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Muted neural response to distress among securely attached people

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Neural processes that support individual differences in attachment security and affect regulation are currently unclear. Using electroencephalography, we examined whether securely attached individuals, compared with insecure individuals, would show a muted neural response to experimentally manipulated distress. Participants completed a reaction time task that elicits error commission and the error-related negativity (ERN)—a neural signal sensitive to error-related distress—both before and after a distressing insecurity threat. Despite similar pre-threat levels, secure participants showed a stable ERN, whereas insecure participants showed a post-threat increase in ERN amplitude. These results suggest a neural mechanism that allows securely attached people to regulate distress.

Keywords: attachment; security; error-related negativity; distress

Seminal attachment theorists proposed that the proximal function of attachment behavior is affect regulation. Bowlby (1973) noted that when faced with distress, most infants seek comfort by approaching and engaging an attachment figure. Other infants, however, seem unable to regulate their distress through proximity-seeking behaviors. Ainsworth *et al.* (1978) similarly observed that infants vary remarkably in attachment-seeking tendencies and affect regulation. Ainsworth pioneered the 'Strange Situation' paradigm, which allows researchers to unobtrusively view infant responses to being separated from their mothers and left with an unfamiliar adult. Securely attached infants reduce distress by seeking closeness with the mother when she returns. Insecurely attached infants, however, are more distressed by the separation and stranger, and do not reconnect as readily with their mothers.

Hazan and Shaver (1987) found that adults display similarly secure and insecure attachment styles in romantic relationships. And like secure infants, secure adults are better able to regulate distress. For example, secure people are able to confidently acknowledge troubling events while maintaining their mood and a positive and stable self-image (Mikulincer, 1998; Mikulincer and Florian, 1998). Such regulatory abilities may account for why secure attachment is associated with better physical and psychological health throughout the lifespan (Feeney, 2000; Morley and Moran, 2011; Esbjørn *et al.*, 2012).

More recently, research has begun to examine neural mechanisms of attachment-related processes. However, an understanding of the neural systems that support individual differences in attachment security and affect regulation is only beginning to emerge (Coan, 2010). Here, we examine neural responses to distressing experiences among securely and insecurely attached individuals.

ATTACHMENT SECURITY AND AFFECT REGULATION

Attachment security is often characterized as confidence that attachment needs will be reliably met with support and comfort from available significant others (Shaver and Mikulincer, 2007). This sense of security is thought to develop over a history of proximity-seeking experiences with a primary caregiver that successfully reduce distress (Mikulincer *et al.*, 2003) or satisfy basic needs (Hofer, 2006). Over time, secure individuals increasingly internalize and generalize these successful attachment and affect-regulation experiences and progressively strengthen positive mental representations of the self and close others (Fredrickson, 2001; Mikulincer *et al.*, 2003; Shaver and Mikulincer, 2007). Attachment insecurity, on the other hand, develops after a history of inconsistent or insufficient support from attachment figures. Insecurely attached people cannot reliably turn to relationships for affect regulation and so they develop alternate strategies to manage emotion, such as hyper-vigilance for, or cognitive suppression of, threatening experiences (Mikulincer and Florian, 1998).

Empirical evidence consistently demonstrates that secure adults are more resilient than their insecure counterparts. Secure individuals react to threats with less rumination, lower levels of negative affect, more stable physiological reactivity, a stable sense of self-esteem and less defensive behavior (Collins, 1996; Feeney and Kirkpatrick, 1996; Mikulincer, 1998; Mikulincer and Florian, 1998; Mikulincer *et al.*, 2003; Shaver and Mikulincer, 2007; Quirin *et al.*, 2008). Whereas the neural processes that support individual differences in attachment security and affect regulation are currently unclear (Coan, 2010), preliminary research suggests that secure people show reduced distress-related brain activity in threatening situations.

For example, in response to angry faces or stressful stimuli, secure attachment has been correlated with decreased amygdala activity, a subcortical group of nuclei involved in fear and anxiety (Lemche *et al.*, 2006; Vrticka *et al.*, 2008). Secure attachment is also correlated with increased hippocampal cell density, a structural marker of resilience (Quirin *et al.*, 2010; cf. Hubel, 1978).

