Manipulation of frontal EEG asymmetry through biofeedback alters self-reported emotional responses and facial EMG

JOHN J.B. ALLEN,[a] EDDIE HARMON-JONES,[b] AND JAMES H. CAVENDER[a]

[a]Department of Psychology, University of Arizona, Tucson, USA
[b]University of Wisconsin, Madison, USA

Abstract

Individual differences in resting asymmetrical frontal brain activity have been found to predict subsequent emotional responses. The question of whether frontal brain asymmetry can cause emotional responses has yet to be addressed. Biofeedback training designed to alter the asymmetry of frontal brain activity was therefore examined. Eighteen right-handed female participants were randomly assigned to receive biofeedback training designed to increase right frontal alpha relative to left frontal alpha ($n = 9$) or to receive training in the opposite direction ($n = 9$). Five consecutive days of biofeedback training provided signals of reward or nonreward depending on whether the difference between right (F4) and left (F3) frontal alpha exceeded a criterion value in the specified direction. Systematic alterations of frontal EEG asymmetry were observed as a function of biofeedback training. Moreover, subsequent self-reported affect and facial muscle activity in response to emotionally evocative film clips were influenced by the direction of biofeedback training.

Descriptors: Frontal EEG asymmetry, Biofeedback, Emotion, Approach-withdrawal model

Asymmetrical activation of the anterior cortical regions appears to influence emotional responding, with left hemisphere activity relating to approach-related emotional responses and right hemisphere activity relating to withdrawal-related emotional responses. This observation is based on studies that have examined relationships between individual difference measures and resting cortical electroencephalographic (EEG) activity—particularly in the alpha frequency band, which is inversely associated with cortical activation. To illustrate, less right than left frontal alpha (i.e. increased relative right activity) is seen in depression and those with a history of depression (Allen, Iacono, Depue, & Arbisi, 1993; Gotlib, Ranganath, & Rosenfeld, 1998; Henriques & Davidson, 1990, 1991), and in those with Panic Disorder (Wiedemann et al., 1999). The opposite pattern is seen in individuals high in trait anger (Harmon-Jones & Allen, 1998), and those high in behavioral approach sensitivity (Harmon-Jones & Allen, 1997).

Individual differences in resting frontal EEG asymmetry have also been found to predict subsequent emotional responses in a wide variety of contexts. For example, a consistent pattern of relatively greater right midfrontal activity (compared to left) characterizes those participants who later show larger negative and smaller positive affective responses to emotional film clips (e.g., Wheeler, Davidson, & Tomarken, 1993). Additionally, infants with decreased left midfrontal activity have been found to be more likely to cry in response to maternal separation (Davidson & Fox, 1989). Collectively, these findings (and others) support the hypothesis that resting frontal EEG asymmetry taps a fundamental dimension of temperament or affective style related to risk for depression (Coan & Allen, in press; Davidson, 1993, 1998; Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997), and that the asymmetry—depending on its magnitude and direction—taps a propensity to respond to emotionally evocative events with predictable emotional responses.

Although the neurophysiological underpinnings of this model remain to be fully elucidated, individual differences in and alterations of asymmetrical frontal brain activity are likely to be functional, and not the result of underlying structural differences (Davidson, 1998). Several authors (e.g. Davidson, 1998; Harmon-Jones & Allen, 1997, 1998; Sutton & Davidson, 1997; Wiedemann et al., 1999) have suggested that these frontal asymmetries tap not positive or negative affect per se, but a broader motivational tendency towards approach-related or withdrawal-related behaviors and emotions. In this view, depression and sad states represent a reduction in the left-frontally mediated propensity to approach and engage with the environment, and panic and fear represent a

right-frontally mediated propensity to withdraw from the environment. In assessing the adequacy of the theoretical accounts of frontal brain asymmetry, emotions such as sadness and fear are not especially informative, as valence and motivational tendency are confounded; that is, both a valence explanation and a motivational explanation would make similar predictions. Recent research with the emotion of anger, a negatively valenced but approach-related emotion, has suggested that the motivational model is a more adequate explanation for the pattern of data. Whereas a valence explanation would predict that anger, like other negatively valenced emotions, is characterized by relative right frontal activation, a motivational explanation would predict that anger is characterized by relative left frontal activation. Recent data (Harmon-Jones & Allen, 1998; Harmon-Jones & Sigelman, 2001) are consistent with the motivational explanation.

The Present Study

Although previous research provides support for the hypothesis that asymmetrical resting frontal brain activity influences the propensity to respond with relatively greater emotional responses associated with approach and withdrawal motivation, the findings are not definitive, for studies have merely examined the correlation between resting EEG and emotional responding—an approach that does not warrant causal inferences. Stronger support for the hypothesis that the asymmetrical activation of the anterior cortical regions causally influences responses to emotionally evocative stimuli would be found in an experiment in which the anterior asymmetry was manipulated and the effects of this manipulation on emotional responding were then observed. This is the approach adopted in the present study.

Biofeedback training has proven successful in altering EEG asymmetry in a variety of contexts (Baehr, Rosenfeld, & Baehr, 1997; Hardman et al., 1997; Rosenfeld, Cha, Blair, & Gotlib, 1995; Schwartz, Davidson, & Pugash, 1976). Although evidence suggests that changes in resting frontal asymmetry covary with changes in mood state in patients undergoing biofeedback treatment for depression (Baehr et al.), this evidence is not unequivocally causal in nature, as these clinical case studies involved no control groups and participants received treatments in addition to biofeedback. Moreover, these studies trained participants in only the direction hypothesized to be therapeutic (increasing relative left frontal activity), but never in the opposite direction; this leaves open the possibility that the nonspecific aspects of the biofeedback training protocol, and not its specific effects on cortical activation, were therapeutic. The present study therefore sought to determine whether manipulation of frontal asymmetry was causally related to emotional responding. Specifically, it sought to determine whether EEG change could be obtained in both directions: increasing right-versus-left alpha power, and decreasing right-versus-left alpha power. To determine whether alteration of frontal EEG asymmetry could alter subsequent emotional responses, participants viewed emotionally evocative film clips after the conclusion of training and reported their affective responses to the films.

