial eta-squared ( $\eta_p^2$ ) was reported as a measure of the effect size. The  $\eta_p^2$   
20 values considered to represent small, medium, and large effects are .01, .06, and .14, respectively  
21 (Cohen, 1988).

1            In order to evaluate the relationship between training-induced changes in frontal alpha  
2 asymmetry, alpha power at left (F3) and right (F4) sites, and subjective measures, Pearson's  
3 correlations were performed between changes in these measures (post-training minus pre-training  
4 scores).

5            STATISTICA 6.1 software (StatSoft Inc, Tulsa, OK) was used for statistical analysis.

## 1 **Results**

### 2 *Characteristics of the Participants in the Asymmetry and Active Control Groups*

3 ANOVAs yielded no group differences for age ( $F_{(1, 30)} = 0.75, p = .40, \eta_p^2 = 0.02$ ), education ( $F_{(1, 30)} = 0.11, p = 0.74, \eta_p^2 = 0.004$ ), pre-training alpha at left ( $F_{(1,30)} = 0.27, p = .61, \eta_p^2 = 0.01$ ), midline ( $F_{(1, 30)} = 0.21, p = 0.65, \eta_p^2 = 0.01$ ) and right ( $F_{(1,30)} = 0.04, p = .83, \eta_p^2 = 0.001$ ) electrodes (i.e., F3, Fz and F4). The descriptive statistics for each group are reported in Table 1.

### 8 *Effects of Neurofeedback on EEG Measures*

9 From the ANOVA on frontal alpha asymmetry a significant Group  $\times$  Time interaction emerged  
10 ( $F_{(1, 30)} = 4.94, p < .05, \eta_p^2 = 0.14$ ), as depicted in Figure 1. In order to further characterize this  
11 interaction, changes in alpha power at left and right sites were analyzed, specifically, a Group by Time  
12 ANOVA on right (F4) and left (F3) alpha power was run. A significant effect for Lateralization ( $F_{(1, 30)} =$   
13  $8.26, p < .01, \varepsilon = .99, \eta_p^2 = 0.22$ ), in the context of a Group  $\times$  Time  $\times$  Lateralization interaction emerged  
14 ( $F_{(1, 30)} = 4.94, p < .05, \varepsilon = .99, \eta_p^2 = 0.14$ ; see Figure 2). Tukey post-hoc showed a significant increase in  
15 alpha power at right (F4) site from pre- to post-training in the asymmetry group ( $p < .001$ ), whereas  
16 no significant difference in alpha power at right (F4) and left (F3) sites from pre- to post-training was  
17 found in the active control group ( $p = .90$ ). No other main effects or interactions emerged (all  $p$ 's  $>$   
18  $.10$ ). ANOVA did not show any main effect for Group and Time or Group  $\times$  Time interaction on midline  
19 alpha (Fz) activity (all  $p$ 's  $> .17$ ).

20 In order to visualize the changes in frontal alpha asymmetry and alpha power at left and right  
21 sites, alpha power during baseline preceding each training session, after the first one, were extracted  
22 and plotted in Figure 3. Although there was variability across sessions, the linear trend supported the

1 increase in frontal alpha asymmetry from pre- to post-training in the asymmetry group, and a steeper  
2 gradient of increase in alpha power at right (F4) compared to left site (F3).

3 As complementary analyses, separate ANOVAs with Group as a between-subjects factor, Time  
4 and Lateralization as within-subjects factors were run for power changes in delta (0.5-4 Hz), theta (4-8  
5 Hz) and beta (13-30 Hz) bands. It emerged that the Group  $\times$  Time  $\times$  Laterality interaction was neither  
6 statistically significant for delta ( $F_{(1, 30)} = 1.99, p = .17, \epsilon = .99, \eta_p^2 = 0.06$ ) nor for theta bands ( $F_{(1, 30)} =$   
7  $1.85, p = .18, \epsilon = .99, \eta_p^2 = 0.06$ ). On the contrary, the Group  $\times$  Time interaction was significant for the  
8 beta band ( $F_{(1, 30)} = 6.75, p < .05, \epsilon = .99, \eta_p^2 = 0.18$ ), as determined by an increase in power from pre-  
9 to post-training at right, but not left, frontal site ( $p < .01$ ).