Several functional magnetic resonance imaging (fMRI) studies implicate the anterior cingulate cortex (ACC) in attachment security processes. In one study, lower scores on attachment anxiety (i.e. more attachment security) correlated with reduced activation in the ACC in response to negative thoughts (Gillath *et al.*, 2005). In another study, attachment anxiety correlated with ACC activation during a rejection experience (though, curiously, attachment avoidance was correlated with reduced ACC activation, DeWall *et al.*, 2012). Finally, attachment-related behavior (i.e. holding someone's hand) or simply viewing attachment figures have both attenuated ACC activation (Coan *et al.*,

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2006; Eisenberger *et al.*, 2011). The ACC can therefore be used as a marker of insecurity-related distress (Eisenberger *et al.*, 2003; Shackman *et al.*, 2011).

The current research used a pre–post design to examine how attachment might moderate ACC-generated distress responses after threat. Whereas the above research has focused on correlations between brain activity elicited during relational scenarios and levels of attachment anxiety/avoidance, this study examined reactive neural processes among secure and insecure people before and after a poignant, distress-inducing experience. Specifically, we measured threat-induced changes in the error-related negativity (ERN), an event-related potential that is associated with ACC activation and distress.

THE ERROR-RELATED NEGATIVITY: A NEURAL SIGNAL SENSITIVE TO DISTRESS

The ERN is an electrical waveform measured with electroencephalography (EEG) after participants make errors on reaction time (RT) tasks (Falkenstein *et al.*, 1990; Gehring *et al.*, 1993). The ERN has been source localized to the ACC (Dehaene *et al.*, 1994). Many theorists view the ERN as a neural response to some form of cognitive conflict—either conflict between predicted and actual outcomes (Holroyd and Coles, 2002) or conflict between simultaneous activation of correct and incorrect responses (Yeung *et al.*, 2004). However, researchers have increasingly noted that the ERN may reflect not only conflict detection but also the aversive reaction to such conflict. For example, errors, upon which the ERN is locked, are far from affectively neutral events; rather, they are aversive, prompting sympathetic arousal and potentiating the startle threat response (Critchley *et al.*, 2003, 2005; Hajcak *et al.*, 2003a,b; Hajcak and Foti, 2008). Importantly, the ERN predicts such aversive states (Hajcak and Foti, 2008). Furthermore, larger ERN amplitudes are associated with anxiety-related traits (Hajcak *et al.*, 2003b), the ERN is muted by anxiolytics (Johannes *et al.*, 2001), and experimentally reducing anxiety decreases ERN amplitude (Bartholow *et al.*, 2012; Inzlicht and Al-Khindi, 2012). Thus, the ERN response to error commission may reflect a type of distress that enhances error sensitivity (Bartholow *et al.*, 2005). While this 'error-related distress' may serve to motivate subsequent behavioral control, the ERN is also dissociable from actual performance (Inzlicht and Al-Khindi, 2012; Weinberg *et al.*, 2012).

Consistent with the role of distress in error processing, a recent meta-analysis examining the medial aspect of the ACC found that negative affect, cognitive conflict and pain all activate this same brain region (Shackman *et al.*, 2011). The authors conclude that the medial ACC functions as a mechanism of 'adaptive control' that biases avoidant behaviors by signalling aversive information or uncertainty (Shackman *et al.*, 2011). As a signal generated by the ACC, the ERN is thus amplified by other aversive states that indicate greater need for control, including distress.

In this study, participants twice completed a RT task to elicit behavioural errors. They completed it before and after experiencing a distressing insecurity threat that has caused defensive reactions in past research. Because states of distress reliably predict the ERN (e.g. Inzlicht and Al-Khindi, 2012), we hypothesized that insecure individuals would show increased ERN amplitude after threat whereas secure individuals, who would not be distressed by the threat, would show no increase in ERN amplitude. A pre–post design allowed us to test our prediction that attachment groups would not differ in ERN amplitude at baseline, as secure and insecure people respond similarly to minor stressors (Shaver and Mikulincer, 2007), but differ only following the experimentally induced distress manipulation.

METHODS

Seventy-six right-handed introductory psychology students participated. ERN calculations were based on data from sixty participants who had no fewer than four artefact-free error trials (Olvet and Hajcak, 2009).[1] Four subjects were also excluded due to equipment malfunction ($N = 1$) or incorrectly completing the study materials ($N = 3$), leaving fifty-six participants for analyses (38 females; age mean = 18.5 years, s.d. = 1.2). After completing an attachment style measure, participants then completed a pre-threat multi-source interference task (MSIT). This task reliably induces incorrect responding and activates the ACC during error commission (Bush and Shin, 2006). After the pre-threat MSIT task, all participants completed a two-part insecurity threat, and then completed a post-threat MSIT.

