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Research Paper

Attention bias modification reduces neural correlates of response monitoring

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ABSTRACT

The error-related negativity (ERN) is an electrophysiological response to errors. Individual differences in the ERN have been posited to reflect sensitivity to threat and linked with risk for anxiety disorders. Attention bias modification is a promising computerized intervention that has been shown to decrease threat biases and anxiety symptoms. In the present study, we examined the impact of a single session of attention bias modification, relative to a control task, on the neural correlates of response monitoring, including the ERN, correct response negativity (CRN), and their difference (i.e., the ERN – CRN or ΔERN). The final sample included 60 participants who first completed a flanker task to elicit the ERN and CRN, and were then randomly assigned to attention bias modification (n = 30) or a control task (n = 30). After completing the attention bias modification or control task, participants completed the same flanker task to again elicit the ERN and CRN. Among participants who completed attention bias modification training, the ERN, CRN, and ΔERN decreased from the pre- to post-training assessment. In contrast, in participants who completed the control task, the CRN, ERN, and ΔERN did not differ between the pre- and post-training assessment. The presents study suggests that a single session of attention bias modification reduces neural correlates of response monitoring, including error-related brain activity. These results also support attention bias modification as a potential mechanistic-based intervention for the prevention and treatment of anxiety pathology.

1. Introduction

Errors are motivationally-salient events that have the potential to place an individual in danger (Weinberg, Riesel, & Hajcak, 2012). The detection of errors is evolutionarily important as errors may signal potential harm (e.g., slipping and cutting oneself) or missed opportunities (e.g., food acquisition). Error commission elicits a number of physiological changes consistent with defense system activation, including skin conductance response (Hajcak, McDonald, & Simons, 2003), heart rate deceleration (Hajcak et al., 2003), pupil dilation (Critchley, Tang, Glaser, Butterworth, & Dolan, 2005), potentiated startle reflex (Hajcak & Foti, 2008), and amygdala activation (Pourtois et al., 2010). As such, error detection is considered an important element of a general performance monitoring system that further evaluates the consequences of behavior and makes adjustments to optimize outcomes (Holroyd & Coles, 2002).

A neural index of error detection is the error-related negativity (ERN), a negative deflection in the event-related potential (ERP) that peaks at frontocentral electrodes approximately 50 ms following error commission (Hajcak, 2012). The ERN magnitude is sensitive to the motivational salience of errors, such that it is enhanced when errors are punished (Riesel, Weinberg, Endrass, Kathmann, & Hajcak, 2012), performance is evaluated (Barker, Troller-Renfree, Pine, & Fox, 2015; Hajcak, Moser, Yeung, & Simons, 2005; Kim, Iwaki, Uno, & Fujita, 2005), or accuracy is emphasized over speed (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Gehring, Goss, & Coles, 1993). The ERN has excellent psychometric properties, including high test-retest reliability across two weeks (Olvet & Hajcak, 2009a) and two years (Weinberg & Hajcak, 2011), and high internal consistency in as few as six trials (Olvet & Hajcak, 2009b). The ERN is also moderately heritable (Anokhin, Golosheykin, & Heath, 2008) and related to particular genotypes (Manoach & Agam, 2013), suggesting genetic contributions.

Although there are many theories surrounding the mechanisms that underlie the generation of the ERN (see Weinberg, Dieterich, & Riesel, 2015 for review), it is commonly believed to reflect the activity of a generic error monitoring system which tracks ongoing performance

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(Falkenstein et al., 2000; Gehring et al., 1993; Holroyd & Coles, 2002). In addition to its role in a generic performance monitoring system, there is growing evidence that variability in the magnitude of the ERN indexes individual differences in sensitivity to errors. Consistent with this notion, an enhanced ERN has been associated with increased anxiety symptoms (Hajcak, 2012; Moser, Moran, Schroder, Donnellan, & Yeung, 2013; Proudfit, Inzlicht, & Mennin, 2013), and risk for anxiety disorders. Specifically, the ERN is larger in healthy individuals with a family history of obsessive-compulsive disorder (Carrasco et al., 2013; Riesel et al., 2011), and an enhanced ERN prospectively predicts the new onset of anxiety disorders in children (Meyer, Hajcak, Torpey-Newman, Kujawa, & Klein, 2015). Thus, the ERN has been suggested to be a potential marker of risk for anxiety disorders (Hajcak, 2012; Meyer, 2016; Olvet & Hajcak, 2008).