10

#### 11 *Effects of neurofeedback on Affect, Anxiety and Depressive symptoms*

12 ANOVA on PANAS Negative Affect scores showed a significant main effect for Time ( $F_{(1, 30)} =$   
13  $6.78, p < .05, \eta_p^2 = 0.18$ ) and a Group  $\times$  Time ( $F_{(1, 30)} = 4.13, p = .05, \eta_p^2 = 0.12$ ) interaction. Tukey post-  
14 hoc comparisons revealed a significant decrease in PANAS Negative Affect scores from pre- to post-  
15 training in the asymmetry group ( $p < .05$ ), whereas no significant difference in the NA-PANAS scores  
16 from pre- to post-training was found in the active control group ( $p = .98$ ). On the contrary, the group  
17 by time ANOVA on PANAS Positive Affect scores did not reveal any significant effect for Group ( $F_{(1, 30)}$   
18  $= 0.43, p = .52, \eta_p^2 = 0.01$ ), Time ( $F_{(1, 30)} = 1.10, p = .30, \eta_p^2 = 0.04$ ), and Group  $\times$  Time ( $F_{(1, 30)} = 0.12, p =$   
19  $.73, \eta_p^2 = 0.004$ ).

20 The Group  $\times$  Time ANOVA on BAI scores yielded a significant effect for Time ( $F_{(1, 30)} = 12.27, p <$   
21  $.01, \eta_p^2 = 0.29$ ), further characterized by a Group  $\times$  Time interaction ( $F_{(1, 30)} = 5.51, p < .05, \eta_p^2 = 0.16$ ).  
22 Tukey post-hoc comparisons showed a significant decrease in BAI scores from pre- to post-training in



1 the asymmetry group ( $p < .01$ ), whereas no significant difference in the BAI scores from pre- to post-  
2 training emerged in the active control group ( $p = .85$ ).

3 The Group  $\times$  Time ANOVA on BDI-II scores yielded a significant effect for Time ( $F_{(1, 30)} = 5.07$ ,  $p$   
4  $< .05$ ,  $\eta_p^2 = 0.14$ ). No main effect for Group or Group  $\times$  Time interaction emerged (all  $p$ 's  $> .19$ ). All  
5 means (SD) and statistical details are reported in Table 2.

6

### 7 *Correlational analyses*

8 No significant correlations emerged, after multiple comparisons correction, between changes  
9 in frontal alpha asymmetry (as well as changes in left and right absolute alpha power) and changes in  
10 subjective measures from pre- to post-training (see Table 3).

## 1 Discussion

2 The present findings support the efficacy of the frontal alpha asymmetry neurofeedback in  
3 *increasing the frontal alpha asymmetry index (F4 – F3)*, in line with previous research (Harmon-Jones  
4 et al., 2008; Peeters, Ronner, et al., 2014). More importantly, to our knowledge, this is the first study  
5 to report that this effect is subtended by a specific *reduction in the right frontal activity from pre- to*  
6 *post-training*, as revealed by a significant increase in alpha power at the right, but not left, scalp site.  
7 As far as the self-report measures are concerned, a significant decrease in negative affect emerged  
8 from pre- to post-training for the asymmetry group, but not for active controls, while positive affect  
9 showed no modulation. Furthermore, levels of anxiety were specifically reduced after the asymmetry  
10 neurofeedback, while no difference between groups emerged for changes in depressive symptoms.

11 These results align with the initial hypothesis that a decrease in right compared to left  
12 prefrontal activity would be associated with a reduction of negative affect and anxiety, which have  
13 been related to a dominance of the right over the left prefrontal cortex (Jacobs & Snyder, 1996;  
14 Schaffer et al., 1983; Tomarken et al., 1992). This is in line with the conceptualization that anxiety and  
15 negative affect manifest due to an increase in withdrawal motivation and heightened vigilance for  
16 threat, which has been shown to be subtended by prevalent right-sided frontal activation (Davidson,  
17 1998a; Mathersul, Williams, Hopkinson, & Kemp, 2008). In the same conceptualization, depressive  
18 symptoms are thought to be associated with a deficit in approach/appetitive motivation, as revealed  
19 by a left-sided reduction in prefrontal activity, compared to the right. Accordingly, in the present  
20 study, both positive affect and depressive symptoms were unaffected by the frontal asymmetry  
21 training, and this is mirrored by the absence of changes in left frontal activity.