In addition to self-report measures of affective responses to films, facial electromyographic (EMG) responses over the corrugator and zygomatic muscle regions were selected for use in the present study. Corrugator region activity was selected as a measure of negative affect, and zygomatic region activity as a measure of positive affect, consistent with research showing activity in these regions to be associated with the experience (Cacioppo, Martzke, Petty, & Tassinary, 1988; Cacioppo, Petty, Losch, & Kim, 1986) and perception (Dimberg, 1982, 1990; Dimberg, Thunberg, &

Elmehed, 2000) of negative affect and positive affect, respectively. Facial EMG provides a second and independent measure of any potential effects of manipulating frontal EEG asymmetry, and can provide a relatively covert and sensitive measure of emotional expression (Cacioppo, Klein, Berntson, & Hatfield, 1993; Dimberg, 1990; Harmon-Jones & Allen, 2001). EMG is sensitive to even minute contractions of the facial musculature that produce motor action potentials (Cacioppo, Tassinary, & Fridlund, 1990), often in cases where no observable change in facial expression can be detected (Cacioppo et al., 1986; Schwartz, Brown, & Ahern, 1980).

Method

Participants

Eighteen strongly right-handed women aged 18–38 participated for introductory psychology course credit and monetary remuneration (Handedness scale range = 36–39; Chapman & Chapman, 1987). Participants were randomly assigned to receive biofeedback designed to increase right relative to left frontal alpha ($n = 9$) or to receive biofeedback designed to decrease right relative to left frontal alpha ($n = 9$). Because alpha activity relates inversely with cortical activity, increasing right relative to left frontal alpha should increase left relative to right cortical activity. This training direction group will be referred to as "LEFT," as training in this direction should increase left compared to right frontal activity; theory would suggest that training in this direction should lead to more approach-related responses. The other training direction group will be termed "RIGHT," as training in this direction should increase right compared to left frontal activity; theory would suggest that training in this direction should lead to more withdrawal-related responses. Thus training groups were named according not to the relative direction of alpha change, but the inferred direction of change in cortical activation.

Procedure and Materials

Participants visited the laboratory on five consecutive afternoons or evenings, starting each session within the same 3-hr time window. Whereas all days involved biofeedback training, the first and last day involved viewing of short film clips to elicit emotion before the start of training on Day 1, and after its conclusion on Day 5. This pre–post design allowed for responses during the film—both self-report and facial EMG responses—to serve as dependent measures of the impact of manipulating EEG asymmetry with biofeedback training.

On the first day, after obtaining informed consent, participants were fitted with a stretch-lycra cap to record electroencephalographic (EEG) activity and with facial electrodes to monitor eye movements and to record electromyographic (EMG) activity. Participants were then escorted to the adjacent sound-dampened dimly lit recording room where they viewed three short silent films that were pretested to elicit happy, neutral, or sad emotional responses (Tomarken, Davidson, & Henriques, 1990). Films were presented in one of two orders randomized across participants: happy–neutral–sad, or sad—neutral–happy. Facial EMG was recorded for 1 min during each film, coinciding with the point in the film that pretesting indicated should elicit the target emotion. Participants rated their emotional responses following each film using a 9-point scale for each of the following emotions: interest, amusement, happiness, sadness, fear, disgust, and anger.

Biofeedback Training

Following the film viewing and emotion rating, biofeedback training began.[1] On the first day only, training began with a baseline session in which noncontingent feedback was delivered, with reward tones presented randomly for 20% of the time. The purpose of this session was to establish the baseline asymmetry in a training-like environment. This baseline asymmetry was then used to compute the criterion for contingent feedback in the subsequent training trial.

Five 6-min biofeedback training blocks followed, with a 1-min break between blocks. Each block involved 150 2-s epochs. During the first second of each 2-s epoch, EEG data were sampled at 256 Hz. Alpha power (8–13 Hz) was then computed at right (F4) and left (F3) frontal leads using a fast Fourier transform algorithm with a Hamming window function. The difference in alpha power between right and left (R − L) was then computed and compared against the criterion value (see below) established for that block. If the R − L alpha power difference exceeded the criterion value in the desired direction, a 300 Hz reward tone was played over the audio speakers; if the criterion was not exceeded, a 150 Hz non-reward tone was played over the audio speakers. Tones were continuous, such that onset of one tone coincided with the offset of the previous tone. Epochs where ocular activity exceeded 50 μV resulted in no tone for the next 2 s, and the data from those epochs were not analyzed. Epochs where EEG activity exceeded the input range of the A-D card also halted tones for 2 s and were excluded. Following each block of 150 epochs, the mean R − L value and standard deviation were calculated. The criterion value for the next training block was then defined in terms of each participant's previous mean and standard deviation. For LEFT participants, reward tones were presented when the R − L alpha value exceeded the criterion of the mean + 0.85 standard deviations; for RIGHT participants, reward tones were presented when the R − L alpha value was less than the criterion of the mean − 0.85 standard deviations. This criterion value should, assuming a normal distribution of right–left values across the 150 epochs, result in reinforcement on approximately 20% of the trials (Rosenfeld et al., 1995). Moreover, by adjusting the criterion for each training block, the rate of reinforcement should remain relatively constant, regardless of whether participants are altering their right–left asymmetry scores. This strategy of constantly adjusting the training criterion should keep the rate of reward, which itself could alter emotion, comparable for all subjects regardless of their success in altering EEG asymmetry, and regardless of whether subjects were trained in the LEFT or RIGHT direction.