In a recent investigation, Nelson, Jackson, Amir, and Hajcak (2015) examined whether a single session of attention bias modification could reduce the ERN. Attention bias modification is a computerized intervention that trains attention away from negative stimuli and towards positive stimuli, and targets a core mechanism of dysfunction in anxiety disorders (i.e., attentional bias toward threat) (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007). Attention bias modification has been shown to successfully decrease threat biases and anxiety symptoms (Kuckertz & Amir, 2015; Macleod & Clarke, 2015). Given that attention bias modification is designed to modify attentional biases away from threat and reduce vulnerability to anxiety, we hypothesized that attention bias modification would modulate the ERN, a posited neural index of threat sensitivity (Weinberg et al., 2016). In Nelson et al., participants were randomly assigned to complete attention bias modification either before or after the ERN was measured (i.e., AB/BA design). Results revealed that the ERN was smaller in participants who completed attention bias modification before, relative to those who completed attention bias modification after, the ERN was measured. These results support the hypothesis that individuals who completed attention bias modification first showed a smaller ERN relative to their attention bias modification-naive counterparts. Furthermore, changes in attentional bias occurred on a continuum, with some participants showing more or less change in their biases away from negative and toward positive stimuli. Upon examining these bias scores, we found that greater attentional disengagement from negative stimuli during attention bias modification was associated with a smaller ERN across both groups, suggesting that the ERN may be both a mechanism and predictor of attention bias modification-related changes in attentional bias to threat.

Nelson et al. (2015) provides a critical first indication that the ERN—a posited neural marker of threat sensitivity and risk for anxiety—can be altered by a computerized attention bias modification task. However, Nelson et al. contained several methodological limitations that proscribe causal conclusions about the effect of attention bias modification on the ERN. Specifically, it did not include a control group that completed an analogous cognitive task. Thus, it is unclear if attention bias modification training directly altered the ERN, or if there were other factors (e.g., task fatigue) that indirectly impacted the ERN. Additionally, Nelson et al. did not include pre- and post-training assessments of the ERN, thereby prohibiting the examination of within-subject changes in the ERN.

The present study examined the impact of attention bias modification on the ERN using a pre-test/post-test design, across both attention bias modification and a control task. Specifically, 64 participants completed a flanker task designed to elicit the ERN and correct response negativity (CRN)—a smaller negative deflection in the ERP which also peaks at frontocentral electrodes approximately 50 ms following correct responses—and were then randomly assigned to complete a single session of attention bias modification or a control task. The control task included similar instructions, stimuli, and an identical number of trials, but did not train attention away or toward stimuli. After completing the attention bias modification or control task, participants again completed the flanker task to elicit the ERN and CRN. The present study focused on a sample of individuals who were unselected for initial attention bias or anxiety symptoms to minimize the contribution of psychopathology that may be more prevalent in clinical populations on initial attention bias or the ERN. We hypothesized that participants who completed attention bias modification, but not the control task, would demonstrate a within-subject reduction in the ERN. Furthermore, in the participants who completed attention bias modification, we hypothesized that a greater change in negative attention bias would be associated with a smaller ERN.

2. Method

2.1. Participants

In an attempt to replicate and extend Nelson et al. (2015), the present study recruited a sample that was of similar size and demographic composition. To this end, the sample included 64 undergraduates from Stony Brook University who participated for course credit. Participants were randomly assigned to attention bias modification ($n = 34$) or the control condition ($n = 30$). Informed consent was obtained prior to participation and participants were allowed to terminate participation at any time during the experimental session. The research protocol was approved by the Institutional Review Board at Stony Brook University.

2.2. Measures

2.2.1. Inventory of depression and anxiety symptoms

To verify that the attention bias modification and control groups were comparable on current internalizing symptoms, participants completed the expanded Inventory of Depression and Anxiety Symptoms (IDAS-II) (Watson et al., 2012). The IDAS-II is a 99-item factor-analytically derived self-report inventory of empirically distinct dimensions of depression and anxiety symptoms. Each item assesses symptoms over the past two weeks on a 5-point Likert scale ranging from 1 (*not at all*) to 5 (*extremely*). The present study examined the IDAS-II subscales for depression, panic, social anxiety, claustrophobia, traumatic intrusions, traumatic avoidance, checking, orderliness, and cleanliness.

2.3. Procedure

After providing informed consent, participants completed a self-report demographic questionnaire and the IDAS while an electroencephalography (EEG) cap was applied to the participant's head. Next, EEG was recorded while participants completed a flanker task. After completing the flanker task, participants were randomly assigned to either the attention bias modification or control task. Finally, after completing the attention bias modification or control task, EEG was again recorded while participants completed the same flanker task.

2.3.1. Flanker task

The flanker task was administered with Presentation software (Neurobehavioral Systems Inc., Albany, CA). On each trial, five horizontally aligned white arrowheads were presented for 200 ms. Participants were instructed to indicate the direction of the central arrowhead using the left or right mouse button. Half of the trials were compatible (e.g., < < < < < or > > > > >) and half were incompatible (e.g., < < > < < or > > < > >), and trial type was randomly determined. After the participant response, there was a variable intertrial interval of 600–1000 ms prior to the beginning of the next trial. The arrows filled 2° of visual angle vertically and 10° horizontally, and were presented at a viewing distance of approximately 65 cm. Participants initially completed a practice block containing 20 trials, and the actual task consisted of 11 blocks of 30 trials (330 total trials).