Attachment style measure

Participants completed a single-item, forced-choice measure of attachment style from the Relationships Questionnaire (RQ, see Bartholomew and Horowitz, 1991). Participants read four different descriptions presented simultaneously on the computer screen, each of which reflected an attachment style prototype, and chose the one description that represented them best. These short descriptions were: the *secure* prototype, 'It is relatively easy for me to become emotionally close to others. I am comfortable depending on others and having others depend on me. I don't worry about being alone or having others not accept me'; the *fearful* prototype, 'I am somewhat uncomfortable getting close to others. I want emotionally close relationships, but I find it difficult to trust others completely, or to depend on them. I sometimes worry that I will be hurt if I allow myself to become too close to others'; the *dismissive* prototype, 'I am comfortable without close emotional relationships. It is very important to me to feel independent and self-sufficient, and I prefer not to depend on others or have others depend on me'; and the *preoccupied* prototype, 'I want to be completely emotionally intimate with others, but I often find that others are reluctant to get as close as I would like. I am uncomfortable being without close relationships, but I sometimes worry that others don't value me as much as I value them'. To examine the neural processes of secure *vs* insecure affect regulation, participants who self-identified as having an insecure style (fearful $N = 18$, dismissive $N = 8$, preoccupied $N = 9$) were collapsed into one category, creating a 'secure' ($N = 21$) *vs* 'insecure' ($N = 35$) categorical variable.

Though the RQ measure typically involves forced-choice and Likert ratings of the prototypes, participants completed only the forced-choice item. Importantly, the attachment categories derived from the RQ have been demonstrated to be reliable and valid indices of attachment style (Bartholomew and Horowitz, 1991). For example, 66% of people self-categorized as secure/insecure identify the same self-categorization 8 months later (Scharfe and Bartholomew, 1994). Self-categorization also predicts interview-, parental- and peer-based ratings of attachment style (Griffin and Bartholomew, 1994). Moreover, the larger number of insecure compared to secure people found in this study is consistent with prior research using the RQ measure (Scharfe and Bartholomew, 1994). To further ensure that the RQ measure effectively indexed attachment style, we examined archival data ($N = 206$) that contained this item and the Experiences in Close Relationships-Revised measure (ECR-R; Fraley *et al.*, 2000). The ECR-R is a 36-item measure of attachment-related *anxiety* (degree of fear that close others are unavailable or unresponsive) and *avoidance* (degree of discomfort in getting close to or relying on others)—two

[1]Though Olvet and Hajcak (2009) recommend at least six error trials for a stable ERN, the ERN calculated at four errors appears similarly stable. For example, in Olvet and Hajcak (2009), the signal to noise ratio in the ERN does not change from four to six error trials and ERNs based on four error trials correlate with a grand average ERN at >0.7 (whereas an ERN computed with six error trials correlates with the grand average at >0.8, a non-significant increase).

Table 1 ECR-avoidance and ECR-anxiety means (s.d.) for each RQ attachment category and ECR-mean differences between each RQ category from archival data

	ECR avoidance				ECR anxiety			
	Mean (s.d.)	Mean difference			Mean (s.d.)	Mean difference		
		1.	2.	3.		1.	2.	3.
1. Secure	2.06 (0.58)	—			2.53 (0.63)	—		
2. Fearful	2.85 (0.55)	0.79**	—		3.17 (0.61)	0.64**	—	
3. Dismissive	2.94 (0.63)	0.88**	0.09	—	2.82 (0.59)	0.29†	−0.35*	—
4. Preoccupied	2.65 (0.69)	0.59**	−0.20	−0.29†	3.39 (0.77)	0.86**	0.22	0.57**

*$P < 0.05$; **$P < 0.01$; †$P < 0.10$.

dimensions thought to underlie the four attachment styles (Brennan *et al.*, 1998). As shown in Table 1, people who categorized themselves as secure on the forced choice RQ had significantly lower scores on ECR avoidance and anxiety than people who categorized themselves as preoccupied, fearful or dismissive (all P's < 0.001, except only marginally lower scores than dismissive people on the anxiety subscale). The relatively low anxiety of dismissives is consistent with the definition of ECR dismissiveness as high avoidance and low anxiety (Brennan *et al.*, 1998).

Insecurity threat

All participants were given the insecurity threat. Participants received the following two prompts on the computer: 'Please describe the emotions that the thought of feeling insecure arouses in you' and 'Please jot down, as specifically as you can, what you think will happen to you physically as you feel insecure'. Each prompt was presented for 90 s above a blank text field that allowed participants to type in their responses. In previous research, this threat has caused defensive religious conviction (McGregor *et al.*, 2009) and hostility and aggression towards transgressors or out-group members (see Van den Bos, 2009).