During training, participants were told that biofeedback training involved using the activity of their brains to cause a computer to generate high or low tones, and that they should try to make the high tone stay on. Participants were also informed that occasionally the tone might stop altogether and, that if this happens, they should simply resume their focus on keeping the high tone on. Participants were never explicitly told that the biofeedback was contingent on asymmetry, nor were they told that excessive ocular activity caused the "time outs." No explicit verbal feedback was provided to participants concerning their performance. Following each day of training, participants completed the Positive and Negative Affect Schedule—state version (PANAS; Watson, Clark, & Tellegen, 1988) to assess current mood.

For the second through fifth days, five 6-min biofeedback training blocks were conducted as previously described. The criterion value for the first block of each day was based upon the mean and standard deviation of the previous day's final block. On the fifth and final day, following the five training blocks, participants once again viewed the three short silent films in one of two orders randomized across participants, and rated their emotional responses following each film.

Psychophysiological Recording and Quantification

Electroencephalographic (EEG) and electrooculographic signals were recorded on all five days. Additionally, during the film clips shown on the first and the fifth day, facial EMG signals over corrugator and zygomatic muscle regions were recorded. EEG signals were processed as described above in the section describing biofeedback training, whereas EMG signals were processed as described below.

Recording. EEG signals were recorded with tin electrodes in a stretch-lycra cap from sites F3 and F4 referenced on-line to Cz.[2] Electrode impedances, for these EEG leads as well as all other leads to be described below, were less than 5 KΩ, and F3 and F4 were within 1 KΩ of one another. EEG signals were amplified by a factor of 20,000 with AC differential amplifiers (bandpass 0.1–30 Hz) and digitized at 256 Hz. Facial EMG signals were recorded with miniature Ag/Ag-Cl electrodes attached bilaterally in pairs over the corrugator supercilii and zygomaticus major muscle regions, using placements as described by Fridlund and Cacioppo (1986). Bipolar EMG signals were amplified by a factor of 20,000 with AC differential amplifiers (bandpass 0.1 and 1,000 Hz), and digitized continuously at 1024 Hz. To monitor eye movements, Ag-AgCl electrodes were affixed to the superior orbit and inferior orbit (amplification = 5 K, bandpass = 0.1–30 Hz) and digitized at 256 Hz.

Quantification of EMG. EMG data, recorded only on Day 1 and Day 5 during the presentation of the three films, were high-pass filtered (1/2 amplitude frequency = 10 Hz), and rectified off-line. Signals were then segmented into 2-s epochs. The mean rectified activity across all artifact-free epochs for a given film clip was taken as the index of EMG activity. These indices were then Z-transformed within each participant and each muscle region (using the six data points—three films before training and three after); Z-transformations preserve the pattern of response for each participant across films and time, while minimizing overall differences between participants in muscle activity.

Results

EEG Training Effects

Frontal asymmetry scores (R − L alpha) were first baseline adjusted for each participant, reflecting changes in asymmetry from

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[1] Biofeedback training was controlled by a PC-compatible computer program generously provided by Peter Rosenfeld.

[2] Several reference montages have been used in the research literature of EEG asymmetry and emotion, and the correspondence between asymmetry scores from data collected using different montages can vary substantially (see Reid, Duke, & Allen, 1998). Although it is increasingly common, and desirable, to analyze EEG asymmetry data derived from several off-line re-referenced montages (e.g., computer-averaged mastoids, average reference, Cz reference), this strategy to date has not demonstrated a clear superiority of one reference montage (Reid et al., 1998). Given that in the present study feedback was to be presented on-line, the feedback needed to be provided on the basis of EEG asymmetry scores derived from a single reference montage.
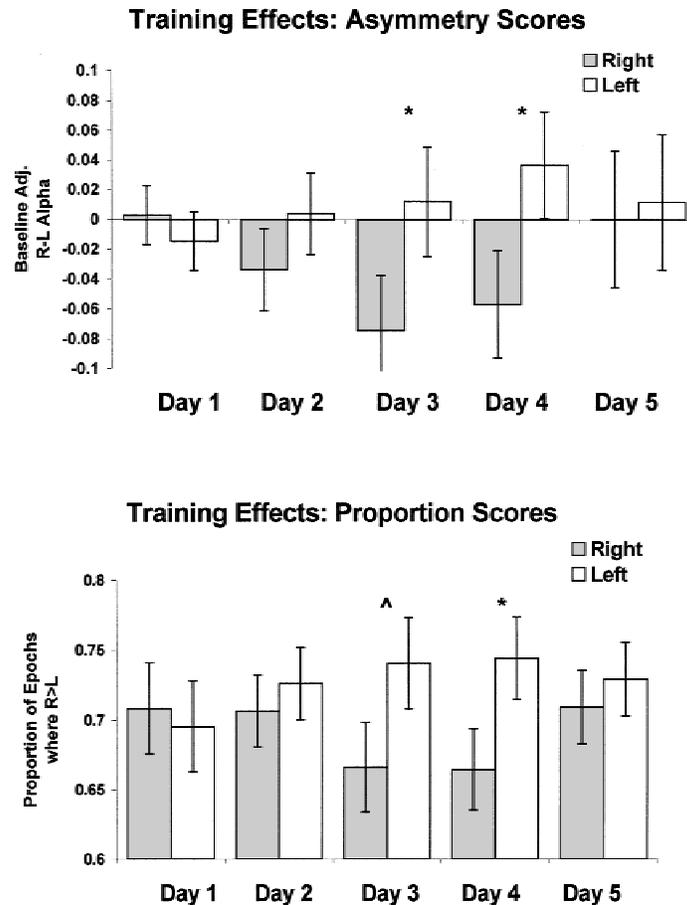
Training Effects: Asymmetry Scores