2.3.2. Attention bias modification

Similar to Nelson et al. (2015), participants completed an adaptive version of attention bias modification that contained several modifications that differed from traditional versions (Amir, Weber, Beard, Bomyea, & Taylor, 2008; MacLeod, Rutherford, Campbell, Ebsworthy, & Holker, 2002). Specifically, the attention bias modification program (1) only showed one word above or below a fixation point that either cued participants to disengage (negative words) or sustain (positive words) attention, (2) utilized idiographic stimuli (5 negative, 5 positive, and 5 neutral words) generated by the participant,[1] (3) contained multiple training components and adjusted the criteria, within person, to improve their attentional bias over the course of training, and (4) trained multiple components of attention, including the ability to disengage attention away from negative stimuli (negative bias) and direct and sustain attention toward positive stimuli (positive bias).

Each attention bias modification trial began with a fixation cross presented in the center of the screen for 500 ms. Immediately following termination of the fixation cross, a neutral, positive, or negative word appeared either above or below the fixation cue for 500 ms. After presentation of the word, a probe (the letter *E* or *F*) appeared above or below the fixation cue. Participants were instructed to click the left mouse button for *E* and the right mouse button for *F*, and the letter stayed on the screen until a response had been registered. To aid participants in improving their attentional bias, both speed and accuracy of responses were emphasized. Attention was trained away from negative stimuli and toward positive stimuli by always presenting the probe in the *opposite* location of negative words and the *same* location as positive words. For neutral words, the probe appeared in the opposite and same location with equal frequency. Participants completed 720 trials that comprised various combinations of probe type (*E* or *F*), probe position (top or bottom), and word valence (positive, negative, or neutral).

The attention bias modification program contained several adaptive elements that occurred across two training phases. In the first phase (i.e., levels 1–30), participants progressed based on their response accuracy in that they advanced to the next level after every seven correct trials. For levels 1–10, participants were presented with a green or red fixation cross, followed by a neutral, positive, or negative word appearing above or below the fixation cross, and then the letter *E* or *F* appearing above or below the fixation cross. Participants were instructed that when the fixation cross was green, the letter would appear in the same location as the word, and when the fixation cross was red, the letter would appear in the opposite location as the word. The green fixation cross was always followed by a positive or neutral word, and the red fixation cross was always followed by a negative or neutral word. For levels 11–20, participants were told that the valence of the word could be used to predict where the cue would appear. Specifically, for positive words the letter would appear in the same location, for negative words the letter would appear in the opposite location, and for neutral words the letter would appear in either location. Furthermore, as participants progressed through levels 11–20, the color of the fixation cross began to fade to white, and toward the final trials the participant was completely reliant on the valence of the word to predict the location of the cue. For levels 21–30, the cue (*E* or *F*) was flanked by either congruent (i.e., EEEEE or FFFFF) or incongruent (i.e., EEFEE or FFEFF) letters, and participants were told to only respond to the middle letter. This required participants to increase their focus on the cue.

In the second phase (i.e., levels 31 and higher), participants continued to complete the same type of attention bias modification trial as the end of the first phase (i.e., white fixation cross, using word valence to predict location of the cue, responding to the middle letter and not flanked letters). However, participants now advanced to the next level by improving their positive or negative bias by 1 ms relative to the cumulative bias of all preceding trials. The inclusion of levels was intended to motivate participants to continue improving their attention bias, and participants were able to view their level progression throughout the training. If participants completed 100 consecutive trials without advancing to the next level, the attention bias modification training was automatically paused and the computer instructed participants to take a short break. At this time the participants' attention bias scores were re-calibrated, such that they were reset to the highest level reached for positive words and the lowest level reached for negative words. This allowed the training to continue if participants had reached an attention bias which they could no longer surpass. Participants were able to self-resume the training when they were ready. Inaccurate response trials (e.g., probe was *E* and participant clicked right for *F*) and response latencies less than 200 ms or greater than 2000 ms were excluded from analyses. After 70 accurate trials the program calculated an idiographic mean and standard deviation for each participant and eliminated response latencies that were two standard deviations away from their mean response latency. These ranges were determined based on previous research.

Similar to Nelson et al. (2015), change in attention bias was calculated for each participant that completed the attention bias modification training. Attention bias was calculated using response latencies for valid (i.e., word appeared in same location as the probe) and invalid trials (i.e., word appeared in opposite location of the probe). For negative attention bias (reaction time during negative invalid – reaction time during neutral invalid), lower numbers indicated greater disengagement from negative, relative to neutral, trials. For positive attention bias (reaction time during positive valid – reaction time during neutral valid), higher numbers indicated greater engagement for positive, relative to neutral, trials. To quantify change in attention bias across training, a beta score was calculated that represented the average change in attention bias as a function of attention bias modification level (i.e., trainability). The beta was calculated by regressing the attention bias score on attention bias modification level, with the beta value representing the slope (i.e., rate of change). For the negative attention bias beta score a more negative value indicated greater disengagement from negative stimuli. Conversely, for the positive attention bias beta score a more positive value indicated greater engagement with positive stimuli.