For this study, however, it was important to demonstrate that this manipulation also specifically causes anxiety and distress. Thus, we ran a pilot study in which participants ($N = 100$) were randomly assigned to either the insecurity threat or a control condition that replaced the insecurity words with 'pain at the dentist'. This control condition has been used in dozens of threat studies, and although unpleasant it has not caused pronounced distress or defensiveness in past research (see Burke *et al.*, 2010). After a short delay, participants then reported how the insecurity or dental pain materials made them feel on a range of positive and negative adjectives (from 1—not at all to 5—extremely), which included good, happy, smart, successful, likeable, meaningful, frustrated, confused, uncertain, empty, anxious, ashamed, insecure, lonely, stupid and out of control. We found that compared to the control condition, the insecurity threat caused participants to specifically report more anxiety, $F(1, 98) = 6.49$, $P < 0.05$, $\eta_p^2 = 0.06$. Participants in the insecurity condition also reported marginal increases in feeling uncertain, $F(1, 98) = 3.45$, insecure, $F(1, 98) = 2.98$ and out of control, $F(1, 98) = 3.39$, all P's < 0.10. All other adjectives were non-significant. Thus, the insecurity threat primarily aroused feelings of uncomfortable anxiety, a distressed state related to ERN amplitude (Inzlicht and Al-Khindi, 2012).

The multi-source interference task

Participants were first instructed to press either the numbers 1, 2 or 3 on a keyboard to correspond to a unique digit in a set of three (either 1, 2, 3 or 0) presented on the centre of a computer screen. The unique digit either matched or mismatched its keyboard position. For example, a match trial could show the digits '122' and would require the keystroke '1', whereas a mismatch trial could show the digits '332' and require the keystroke '2'. Each trial began with a row of x's presented in the centre of the screen for 500 ms for fixation. The three-digit set immediately followed for 200 ms. The response window began at digit presentation and lasted until response. Feedback was displayed if the response exceeded 800 ms that read 'Please try to respond faster'. Each MSIT session (pre- and post-threat) involved 3 blocks of 45 trials, in which there were 30 'match' trials and 15 'mismatch' trials.

To examine whether the distress manipulation might differentially change task performance as well as ERN amplitude among insecure *vs* secure people, we also investigated how quickly and accurately participants were able to complete the MSIT trials. For measures of performance we assessed overall error rate, match and mismatch errors, overall RT, match and mismatch RT, the interference effect of mismatch trials (i.e. how much more slowly participants responded to mismatched than matched trials; computed as mismatch trials RT−match trials RT) and post-error slowing (i.e. behavioral adjustment after error commission; computed as post-error trials RT−post-correct trials RT). We also correlated ERN amplitude with post-error slowing to test whether increased ERN amplitude would predict performance adjustments. However, distress could presumably both help and hinder aspects of performance, increasing sensitivity to errors but making people more hesitant and less efficient. Because recent research has demonstrated that anxiety predicts heightened ERN amplitude but not necessarily performance changes (Inzlicht and Al-Khindi, 2012), we anticipated that secure and insecure participants might differ in their ERN amplitude responses to distress but not in task performance.

EEG recording and processing

During both the pre- and post-threat MSIT, EEG and right-eye vertical electro-oculogram activity were recorded and digitized at 512 Hz with average ear reference and forehead ground. Recordings were collected from 32 tin electrode sites positioned according to the 10–20 system, and all impedances were below 5000 Ω. EEG was digitally filtered between 1 and 15 Hz and corrected off-line for eye-blinks using the second-order blind identification (SOBI) procedure (Tang *et al.*, 2005). Movement artefacts were automatically detected with a −75 and +75 μV threshold. For each artefact-free trial, a 1000 ms epoch of EEG signal locked on the button press was selected for averaging (200 ms before–800 ms after the response). The EEG signal was baseline-corrected by subtracting the average voltage during the 300–200 ms time period prior to the response. The ERN was quantified as the peak negative amplitude between 50 ms before and 150 ms after an incorrect response at fronto-central midline electrodes (Cz and FCz). Table 1 shows the average error rate for secure and insecure in the pre- and post-threat MSITs. Higher ERN amplitude is indicated by more negative values. A correct-related negativity (CRN) peak amplitude score was also computed at Cz and FCz and averaged across correct MSIT trials.[2]