Training Effects: Proportion Scores

Figure 1. Top panel displays EEG R − L alpha asymmetry (± *SE*) as a function of training day. Higher numbers on the Y axis reflect greater right than left frontal alpha, and therefore putatively greater left than right frontal activity. Lower panel displays the proportion of time that the asymmetry score (R − L alpha) was greater than zero. Asterisks signify that participants trained LEFT (open bars) differed significantly from those trained RIGHT (shaded bars) and the ∧ symbol indicates the difference between the two groups approached significance (*p* < .06).

the baseline obtained during noncontingent reinforcement prior to the start of biofeedback training. The LEFT (mean = 0.23) and RIGHT (mean = 0.15) groups did not differ on this baseline asymmetry score, $F(1,16) = 1.49$, *ns*. Asymmetry scores were analyzed in a Direction (RIGHT/LEFT) × Day (1–5) × Block (1–5 within each day) repeated measures analysis of variance (ANOVA). In the absence of any significant main effects or other interactions, a significant Direction × Day interaction emerged, $F(4,64) = 2.58$, $p < .05$, which was marginally significant following Greenhouse–Geisser (G-G) epsilon correction, $\epsilon = .64$, $p < .07$. Planned comparisons between the two groups on each day of training revealed that those participants trained RIGHT differed from those trained LEFT on days 3 and 4, $ps < .01$ (see upper panel of Figure 1). Within each group, comparing training on Days 2–5 to that on Day 1 revealed that for participants trained RIGHT, significant training effects emerged on Days 3 and 4, $ps < .05$, whereas no significant training effect was evident for participants trained LEFT.

It has been reported that a potentially better index of frontal EEG asymmetry is the percentage of time that the alpha asymmetry score is greater than zero (i.e., R − L > 0; Baehr, Rosenfeld,

Baehr, & Earnest, 1998).[3] Therefore, this percentage was examined in a Direction (RIGHT/LEFT) × Day (1–5) × Block (1–5 within each day) repeated measures ANOVA. In the absence of any significant main effects or other interactions, a significant Direction × Day interaction emerged, $F(4,64) = 3.04$, $p < .05$, which remained significant following G-G epsilon correction, $\epsilon = .63$, $p < .05$. Planned comparisons between the two groups on each day of training revealed that those participants trained RIGHT differed from those trained LEFT on Days 3 and 4, $ps < .01$ (see lower panel of Figure 1). Within each group, comparing training on Days 2–5 to that on Day 1 revealed that for participants trained RIGHT, significant training effects emerged on Day 4, $p < .05$, and a marginally significant effect emerged on Day 3, $p < .06$, whereas

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[3]Baehr et al. (1998) used a slightly different metric, namely a ratio score of (R − L)/(R + L) > 0. This metric may be preferred because the R − L metric can change with changes in overall alpha in both hemispheres, whereas this concern is mitigated (but not eliminated) through the use of the ratio score. On the other hand, for the purpose of the present analysis, this is not of great concern, for any time that R − L is greater than zero, so too would the ratio (R − L)/(R + L).

once again no significant training effect was evident for participants trained LEFT.

These training effects were not the result of differential rates of reinforcement, as LEFT participants and RIGHT participants differed neither in the rates of reinforcement (LEFT receiving reinforcement on 13.8% ± 2.1% [mean ± *SD*] of trials; RIGHT receiving 13.7% ± 2.5%), nor in frequency of time-outs (LEFT 2.2 ± 2.0 times per trial; RIGHT 2.5 ± 2.3 times). A significant decrease in time-outs across days for all participants, $F(4, 64) = 3.72$, $p < .01$, indicated that participants made fewer large ocular movements as training proceeded. Additionally, there was a trend for reinforcement rate to vary by day, $F(4, 64) = 1.96$, $p = .14$, G-G corrected, but this trend appeared to be accounted for entirely by a low rate of reinforcement on the last day. When reinforcement rate on Day 5 was directly compared to the mean rate on Days 1–4, reinforcement rate on Day 5 was found to be significantly lower than the average of the preceding days, $F(1, 16) = 12.73$, $p < .01$.

In sum, frontal EEG asymmetry was altered as a function of direction of training. It did not appear to be altered as a result of differential reinforcement or time-outs. All participants, however, received a lower rate of reinforcement on the final day of training, a point that will be further discussed subsequently.

Self-Reported Emotion

For each film, participants rated seven self-reported emotions: interest, amusement, happiness, sadness, fear, disgust, and anger. Figure 2 presents mean self-report ratings for each emotion for each film after training as a function of training direction. Responses to each film were analyzed in a Direction (RIGHT/LEFT) × Emotion (seven levels) × Day (pre/post training) repeated measures ANOVA. The interaction between direction, day, and emotion was of interest, as it would reflect a different pattern of emotional responding as a function of training. This interaction was significant for the happy film, $F(6, 96) = 3.00$, $p < .01$, but not for the neutral film, $F(6, 96) = .81$, *ns*, or the sad film, $F(6, 96) = .40$, *ns*. Simple effects analyses for the happy film indicated that whereas there were no differences in the pattern of emotional responses between LEFT and RIGHT participants in emotional responses prior to training (Direction × Emotion $F[6, 96] = 0.80$, *ns*), the pattern of emotional responses following training differed for the LEFT and RIGHT participants (Direction × Emotion $F[6, 96] = 4.56$, $p < .001$). Planned comparisons revealed this effect was accounted for by RIGHT participants reporting significantly less ($p < .01$) interest, amusement, and happiness than LEFT participants.