2.3.3. Control task

The control task was a variant of a classic probe detection task that was nearly identical to the attention bias modification training, but did not train attention toward or away from any stimuli. Each control task trial began with the presentation of a fixation cross in the center of the screen for 500 ms. The fixation was immediately followed by two words (either neutral or negative), one presented above and one below the fixation cue. The words were shown for 500 ms and participants were instructed to read the top word on each trial. The words were then followed by either the letter *E* or *F*, which appeared above or below the fixation cue. Participants were instructed to respond to the letter by pressing the left mouse button for *E* and the right mouse button for *F*, and the letter remained on the screen until a response was registered. Importantly, the probe (*E* or *F*) appeared with equal frequency behind neutral and negative words. Similar to the attention bias modification training, the control task consisted of 720 trials, and trials were balanced for probe type (*E* or *F*), position (top or bottom), and word valence (neutral or negative). Thus, the valence of the word did not provide any information to anticipate the location of the probe or alter threat bias. Attention bias to negative words was calculated using the following equation (MacLeod & Mathews, 1988; Mogg et al., 1995): ½[(reaction time during neutral top, threat bottom trials with probe on

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[1] At the beginning of the training session, attention bias modification participants were asked to generate 5 neutral, 5 positive, and 5 negative words, and control task participants were asked to generate 5 neutral and 5 negative words. These idiographic words were then used in the attention bias modification and control tasks.

top − reaction time during in neutral top, threat bottom trials with probe on bottom) + (reaction time during threat top, neutral bottom trials with probe on bottom − reaction time during threat top, neutral bottom trials with probe on top)].

2.3.4. *EEG recording and processing*

Continuous EEG was recorded during the flanker task using an elastic cap with 34 sintered Ag/AgCl electrode sites placed according to the international 10/20 system and two electrodes placed on the left and right mastoid. The electrooculogram was recorded from electrodes placed above and below the right eye and two placed on the outer canthus of both eyes. Data were recorded using the ActiveTwo system (BioSemi, Amsterdam, Netherlands). The EEG was digitized with a sampling rate of 1024 Hz using a low-pass fifth order sinc filter with a half-power cutoff of 204.8 Hz. A common mode sense active electrode producing a monopolar (non-differential) channel was used as recording reference.

EEG data were analyzed using BrainVision Analyzer (Brain Products, Gilching, Germany). Data were referenced offline to averaged mastoids, band-pass filtered (0.1–30 Hz), and corrected for blinks and horizontal eye movements (Gratton, Coles, & Donchin, 1983). Response-locked epochs with a duration of 1000 ms, including a 500 ms pre-response interval, were extracted. Epochs containing a voltage greater than 50 μV between sample points, a voltage difference of 300 μV within a segment, or a maximum voltage difference of less than 0.50 μV within 100 ms intervals were rejected. Additional artifacts were identified and removed based on visual inspection, and trials with response times below 200 ms and above 700 ms were excluded from averaging. The 500–300 ms pre-response interval was used as the baseline.

Visual examination of the ERP waveforms and scalp distributions indicated significant spatial and temporal overlap between stimulus-locked ERP components (e.g., P300) and the response-locked ERP component (e.g., the CRN and ERN). This overlap makes it challenging to determine whether group differences are due to changes in the ERP response to the stimulus, response, or both. Therefore, to better isolate the response-locked ERP components, we applied a current source density (CSD) transform (order of splines = 4, maximal degree of Legendre polynomial = 10; λ smoothing parameter = 10^{-5}) to compute an estimate of the surface Laplacian based on the EEG voltage across the scalp electrodes. Laplacian data are relatively free from activities originating from remote sources and the adverse effects of volume conduction on the EEG are considerably attenuated (Vidal, Burle, Bonnet, Grapperon, & Hasbroucq, 2003; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). Following the CSD transform, a negative deflection was observable after both error (i.e., the ERN) and correct trials (i.e., the CRN). The ERN and the CRN were quantified as the mean amplitude between 0 and 100 ms after responses at electrode FCz, where the components were maximal.