1           Nonetheless, linear correlation between changes in frontal alpha asymmetry and changes in  
2 affective measures did not emerge. Although participants who underwent frontal alpha asymmetry  
3 training showed both a decrease in right frontal activity, and a parallel reduction in subjective  
4 measures of negative affect and anxiety, these changes were not linearly related. Several studies  
5 supported the idea that these measures are linearly related during the execution of emotional tasks  
6 (Coan, Allen, & Mcknight, 2006; Mennella et al., 2015; Stewart et al., 2011), but that this relationship  
7 may not emerge in resting conditions (Elgavish, Halpern, Dikman, & Allen, 2003; Hagemann,  
8 Naumann, Becker, Maier, & Bartussek, 1998; Heller & Nitscke, 1997; Hewig, Hagemann, Seifert,  
9 Naumann, & Bartussek, 2004; Hofmann, 2007; Reid, Duke, & Allen, 1998). In particular, the capability  
10 model of individual differences in frontal alpha asymmetry (Coan et al., 2006) suggests that approach  
11 and withdrawal motivational tendencies, as revealed by frontal alpha asymmetry, are more  
12 powerfully detected during an emotional challenge compared to resting conditions. On one hand, this  
13 may be due to the fact that emotional tasks actively stimulate motivational tendencies, which  
14 subtend each individual's affective style. On the other hand, measuring frontal EEG asymmetry in  
15 response to emotional stimuli or situations has been shown to reduce the contribution of  
16 uncontrolled variance due, for instance, to the choice of the reference electrode and other  
17 confounds. Accordingly, frontal alpha asymmetry during emotional tasks has been reported to predict  
18 affect and mood better than frontal alpha asymmetry at rest (Coan et al., 2006; Stewart et al., 2014).  
19 Therefore, future studies ought to investigate whether neurofeedback-related changes in EEG  
20 asymmetry, although not linearly related to unprovoked affect, predict state affect and emotional  
21 reactivity in emotional contexts. For instance, it would be worth investigating whether the observed  
22 increase in right frontal alpha would correlate with reduced negative affect in threatening situations,

1 as well as lower self-reported unpleasantness for threatening stimuli, as suggested by the capability  
2 model.

3 Overall, the present results suggest that the training could have an impact in reducing anxiety  
4 symptoms in clinical populations. Anxiety symptoms have been found to be associated with increased  
5 right compared to left frontal activity, as measured by frontal alpha asymmetry (Mathersul et al.,  
6 2008); also, this cortical pattern has been related to heightened negative affect and withdrawal  
7 tendencies (Shankman & Klein, 2003). Surprisingly, so far not many studies assessed the effects of  
8 frontal alpha asymmetry neurofeedback on anxiety symptoms. Results from the present study lay the  
9 foundations for a wider testing of the frontal alpha asymmetry protocol in clinical anxiety, providing a  
10 rationale for its application. Since we observed changes in frontal asymmetry at rest and in trait  
11 anxiety, this training may be helpful especially in conditions characterized by a trait-like increase in  
12 anxiety, such as the generalized anxiety disorder. As far as state-dependent anxiety is concerned,  
13 future studies ought to test whether reducing withdrawal motivation might be beneficial for a more  
14 adaptive response to threatening stimuli or situations. Therefore, the impact of asymmetry  
15 neurofeedback could also be assessed in psychopathologies associated with state-dependent  
16 increases in anxiety, such as phobias or panic disorder.

17 On the other hand, we hypothesize that, in order to have an impact on clinical depression,  
18 neurofeedback should be aimed at increasing left compared to right prefrontal activity, thus  
19 stimulating approach motivation and positive affect. Accordingly, depressed individuals are typically  
20 characterized by a left-sided prefrontal hypo-activation, compared to right (Davidson, 1998a, 2004).  
21 In line with this conceptualization, case report studies yielded positive results in the treatment of  
22 clinical depression by inhibiting slow alpha and theta activity while reinforcing higher frequencies at

1 left frontal sites (i.e., FP1 and F3) (Hammond, 2000, 2005). At the same time, the possibility that  
2 clinically depressed patients would benefit from the alpha asymmetry training cannot be ruled out. It  
3 is conceivable that the pre-existent left-sided hypo-activation in depressed patients would interact  
4 with the effect of the training. For instance, in depressed individuals, the same training could  
5 decrease alpha at left vs. right sites, in contrast with the pattern observed in our sample, thus being  
6 beneficial. In this regard, a small number of case studies supported the effectiveness of the frontal  
7 alpha asymmetry training in reducing depressive symptoms, although no specific information on  
8 hemispheric modulation (left or right frontal) was provided (Baehr & Baehr, 1997; Baehr, Rosenfeld, &  
9 Baehr, 1997, 2001; Choi et al., 2011; Earnest, 1999; Peeters, Oehlen, Ronner, Van Os, & Lousberg,  
10 2014). Therefore, the training ought to be run on both anxious and depressed patients, in order to  
11 discriminate its specific effects. Importantly, there is a strong need for a control condition such as the  
12 one employed in the present work, since the vast majority of studies in the field are still uncontrolled  
13 (Baehr & Baehr, 1997; Baehr et al., 1997, 2001; Choi et al., 2011; Earnest, 1999; Hammond, 2000,  
14 2005; Hammond & Baehr, 2009; Peeters, Oehlen, et al., 2014). Of note, in the present study, no  
15 modulation in negative affect and anxiety was observed in the control condition. It is worth  
16 highlighting that neurofeedback to increase alpha power has been traditionally used for the reduction  
17 of stress and anxious symptoms (Brown, 1970; Hammond, 2005; Hardt & Kamiya, 1978), targeting the  
18 occipital and parietal sites. Since no modulation of mid-frontal alpha emerged in the present study,  
19 neurofeedback for the increase of alpha power at mid-frontal sites seems less effective compared to  
20 posterior sites, therefore representing an ideal control condition for the frontal alpha asymmetry  
21 training.