In addition to self-report measures of mood in response to films, daily mood measures were also obtained daily using the PANAS. Several studies have found that EEG asymmetry is not related to resting unprovoked mood in nonclinical samples (e.g. Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997; Wheeler et al., 1993). To assess whether manipulation of frontal EEG asymmetry affected unprovoked mood, PANAS scores, which were obtained following each day's training, were subjected to a 2 (Direction) × 5 (Day) × 2 (Valence: positive or negative affect) repeated measures ANOVA. The only significant effect to emerge from this analysis was a main effect of Valence, $F(1, 16) = 31.8$, $p < .001$, which indicated that all participants reported significantly higher positive affect, $M = 21.5$, than negative affect, $M = 13.2$, across all days. All other effects in the analysis were far from statistical significance, all Fs < 1.22.

Thus self-reported affect elicited by one of the two emotionally evocative films was influenced by direction of training. Consistent with other reports, however, unprovoked state mood on each day
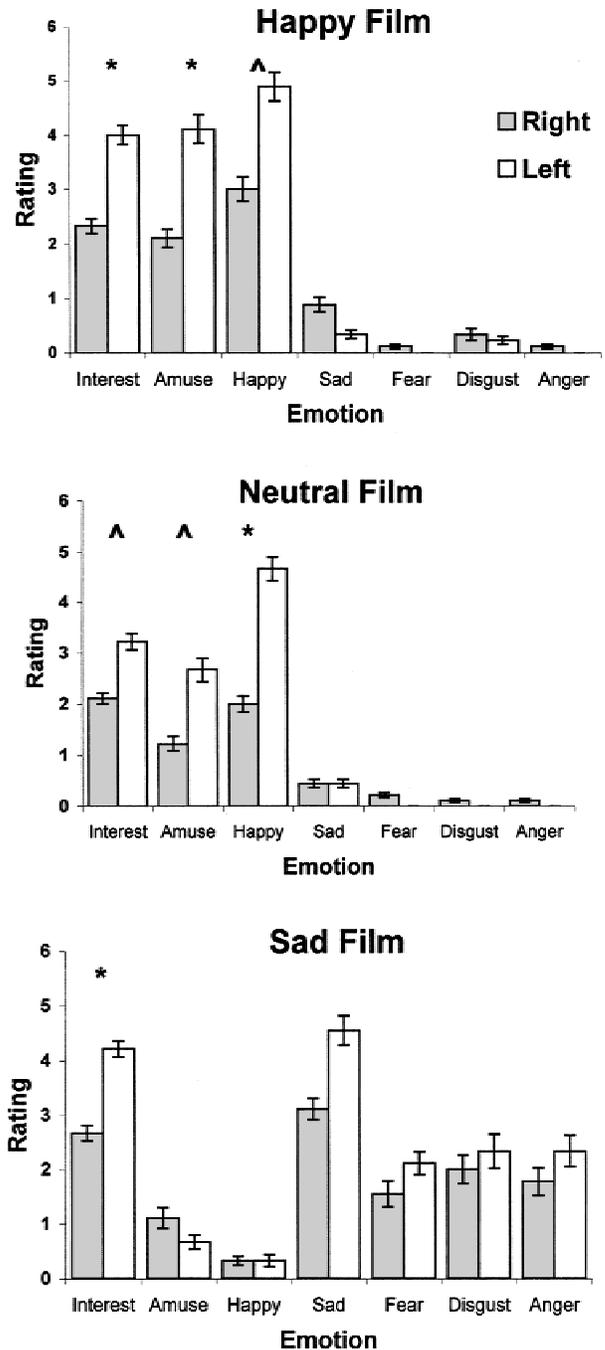

Figure 2. Ratings of the extent to which participants experienced various emotions while watching film clips following biofeedback training. Asterisk indicates LEFT (open bars) participants differed significantly ($p < .05$ *t* test) from RIGHT (shaded bars) participants, and the ∧ symbol indicates the difference between the two groups approached significance ($p < .10$). Note that several bars for the LEFT participants depict a value of zero (happy film ratings of fear and anger, and neutral film ratings of fear, disgust, and anger).

of training was not impacted by direction of training. This latter finding suggests that the differences between groups in self-reported emotional responses to films following training were not merely a reflection of mood-state differences between training groups, or mood state differences that resulted from training.

Facial Muscle Activity During Films

Z-transformed EMG scores were analyzed in a Training Direction $\times$ Day (pre, post) $\times$ Muscle Region (zygomatic, corrugator) $\times$ Film Valence (happy, neutral, sad) repeated measures ANOVA. As a validity check, the Film Valence $\times$ Muscle Region interaction was significant, $F(2,32) = 18.45$, $p < .001$, G-G corrected, providing support that facial EMG is sensitive to emotional valence. Planned comparisons indicated that zygomatic activity was greater, $p < .01$, during the positive film (mean $Z = .52$) than the neutral film (mean $Z = -.21$) or negative films (mean $Z = -.30$) the latter not differing ($p > .65$) from one another. Corrugator activity, by contrast, was significantly greater, $p < .001$, during the sad film (mean $Z = .62$) than during the neutral (mean $Z = -.29$) or happy films (mean $Z = -.33$) the latter not differing ($p > .85$) from one another.