2.4. *Data analysis*

Four participants were excluded from analyses for having outlier ERN values (> 3 standard deviations from the mean; $n = 2$ attention bias modification participants) or not completing the entire attention bias modification training ($n = 2$) leaving a final sample of 30 attention bias modification and 30 control participants. Attention bias modification and control group differences in flanker task behavioral data (i.e., accuracy, reaction time [RT], post-error slowing) were examined using a Group (attention bias modification vs. control) X Time (pre-training vs. post-training) mixed-measures analysis of variance (ANOVA), with group as the between-subjects factor and time as the within-subject factor. Group differences in ERP responses were examined using a Group (attention bias modification vs. control) X Outcome (error vs. correct response) X Time (pre-training vs. post-training) mixed-measures ANOVA, with group as the between-subjects factor and outcome and time as within-subject factors. Group X Outcome X Time interactions were followed-up by conducting separate Outcome X Time repeated measures ANOVAs for attention bias modification and control participants. Across all participants and both pre- and post-training assessments, faster reaction time and making fewer errors during the flanker task were associated with an increased ΔERN (i.e., ERN – CRN), $\beta = 0.35$, $p < 0.01$; $\beta = 0.28$, $p < 0.05$, respectively. Therefore, accuracy and reaction time were included as covariates in the ERP analyses. Finally, the association between the attention bias beta score and ERP responses was examined using an Attention Bias X Outcome (error vs. correct response) X Time (pre-training vs. post-training) analysis of covariance (ANCOVA), with attention bias as a continuous covariate and outcome and time as within-subject factors. In attention bias modification participants, separate analyses were conducted for negative and positive attention bias beta scores. Similar analyses were conducted in control participants with the negative attention bias scores. All analyses were conducted in IBM SPSS Statistics, Version 22.0 (Armonk, NY, USA).

3. Results

3.1. *Demographics*

Table 1 presents descriptive and inferential statistics for demographics. Attention bias modification and control participants were matched on all demographics and current depression and anxiety symptoms.

Table 1
Demographics and Flanker Task Behavior.

	Group ABM ($n = 30$)	Control ($n = 30$)	*t* or χ^2
Demographics			
Age (years)	19.40 (2.19)	20.53 (2.62)	$t = -1.82$
Sex (% female)	63.3%	60.0%	$\chi^2 = 0.07$
Ethnicity			$\chi^2 = 1.87$
Caucasian	30.0%	26.7%	
Black	13.3%	10.0%	
Hispanic	13.3%	13.3%	
Asian	33.3%	46.7%	
Other	10.0%	3.3%	
IDAS			
Depression	44.70(13.57)	46.03 (14.61)	$t = -0.37$
Panic	10.97 (4.50)	13.17 (5.95)	$t = -1.62$
Social Anxiety	11.83 (5.80)	12.17 (5.49)	$t = -0.23$
Claustrophobia	6.73 (2.72)	6.37 (2.50)	$t = 0.54$
Traumatic Intrusions	7.13 (3.86)	6.87 (3.81)	$t = 0.27$
Traumatic Avoidance	8.63 (4.92)	8.73 (4.62)	$t = -0.08$
Checking	5.90 (3.06)	6.40 (3.19)	$t = -0.62$
Orderliness	8.47 (3.43)	9.10 (4.92)	$t = -0.58$
Cleanliness	11.20 (4.55)	10.37 (4.61)	$t = 0.71$
Flanker Task Behavior			
Pre-Training			
Accuracy (%)	89.77 (5.52)	91.44 (4.09)	$t = -1.33$
Correct RT (ms)	414.02 (55.48)	404.17 (63.05)	$t = 0.64$
Error RT (ms)	389.79 (44.24)	386.86 (53.26)	$t = 0.23$
Post-Error Slowing (ms)	26.24 (36.98)	14.48 (18.96)	$t = 1.55$
Post-Training			
Accuracy (%)	88.70 (4.84)	89.38 (4.73)	$t = -0.55$
Correct RT (ms)	328.47 (31.21)	323.33 (43.96)	$t = 0.52$
Error RT (ms)	333.24 (46.22)	317.56 (33.53)	$t = 1.49$
Post-Error Slowing (ms)	26.06 (44.81)	19.27 (23.74)	$t = 0.72$

Note. Standard deviations are presented in parentheses. ABM = attention bias modification; IDAS = Inventory of Depression and Anxiety Symptoms; ms = milliseconds; RT = reaction time.

3.2. Behavior

Table 1 also presents flanker behavioral performance. For response accuracy, results indicated a main effect of time, $F(1, 58) = 8.00$, $p < 0.01$, $\eta_p^2 = 0.12$, such that participants were less accurate during the post- relative to pre-training assessment. However, there was no main effect or interaction involving group ($ps > 0.29$), suggesting that attention bias modification and control participants did not differ in flanker task accuracy at either the pre-training or post-training assessment. For reaction time,[2] there was a main effect of time for both correct responses, $F(1, 57) = 239.48$, $p < 0.001$, $\eta_p^2 = 0.81$, and errors, $F(1, 57) = 167.53$, $p < 0.001$, $\eta_p^2 = 0.75$, such that participants responded faster during the post- relative to pre-training assessment. Similar to response accuracy, there was no main effect or interaction involving group for either reaction time to errors or correct responses ($ps > 0.19$). Together, these results suggest attention bias modification and control participants did not differ on flanker behavioral performance at both pre- and post-training assessments.