RESULTS

We first examined overall error rates. In the pre-threat MSIT participants made 17.07 errors on average (s.d. = 8.99; match trials mean = 0.74, s.d. = 1.49; mismatch trials mean = 16.33, s.d. = 8.16)

[2]We based our choice of electrodes and processing parameters for the ERN on prior research to allow for better comparison (Amodio *et al.*, 2008; Hirsh and Inzlicht, 2008; Inzlicht and Al-Khindi, 2012; Nash *et al.*, 2012; see Luck, 2005). Though a 1 Hz high-pass filter may be viewed as slightly outside the recommendation for more modest filters (Luck, 2005), two recent studies found nearly identical ERN results using a 0.1–15 or a 1–15 Hz window (Inzlicht and Al-Khindi, 2012; Nash *et al.*, 2012). For example, Inzlicht and Al-Khindi (2012) found that an anxiolytic manipulation muted ERN amplitudes computed with both filtering ranges, and that ERN amplitudes were very highly correlated with one another.

Table 2 Means (s.d.s) for pre- and post-threat performance and ERN outcomes between secure and insecure individuals

	Pre-threat MSIT		Post-threat MSIT	
	Secure	Insecure	Secure	Insecure
1. Overall errors	16.7 (7.19)	17.29 (10.00)	17.14 (7.86)	16.32 (10.40)
2. Match errors	0.60 (0.82)	0.82 (1.78)	1.00 (1.18)	0.97 (1.96)
3. Mismatch errors	16.1 (6.91)	16.47 (8.91)	16.14 (7.21)	15.35 (9.11)
4. Overall RT	565.58 (64.79)	533.95 (63.67)	522.98 (55.51)	522.18 (82.12)[a]
5. Match RT	471.35 (61.19)	449.43 (47.47)	442.41 (54.48)	425.48 (36.87)[a]
6. Mismatch RT	754.03 (88.28)	702.99 (134.46)	684.14 (90.84)	715.57 (271.21)
7. Interference effect	282.68 (63.49)	253.56 (125.03)	241.73 (86.13)	290.10 (226.20)
8. Post-error slowing	201.77 (83.48)	162.99 (100.45)	157.58 (68.57)	139.02 (99.34)[a]
9. ERN at Cz	−3.60 (2.55)	−3.98 (2.80)	−4.82 (2.51)	−8.16 (5.54)[b]
10. ERN at FCz	−4.62 (3.40)	−5.02 (3.40)	−5.89 (3.09)	−8.63 (5.42)[b]
11. ERN difference at Cz	−3.43 (2.39)	−3.56 (2.69)	−4.84 (2.99)	−7.71 (5.49)[b]
12. ERN difference at FCz	−3.95 (2.96)	−3.87 (3.21)	−5.63 (3.19)	−7.88 (5.26)

[a]Denotes a significant main effect between pre- and post-MSIT measures across all participants, $P < 0.05$.
[b]Denotes a significant difference between attachment groups within the respective MSIT, $P < 0.05$.

and in the post-threat MSIT participants made 16.64 errors on average (s.d. = 9.44; match trials mean = 0.98, s.d. = 1.69; mismatch trials mean = 15.65, s.d. = 8.38; see also Table 2). We next examined whether attachment security predicted any performance changes on the MSIT task after the insecurity threat. MSIT performance variables—errors (overall, match and mismatch), RT (overall, match and mismatch), interference effect and post-error slowing—were each entered into a between (attachment: secure *vs* insecure) within (pre-threat MSIT *vs* post-threat MSIT) repeated measures ANOVA analysis. All results were non-significant except a general main pre- to post-threat effect on RT variables, including overall RT, $F(1, 54) = 8.43$, $P < 0.05$, $\eta_p^2 = 0.14$; match trial RT, $F(1, 54) = 26.57$, $P < 0.01$, $\eta_p^2 = 0.34$ and post-error slowing, $F(1, 54) = 4.44$, $P < 0.05$, $\eta_p^2 = 0.08$, such that all participants were faster during the post-threat MSIT, particularly match trials (Table 2). These are likely practice effects. Attachment security or the attachment security-threat interaction did not relate to any performance outcomes, however.