The hypothesized Direction $\times$ Time $\times$ Muscle-Region interaction was significant, $F(1,16) = 6.82$; $p < .05$ (see Figure 3), but this was not moderated by a higher order four-way interaction with

Figure 3. Muscle activity in the zygomatic and corrugator regions during film viewing, before and after biofeedback training. Participants trained RIGHT (shaded bars) evidenced significantly less zygomatic activity as a function of training, whereas participants trained LEFT (open bars) evidenced significantly less corrugator activity as a function of training.

Film Type, $F(2,32) = .57$, ns. Planned comparisons indicated that whereas RIGHT participants produced less, $p < .01$, zygomatic ("smile") activity following training, LEFT participants produced less, $p < .05$, corrugator ("frown") activity following training; RIGHT participants demonstrated no change in corrugator activity, whereas LEFT participants demonstrated no change in zygomatic activity. Thus training decreased muscle activity typically associated with positive affect in the RIGHT participants, while decreasing the muscle activity associated with negative affect in the LEFT participants.

Exploring How Emotion and EMG Effects Appear in the Absence of Day 5 Training Differences

The finding that self-reported emotion and facial EMG on Day 5 differed as a function of training direction, in the absence of significant differences in EEG asymmetry between groups on Day 5, is somewhat puzzling and motivated exploratory analyses. Despite significant overall training effects, some participants did not respond especially strongly to the training. For these exploratory analyses, only participants who showed changes in the expected direction as a function of training (i.e., "responders") were examined. Operationally, all asymmetry scores (five blocks and 5 days) were summed, and participants were divided into those above and below the median (median $= -.038$). These asymmetry scores had been baseline adjusted (see above) prior to this summation, so that these scores reflected not trait differences between participants, but movement from each participant's own baseline. When classified in this manner, 5 of the LEFT participants were above the median, and 5 of the RIGHT participants were below the median. For these exploratory analyses, only these 10 participants were included.

As expected, the effects of training were evident in this subsample of responders. Asymmetry scores were analyzed in a Direction (RIGHT/LEFT) $\times$ Day (1–5) $\times$ Block (1–5 within each day) repeated measures ANOVA. In the absence of any significant main effects or other interactions, a significant Direction $\times$ Day interaction emerged, $F(4,32) = 4.11$, $p < .01$, and remained significant following Greenhouse-Geisser epsilon correction, $\epsilon = .69$, $p < .05$. Planned comparisons between the two groups on each day of training revealed that those participants trained RIGHT differed from those trained LEFT on Days 2, 3, 4, and 5, $ps < .01$ (see Figure 4). Planned comparisons of Days 2–5 to Day 1 revealed that for participants trained RIGHT, significant training effects, $p < .05$, emerged on Days 3, 4, and 5. For participants trained Left, a significant training effect was evident only on Day 4, $p < .05$. Thus among participants who were selected as responders, biofeedback training effects were evident despite reduced power. These differences did not reflect differences in trait levels, as scores had been baseline adjusted; moreover, the LEFT and RIGHT responders did not differ from one another on Day 1, but only on subsequent days of training. The important question remaining was whether these responders would show self-report and EMG effects.

Self-report effects essentially replicated for these responders. Responses to each film were analyzed in a Direction (RIGHT/LEFT) $\times$ Emotion (seven levels) $\times$ Day (pre/post training) repeated measures ANOVA. The interaction between direction, day, and emotion was of interest, as it would reflect a different pattern of emotional responding as a function of training. This interaction was significant for the happy film, $F(6,48) = 4.35$, $p < .02$, G-G corrected, but not for the neutral film, $F(6,48) = 2.00$, ns, or the sad film, $F(6,48) = .76$, ns. Simple effects analyses for the happy film indicated that whereas there were no differences in the pattern
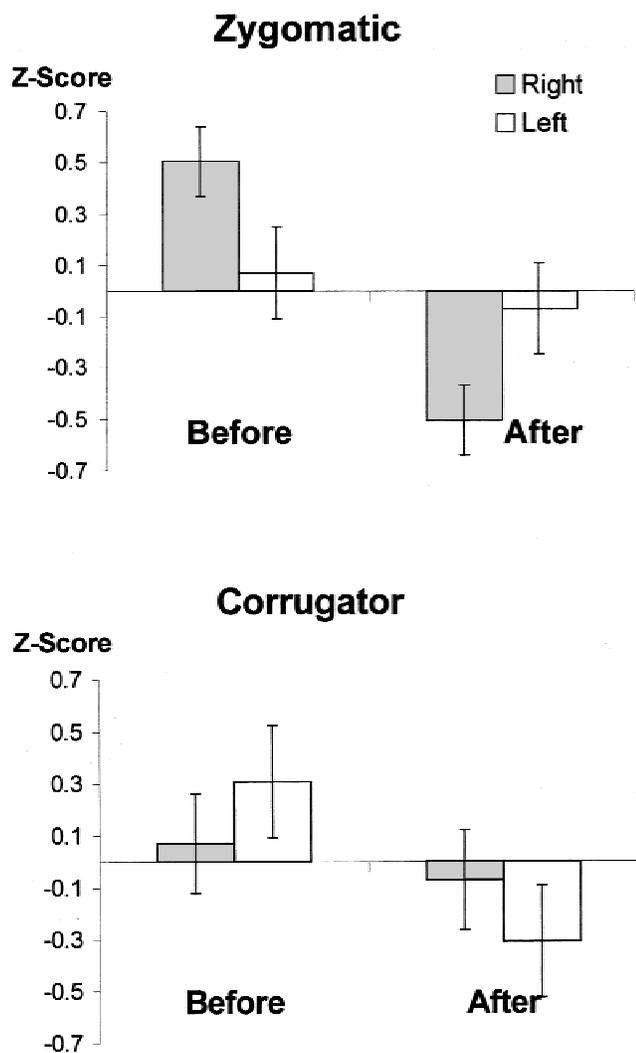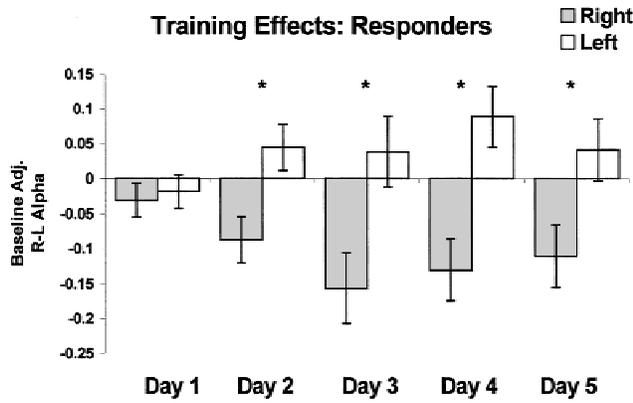
Figure 4. EEG R − L alpha asymmetry (± *SE*) for training responders as a function of training day. Higher numbers on the Y axis reflect greater right than left frontal alpha, and therefore putatively greater left than right frontal activity. Asterisks signify that participants trained LEFT (open bars) differed significantly from those trained RIGHT (shaded bars).