3.3. ERPs

As shown in Fig. 1, the ERN was observed as a negative deflection in the ERP response that peaked at frontocentral electrodes approximately 50 ms after the commission of an error.[3] Across both groups and assessments, the ERP response was more negative following errors (i.e., the ERN) relative to correct responses (i.e., the CRN), $F(1, 56) = 12.46$, $p < 0.001$, $\eta_p^2 = 0.18$. In addition, results indicated a Group X Outcome X Time interaction, $F(1, 56) = 4.07$, $p < 0.05$, $\eta_p^2 = 0.07$. As shown in Fig. 2, in the attention bias modification participants, results indicated main effects of outcome, $F(1, 29) = 34.12$, $p < 0.001$, $\eta_p^2 = 0.54$, and time, $F(1, 29) = 17.66$, $p < 0.001$, $\eta_p^2 = 0.38$, which were qualified by an Outcome X Time interaction that approached significance, $F(1, 29) = 4.00$, $p < 0.06$, $\eta_p^2 = 0.12$, such that the ΔERN (i.e., ERN – CRN) decreased from the pre- to post-training assessment. Examination of each component of the ΔERN difference score indicated that both the CRN, $F(1, 29) = 7.01$, $p < 0.05$, $\eta_p^2 = 0.20$, and ERN, $F(1, 29) = 12.40$, $p < 0.001$, $\eta_p^2 = 0.30$, decreased from the pre- to post-training assessment, but the reduction was greater for the ERN relative to the CRN. In control participants, results indicated a main effect of outcome, $F(1, 29) = 37.92$, $p < 0.001$, $\eta_p^2 = 0.57$, but there was no main effect of time, $F(1, 29) = 0.47$, *ns*, or Outcome X Time interaction, $F(1, 29) = 0.22$, *ns*, suggesting that the CRN, ERN, and ΔERN did not differ between the pre- to post-training assessments (see Supplementary materials for non-CSD transformed [i.e., raw] and peak-to-peak analyses).

3.4. Attention bias scores and ERPs

Attention bias ANCOVA analyses indicated that, among the attention bias modification participants, there were no main effects or interactions involving negative or positive bias beta scores ($ps > 0.10$). Similarly, in control participants there were no main effects or interactions involving negative bias scores ($ps > 0.73$).

4. Discussion

The present study examined the impact of a single session of attention bias modification, relative to a control task, on the neural correlates of response monitoring. Attention bias modification and control participants did not differ in behavioral performance; however, there were group differences in the neural correlates of response monitoring, including error-related brain activity. Specifically, attention bias modification reduced the ERN, CRN, and ΔERN (i.e., ERN – CRN) from the pre- to post-training assessments, and the control task did not impact any of the ERP measures. In contrast to our hypothesis, individual differences in change in negative attention bias across training were not associated with change in the ΔERN. Overall, the present study suggests that attention bias modification reduces neural correlates of response monitoring, including error-related brain activity.

This study replicates and extends Nelson et al. (2015) using a pretest/post-test design and incorporating a control task. However, Nelson et al. found that attention bias modification, relative to no training, reduced the relative difference between the ERN and CRN (i.e., the ΔERN). In contrast, the present study found that attention bias modification, relative to the control task, reduced the ERN, CRN, *and* ΔERN. The ERN and CRN may both contain neural activity of a generic performance monitoring system active on both correct and error trials. Indeed, the ERN and CRN have similar temporal characteristics and scalp topographies (Vidal et al., 2003, 2000) and are both generated in the anterior cingulate cortex (Carter et al., 1998). Therefore, in addition to modifying error-specific neural activity, attention bias modification might also impact broader response monitoring.

In contrast to Nelson et al. (2015), individual differences in change in negative attention bias were not associated with changes in the ΔERN. Attention bias measures have notoriously poor psychometric properties (Cisler, Bacon, & Williams, 2009; Price et al., 2015; Rodebaugh et al., 2016), and it is possible that unreliability in the measurement of attention bias may at least partially contribute to these discrepant findings. It is important to note that the present study utilized a regression-based approach for examining change in attention bias, and this analytic approach generally does not attenuate the reliability of a measure to the same degree as difference scores (Levinson, Speed, Infantolino, & Hajcak, 2017; Meyer, Lerner, Reyes, Laird, & Hajcak, 2017). Therefore, it is possible that other factors beyond poor psychometric properties may have influenced the pattern of results. Future research should consider alternative approaches toward measuring change in attention bias (e.g., ERP indicators of attention bias; Kappenman, Farrens, Luck, & Proudfit, 2014; Kappenman, MacNamara, & Proudfit, 2015).