1 Complementary analyses on frontal asymmetry in other EEG bands showed that the effect in  
2 alpha band extended to beta, but not delta and theta rhythms. In other words, the training was  
3 associated with an increase in both right frontal alpha and beta power. It has been previously  
4 reported that the effects of the frontal alpha asymmetry neurofeedback extended to beta band  
5 (Peeters, Ronner, et al., 2014). Intriguingly, a number of studies supported the notion that both alpha  
6 and beta bands are inversely correlated with the activation of the underlying neural structures, as  
7 measured by functional resonance imaging, both at rest (Moosmann et al., 2003) and during  
8 cognitive/motor tasks (Scheeringa et al., 2011; Yuan et al., 2010). Therefore, it can be speculated that  
9 changes in alpha and beta power reflect a similar training-induced modification. Nonetheless, some  
10 authors reported that correlation between BOLD fluctuations and alpha/beta bands are independent  
11 from each other, possibly mirroring different underlying processes (Scheeringa et al., 2011). This issue  
12 needs to be specifically addressed by future studies, looking at how training-related modifications in  
13 different EEG bands are associated to underlying BOLD fluctuations.

14 The present findings ought to be interpreted in light of some limitations. Firstly, self-report  
15 measures were only collected at pre- and post-training, thus not allowing for a session-by-session  
16 correlation between EEG and subjective measures of affect. This may mitigate the relationship  
17 between changes in asymmetry and changes in self-reported affect, thus potentially explaining null  
18 correlational findings. Nonetheless, our main aim was to evaluate the effectiveness of a short training  
19 on alpha asymmetry and negative affect at a group level, as a first step toward future clinical  
20 application. Evidence for training effectiveness adds to the literature in this field, suggesting that  
21 future studies ought to examine day-by-day changes in clinical populations, and to attest the stability  
22 of the effect through follow-up assessments. Secondly, regarding the method, the Cz reference has

1 been shown not to be ideal for obtaining a measure of frontal alpha uncontaminated by volume-  
2 conducted alpha from other regions (Hagemann, 2004; Hagemann, Naumann, & Thayer, 2001;  
3 Stewart, Bismark, Towers, Coan, & Allen, 2010), although this reference scheme has been employed  
4 in previous neurofeedback studies on frontal alpha asymmetry (Allen et al., 2001; Harmon-Jones et  
5 al., 2008). The current-source-density (CSD) transform of EEG data has been reported to attenuate  
6 the risk that alpha generators in different brain regions impact on the measurements of alpha  
7 asymmetry at frontal sites, providing more consistent results concerning the association between  
8 alpha asymmetry and affective measures (Stewart et al., 2010, 2014). Therefore, future studies ought  
9 to better clarify whether the effects of the training survive when other reference schemes are used.

10 In summary, the present study argues in favor of the employment of frontal alpha asymmetry  
11 neurofeedback to increase right vs. left frontal alpha activity, in order to reduce negative affect and  
12 anxiety levels, laying the foundations for testing on subclinical and clinical populations. On the other  
13 hand, we suggest that future research should investigate the effects of neurofeedback training aimed  
14 at increasing left vs. right prefrontal activity on approach motivation, positive affect and depressive  
15 symptoms.

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19

1 **Tables**

2 **Table 1.** Demographics and pre-training log-transformed alpha power at frontal sites for the  
3 Asymmetry and the Active Control groups.