of emotional responses between LEFT and RIGHT responders in emotional responses prior to training, $F(6,48) = 0.42$, *ns*, the pattern of emotional responses following training differed for the LEFT and RIGHT responders, $F(6,48) = 2.44$, $p < .05$, but $p < .12$ following G-G correction. Planned comparisons revealed this effect was accounted for by RIGHT participants reporting significantly less, $p < .01$, interest, amusement, and happiness than LEFT participants.

EMG effects also essentially replicated. The hypothesized Direction × Time × Muscle-Region interaction was marginally significant, $F(1,8) = 4.85$; $p < .06$, but this was not moderated by a higher order four-way interaction with film type, $F(2,16) = .21$, *ns*. Planned comparisons indicated that whereas RIGHT responders produced less, $p < .05$, zygomatic ("smile") activity following training, LEFT responders produced less, $p < .05$, corrugator ("frown") activity following training; RIGHT responders demonstrated no change in corrugator activity, whereas LEFT responders demonstrated no change in zygomatic activity.

Because analyzing only responders resulted in a reduction in statistical power, it is useful to consider not only statistical significance, but also the effect size (Eta Squared). Considering first the self-report film finding (i.e., the interaction of Direction × Emotion × Day for the happy film), the effect size for all subjects was .16 and for responders it was .35, more than twice as large. Considering the EMG finding (Direction × Time × Muscle-Region interaction), the effect size for the full sample was .30, and for responders it was .38. The consistently larger effect size among responders compared to the entire sample provides further evidence consistent with the hypothesis that manipulating frontal EEG asymmetry produces changes in emotional self-report and facial expression.

Discussion

Extant evidence supporting the approach–withdrawal model of frontal EEG asymmetry is substantial, but based largely on correlational data—that is, the correlation between resting asymmetrical activity and responses to emotionally evocative events, or between resting asymmetry and individual differences related to emotion.[4] The present research was designed to extend this body of evidence by examining whether asymmetrical frontal activity *caused* these emotional responses. The present study must be regarded as preliminary in this regard, but supports the hypothesis that manipulation of frontal EEG asymmetry, and by inference cortical activity, alters the pattern of emotional responding consistent with predictions derived from theoretical accounts of frontal brain asymmetry (e.g., Davidson, 1998; Harmon-Jones & Allen, 1997, 1998).

Although other investigations have shown that EEG alpha asymmetry changes can occur as a result of biofeedback training (Rosenfeld et al., 1995), and that such asymmetry changes cooccur with a reduction in depressive symptoms (Baehr et al., 1997), this is the first controlled investigation of the effect of such training on emotional responses. Biofeedback training of frontal EEG asymmetry produced results generally consistent with the expected pattern of emotional responses, as indicated by both self-report and facial EMG. Consistent self-report effects emerged only when participants viewed the happy film, but not the neutral or the sad films. EMG effects emerged across all films. Neither measure should necessarily be viewed as preferable or more robust, because each measure provides a somewhat independent yet convergent index of emotional response, commensurate with the use of multiple measures advocated by Campbell and Fiske (1959) and others.

When effects were examined only among those participants who responded to biofeedback training (i.e., responders), self-report and EMG effects replicated despite a rather dramatic reduction in power, and effect sizes increased. The responder analyses addressed not whether all participants show biofeedback effects, but rather what the effects of asymmetry manipulation are in those who show training-related changes. Responders trained LEFT and RIGHT did not differ on the first day of biofeedback training, but did on all subsequent days. Because responders were defined by their change from their own baseline, self-report and EMG effects were not due to trait differences, but rather were due to specific changes in asymmetry across the course of training.

Consistent with past research, asymmetrical frontal activity does not relate to unprovoked mood in nonclinical samples, but instead relates to emotional responding to stimuli that evoke approach- or withdrawal-related tendencies (Davidson & Fox, 1989; Harmon-Jones & Allen, 1997, 2001; Wheeler et al., 1993). In clinical samples, asymmetrical frontal activity has often (Allen et al., 1993; Gotlib et al., 1998; Henriques & Davidson, 1990, 1991; Wiedemann et al., 1999) but not ubiquitously (Reid et al., 1998) been found to related to unprovoked mood, but such a relationship has repeatedly not been found in nonclinical college student samples (Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997; Wheeler et al., 1993). In normative samples (college students and infants; e.g., Davidson & Fox, 1989; Wheeler et al., 1993), it has consistently been the case that preexisting differences in frontal asymmetry are manifest in behavior only when the appropriate emotion-eliciting situation arises.