Attention bias modification trains individuals to automatically disengage attention away from threat-relevant information, and also to direct attention toward positive information. A growing body of research has demonstrated that attention bias modification effectively reduces attentional biases toward threat (Beard, Sawyer, & Hofmann, 2012), improves behavioral performance on a stressful task (Amir et al., 2008), and decreases anxiety symptoms (Amir, Beard, Burns, & Bomyea, 2009). Research on the neural mechanisms of attention bias modification indicates that it increases activation in the prefrontal cortex (Browning, Holmes, Murphy, Goodwin, & Harmer, 2010; Clarke, Browning, Hammond, Notebaert, & Macleod, 2014), a region critical to cognitive control and affect regulation (Ridderinkhof et al., 2004). Attention bias modification has been shown to decrease activation in the amygdala, insula, and subgenual anterior cingulate cortex (Taylor et al., 2014), regions implemented in emotional processing. Given that these neural changes are shown to occur even following a single session of attention bias modification, we posit that the reduction in error-related brain activity following training may reflect these underlying neural changes. Specifically, enhanced prefrontal cortex activation may foster greater cognitive control, and thus more efficient completion of task demands—thus a reduced ERN. Moreover, the reduced ERN may result from increased top-down regulation of subcortical processing involved in threat detection.

The present study provided a replication and extension of Nelson et al. (2015), but there are several design features that should be improved upon in future investigations. First, participants only completed

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[2] One control participant was missing reaction time data from the post-training assessment and was excluded from these analyses.

[3] The correlations between the non-CSD (i.e., raw) ERPs and the CSD transformed ERPs were: ERN at pre-training assessment, $r = 0.63$, $p < 0.001$, CRN at the pre-training assessment, $r = 0.67$, $p < 0.001$, ERN at the post-training assessment, $r = 0.78$, $p < 0.001$, and CRN at the post-training assessment, $r = 0.61$, $p < 0.001$.

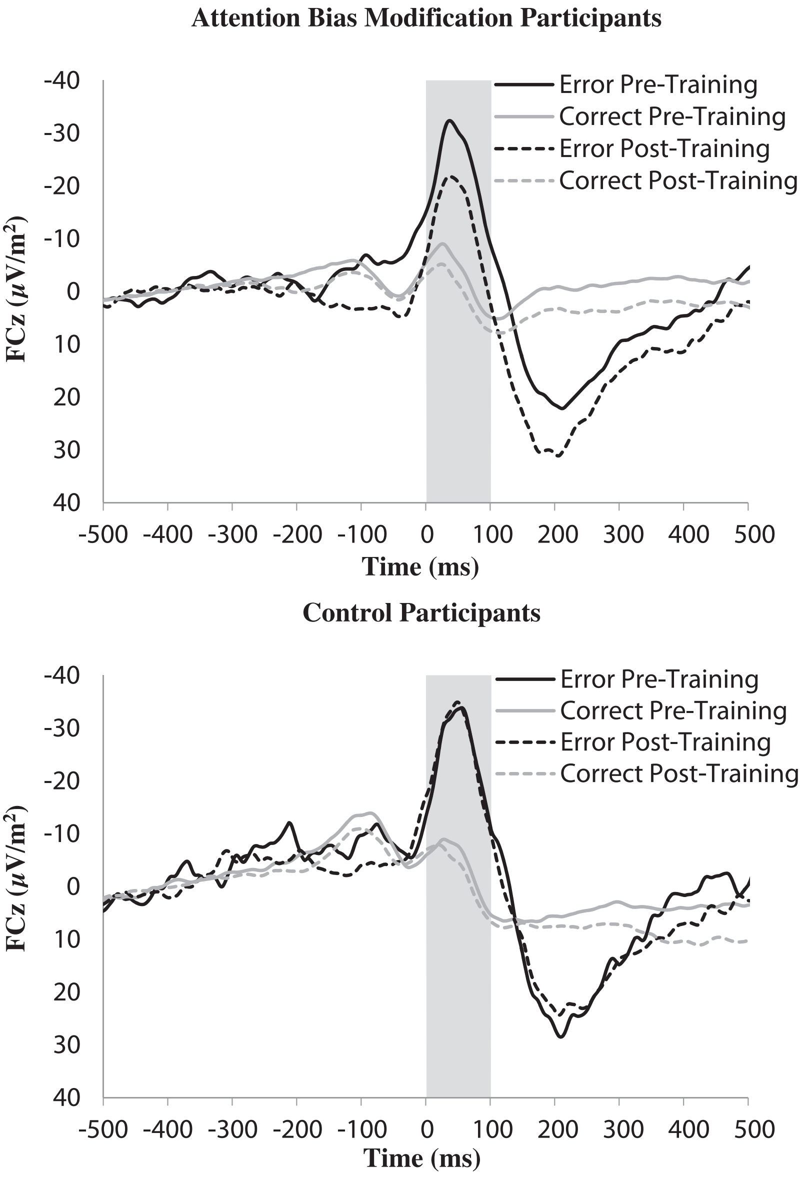

Fig. 1. Attention bias modification (top) and control (bottom) participants' pre- and post-training ERP waveforms. The shaded region in the waveform shows the segment where the error-related negativity (ERN) and correct response negativity (CRN) were scored.