<b>Variables</b>	<b>Asymmetry group (N = 16)</b>	<b>Active control group (N = 16)</b>
<b>Demographics</b>		
Age (years)	22.9 (1.2)	23.3 (1.2)
Education (years)	17.2 (1.1)	17.2 (1.0)
<b>Alpha power (<math>\mu\text{V}^2/\text{Hz}</math>) pre-training</b>		
F3	0.69 (0.3)	0.63 (0.3)
Fz	0.45 (0.3)	0.40 (0.3)
F4	0.62 (0.3)	0.60 (0.3)

4 *Notes:* Data are *M (SD)*. F3 = left frontal site; Fz = mid-frontal site; F4 = right frontal site.

5

1 **Table 2.** ANOVA on Positive and Negative Affect, Anxiety and Depression Scores from Pre- to Post-  
 2 training in Asymmetry Group and Active Control.

Variables	Pre-training	Post-training	<i>p</i>	$\eta_p^2$
<b>PANAS Positive Affect Score</b>			.73 <sup>a</sup>	0.004 <sup>a</sup>
Asymmetry Group	27.56 (10.35)	29.19 (6.53)		
Active Control	29.94 (8.87)	30.75 (10.20)		
<b>PANAS Negative Affect Score</b>			.05 <sup>a</sup>	0.12 <sup>a</sup>
Asymmetry Group	19.25 (9.03)	14.69 (6.46)	< .01 <sup>b</sup>	
Active Control	18.44 (6.64)	17.88 (8.58)	.69 <sup>b</sup>	
<b>BAI</b>			< .05 <sup>a</sup>	0.16 <sup>a</sup>
Asymmetry Group	11.38 (9.56)	6.00 (5.56)	< .001 <sup>b</sup>	
Active Control	10.19 (9.39)	9.13 (8.00)	.42 <sup>b</sup>	
<b>BDI-II</b>			.19 <sup>a</sup>	0.06 <sup>a</sup>
Asymmetry Group	9.75 (12.38)	6.00 (7.90)		
Active Control	8.13 (7.30)	7.19 (9.59)		

3 *Notes:* Data are *M (SD)*. <sup>a</sup> = *p*-values and partial eta-squared referred to the Group × Time interaction  
 4 for the corresponding measure. <sup>b</sup> = *p*-values associated to post-hoc comparisons in the context of a  
 5 statistically significant Group × Time interaction (not reported for non-significant interactions).  
 6 ANOVA = analysis of variance; PANAS = Positive and Negative Affect Schedule; BAI = Beck Anxiety  
 7 Inventory; BDI-II = Beck Depression Inventory II.

8

1 **Table 3.** Pearson's (r) correlation coefficients between changes in alpha power at F3, F4 and  
 2 asymmetry scores and changes in Positive and Negative Affect, Anxiety, and Depression Scores from  
 3 pre- to post-training in Asymmetry Group and Active Control.

		PA		NA		BAI		BDI-II	
		r	p	r	p	r	p	r	p
<b>Asymmetry Group</b>	<b>F3</b>	-0.01	.97	-0.04	.87	0.31	.25	0.14	.60
	<b>F4</b>	0.03	.91	-0.25	.36	0.16	.56	0.13	.62
	<b>F4 - F3</b>	0.05	.87	-0.25	.34	-0.05	.84	0.04	.87
<b>Active Control</b>	<b>F3</b>	0.28	.29	0.13	.62	0.15	.57	-0.23	.39
	<b>F4</b>	0.09	.73	0.23	.39	0.37	.16	-0.18	.51
	<b>F4 - F3</b>	-0.32	.23	0.27	.31	0.54	.03	0.04	.89

4 *Notes:* PA = Positive Affect scale of the PANAS; NA = Negative Affect scale of the PANAS; BAI = Beck  
 5 Anxiety Inventory; BDI-II = Beck Depression Inventory II. *p* = p-values (uncorrected for multiple  
 6 comparisons).

1 **Figures**

2 **Figure 1 Neurofeedback modulation of alpha asymmetry:** the Asymmetry Group, but not the Active  
3 Control, showed a significant increase in alpha asymmetry from pre- to post-training. Error bars  
4 represent the standard error of the mean.

5 **Figure 2 Neurofeedback modulation of left and right alpha power:** the Asymmetry Group, but not  
6 the Active Control, showed a significant increase in resting alpha power at F4, but not F3, from pre- to  
7 post-training. Error bars represent the standard error of the mean.

8 **Figure 3 Session-by-session changes in frontal alpha asymmetry and in absolute alpha power at F3  
9 and F4:** the Asymmetry Group showed a linear positive trend in alpha asymmetry during the training  
10 (*top*), sustained by a steeper increase in alpha power at F4 compared to controls (*bottom*).  $TN =$   
11 baseline preceding neurofeedback session number  $N$ . Error bars represent the standard error of the  
12 mean.