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[4]Some studies in support of the approach–withdrawal model have measured state-dependent changes in frontal asymmetry in response to manipulations designed to elicit emotions [e.g., films (Davidson, Ekman, Saron, Senulis, & Friesen, 1990), an insult (Harmon-Jones & Sigelman, in press), and maternal separation in infants (Fox & Davidson, 1987). Such a design, in which frontal EEG is a dependent variable, does not directly address the central issue of the present study, namely whether resting EEG asymmetry can cause emotional responses.

Methodological Considerations

In the responders as well as the sample as a whole, it was easier to obtain movement in the RIGHT direction. Several factors may have made it easier to obtain effects in this direction, including the use of a nondepressed participant population with baseline asymmetry scores greater than zero and a percentage of epochs favoring left activation (Figure 1, lower panel). Additionally, the protocol required 5 consecutive days in the lab, and involved a limited training time per day (25 min) across only 5 days. Changes in the LEFT direction were observed by Baehr et al. (1997) over the course of more than 34 training sessions. On the other hand, the present study did observe some effects in the LEFT direction among responders.

In the sample as a whole, but not among the responders, EEG asymmetry training effects appear to show regression to baseline by Day 5. This may, in part, reflect that participants came to the lab on 5 consecutive days, and may have fatigued by Day 5 (which was always Thursday, Friday, or Saturday). This speculation is consistent with the observation that the rate of reinforcement for all participants—regardless of training direction—was lower on Day 5 than on the previous 4 days. This observation, however, suggests that future studies (1) should use a training protocol across nonconsecutive days, and 2) should investigate the longer-term effects of training to determine whether regression to baseline is common after more extensive training.

What was manipulated?

In any study of biofeedback, the question naturally arises concerning whether training directly impacted the system of interest, or whether it impacted some third variable that is responsible for the changes in physiology and behavior. As Rosenfeld aptly states, "the only thing we directly manipulate . . . is the reinforcement contingency" (Rosenfeld, 1990, p. 104). Although it is tempting to treat the target of the conditioning—in this case R − L alpha asymmetry scores—as an independent variable, and self-reported emotion and EMG activity as dependent variables, all three measures (EEG asymmetry, self-reported emotion, and EMG) are, strictly speaking, dependent variables. Although it is parsimonious to think that any relationship between EEG asymmetry and the other dependent variables arises from the biofeedback manipulation, this is but one of several interpretations.

An attractive alternative explanation would be that the training protocol in fact altered participants' moods, and that this influenced the asymmetry score as well as the self-reported emotion and EMG activity to the films. Several observations suggest this is not likely to be an adequate account of the present findings. First, the experimental protocol was designed to make the physical feedback comparable for both groups of participants. All participants received the same high and low tones, and received comparable rates of reinforcement and time-outs. If aspects of the training protocol would influence emotion, they should do so comparably for participants trained LEFT and RIGHT. Second, self-report data of unprovoked mood (PANAS) following each day's training suggest that participants' moods did not differ as a function of training direction. If participants were employing emotional strategies to obtain training effects, or if aspects of the training protocol were differentially influencing the mood of participants trained LEFT versus those trained RIGHT, this would likely have been reflected in the PANAS ratings, especially as participants completed the state version where they reported the way they felt "right now, that is at the present moment," which was the time immediately following the each day's last training trial. Third, although participants may have inferred the intent of biofeedback training by virtue of having to rate emotions (for films and for the PANAS), this again should be a constant for those participants trained LEFT versus RIGHT. Finally, at least one study suggests that specifically attempting to alter one's emotions is a poor strategy by which to alter the asymmetry of brain activity. In a study assessing the impact of biofeedback on asymmetry of slow potentials over frontal cortex (Hardman et al., 1997), participants instructed to use emotional strategies did not demonstrate a training effect whereas participants given no such strategy did show a training effect.

Although these observations suggest that it is unlikely that subjects used emotional strategies to alter frontal EEG asymmetry, there remain two possible explanations for how EEG asymmetry was altered. The first is that subjects used some other strategy that did not focus on emotions, but that might plausibly impact asymmetry in accord with predictions of the approach–withdrawal model (e.g., directing attention externally and engaging with the environment or directing attention internally thereby withdrawing from the environment, contemplating approach or withdrawal actions, etc.). The second alternative, and one that would be difficult to establish conclusively, is that the biofeedback training impacted frontal EEG asymmetry directly, without the use of such intervening strategies. The significance of the present results do not hinge upon accepting one or the other of these alternatives. Either explanation supports the conclusion that altering frontal asymmetry, either directly or indirectly, produces changes in emotional responses. Moreover, the logic outlined in the previous paragraph would imply that these changes in emotional response that follow the manipulation of EEG asymmetry are not merely a reflection of emotional changes that occurred during the biofeedback training.

Conclusions

The present research extends the past research by demonstrating that—in the absence of preexisting baseline differences in frontal asymmetry—biofeedback-induced changes in asymmetrical frontal activity influenced subsequent self-reported emotions and facial EMG responses when participants were confronted with emotionally evocative film clips. Thus, the present results suggest a causal role of asymmetrical anterior cortical activity as a diathesis for responding with characteristic approach-related or withdrawal-related emotional responses when confronted with emotionally evocative stimuli. It remains to be determined whether extended biofeedback training of frontal EEG could produce changes in mood among those with clinical disorders, but the present findings suggest the utility of testing this possibility.

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