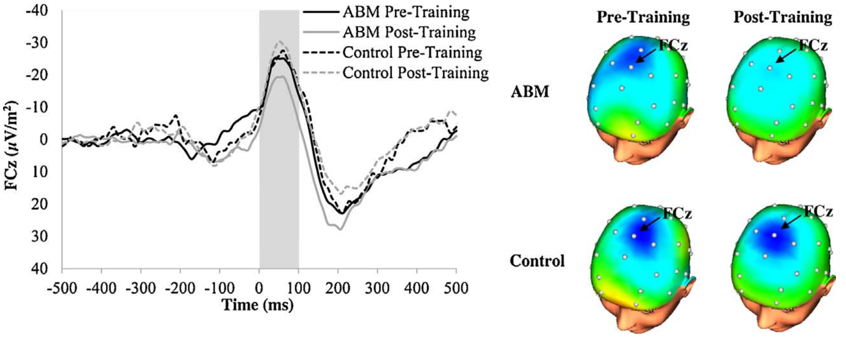

Fig. 2. Attention bias modification and control participants' pre- and post-training error minus correct ERP waveforms (left) and three-dimensional rendered scalp distributions (right) reflecting average activation in the shaded region of the waveform where the ΔERN was scored.

a single session of attention bias modification, and it is unclear whether additional administrations would produce greater reductions in the neural correlates of response monitoring or more reliable measures of change in negative attention bias. Second, the attention bias modification task included neutral, positive, and negative words, while the control task included only neutral and negative words. It is possible that the presence of positive words may have rendered the attention bias modification task more cognitively demanding than the control task, thereby possibly contributing to the reduced ERN, CRN, and ΔERN. Future studies should attempt to match attention bias modification and control tasks on the valence of all the stimuli. Third, the control task did not allow individuals to improve their attention bias. Therefore, it is still unclear whether changes in the neural correlates of response monitoring actually reflect increased attention toward positive information and/or away from negative information, or rather a general improvement in attentional redirection. Future studies should incorporate a more active control task, in which participants can get better at attentional flexibility—to separate out the potential impact of attention *bias* modification from attention modification more broadly. Fourth, the sample was limited to undergraduate participants who were not selected for an aberrant attention bias or high levels of anxiety. Indeed, previous studies suggest that attention bias modification is not likely to have any effect on anxiety in non-pathological samples (Bar-Haim et al., 2007). However, these findings demonstrate that attention bias modification decreases error-related brain activity in individuals with mild to moderate levels of anxiety and lay an important foundation for future research in more severe clinical populations. Finally, it is important to note that the present study employed a CSD transform to the ERN and CRN, which was not conducted in Nelson et al. (2015). Supplementary analyses of the non-CSD (i.e., raw) data indicated that ABM participants demonstrated reductions in the ERN and CRN but not the ΔERN. Similar results were obtained for peak-to-peak analyses; however, it is important to note that peak amplitude can produce a biased measure (Luck, 2005) and is highly sensitive to noise (Clayson, Baldwin, & Larson, 2013). The CSD transform improved spatial and temporal overlap between the response-locked ERP components (e.g., the CRN and ERN) and stimulus-locked ERP components (e.g., P300), and results from these analyses indicated reductions in the ERN, CRN, and the ΔERN. Future studies should consider employing the CSD transform to better isolate response-locked brain activity.

In conclusion, the present study found that a single session of attention bias modification produced a within-subject reduction in the neural correlates of response monitoring, including error-related brain activity. Attention bias modification was designed to target vulnerability to anxiety disorders (Amir et al., 2008; MacLeod et al., 2002), and the ERN has been associated with risk for anxiety disorders (Carrasco et al., 2013; Meyer et al., 2015; Riesel et al., 2011). The present study adds to the attention bias modification literature by indicating that attention bias modification may also alter the ERN—a neural measure posited to reflect individual differences in sensitivity to threat and risk for anxiety. These results are particularly encouraging given that cognitive-behavioral therapy has not been show to impact the ERN (Hajcak, Franklin, Foa, & Simons, 2008; Schoenberg et al., 2014). However, both the present study and Nelson et al. (2015) were conducted in college undergraduates with mild levels of anxiety, and these investigations require replication in clinical and high risk populations. Longitudinal studies are also needed to determine the duration of the effects of attention bias modification on the ERN, and whether the impact of attention bias modification on the ERN leads to decreased anxiety symptoms and the prevention of anxiety disorders.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biopsycho.2017.08.059.

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