For the main analysis we entered the pre-threat-ERN and post-threat-ERN at both Cz and FCz into the same between-within repeated measures ANOVA. Results showed a main effect for the pre–post-threat factor, such that ERN amplitude was greater after the threat; at Cz, $F(1, 54) = 23.42$, $P < 0.001$, $\eta_p^2 = 0.30$ (pre-threat mean = −3.84, s.d. = 2.69; post-threat mean = −6.91, s.d. = 4.89); at FCz, $F(1, 54) = 17.98$, $P < 0.001$, $\eta_p^2 = 0.25$ (pre-threat mean = −4.88, s.d. = 3.38; post-threat mean = −7.60, s.d. = 4.84). Importantly, there was a significant interaction between attachment security and the pre-post-threat factor, at Cz, $F(1, 54) = 7.00$, $P < 0.05$, $\eta_p^2 = 0.12$; at FCz, $F(1, 54) = 4.07$, $P < 0.05$, $\eta_p^2 = 0.07$. Planned comparisons revealed no significant difference between secure and insecure individuals on the pre-threat-ERN, whereas there was a significant difference on the post-threat-ERN; at Cz, $F(1, 54) = 6.77$, $P < 0.05$, $\eta_p^2 = 0.11$; at FCz, $F(1, 54) = 4.46$, $P < 0.05$, $\eta_p^2 = 0.08$. Insecure people showed a significant increase in ERN amplitude from pre- to post-threat; at Cz, $F(1, 54) = 37.35$, $P < 0.001$, $\eta_p^2 = 0.41$; at FCz, $F(1, 54) = 26.10$, $P < 0.01$, $\eta_p^2 = 0.33$, whereas secure people did not, at Cz, $F(1, 54) = 1.92$, $P > 0.10$; at FCz, $F(1, 54) = 1.98$, $P > 0.10$, (Table 2; Figure 1).[3]

ERN difference scores (ERN minus the CRN) at Cz and FCz nodes were also computed to remove processes common to both event-related potentials and isolate an error-specific variable (Luck, 2005). Analyses using pre-threat and post-threat ERN difference scores were nearly identical, as the interaction between attachment and the pre-post-threat factor was again significant; at Cz, $F(1, 54) = 5.39$, $P < 0.05$, $\eta_p^2 = 0.09$; and marginally significant at FCz, $F(1, 54) = 3.60$, $P = 0.06$, $\eta_p^2 = 0.06$. There were no pre-threat differences related to attachment security but there was a significant effect on the post-threat ERN difference score at Cz, $F(1, 54) = 4.84$, $P < 0.05$, $\eta_p^2 = 0.08$; and a marginal effect at FCz, $F(1, 54) = 3.14$, $P = 0.08$, $\eta_p^2 = 0.06$. Specifically, insecure people had a higher ERN difference score than secure people after the threat. Insecure people also showed a large increase in ERN difference score from pre- to post-threat; at Cz $F(1, 54) = 32.99$, $P < 0.001$, $\eta_p^2 = 0.38$; at FCz, $F(1, 54) = 28.33$, $P < 0.001$, $\eta_p^2 = 0.34$. Secure people did not show a significant increase in ERN difference amplitude [though at FCz, there was a marginal increase, $F(1, 54) = 2.97$, $P = 0.09$; see Table 2].

Finally, we explored whether post-error behavioral adjustments may have been related to ERN amplitude within groups. We thus correlated pre-threat-ERN and post-threat-ERN (at Cz and FCz) with the respective post-error slowing variable for both secure and insecure groups. We found that during the pre-threat MSIT, post-error slowing was unrelated to ERN amplitude for both groups (all P's > 0.2). However, during the post-threat MSIT, there was a significant correlation within the secure group, such that larger ERN amplitudes predicted increased post-error slowing; at FCz, $r = -0.61$, $P < 0.05$, at Cz, $r = -0.37$, $P < 0.10$. The same correlation was not significant within the insecure group (P's > 0.5).

In sum, insecure people exhibited a large post-threat increase in ERN amplitude, consistent with research that indicates the ERN is amplified by distress. In contrast, secure individuals showed a much smaller (non-significant) increase in ERN amplitude, suggesting that secure people recovered more quickly from the insecurity threat.[4]

DISCUSSION

This study indexed participants' ERN both before and after an insecurity threat. Because the ERN is thought to be a neural signal of performance monitoring sensitive to (i.e. heightened by) distress (Bartholow *et al.*, 2005; Shackman *et al.*, 2011), we hypothesized that insecure people would be distressed by the threat and show an increased ERN, whereas secure people would not. Results supported this hypothesis. Initially, secure and insecure individuals showed equal ERN amplitudes, suggesting that secure and insecure people respond similarly to minor stressors (Shaver and Mikulincer, 2007), such as error commission. After the threat, however, insecure people showed an increase in ERN amplitude, whereas secure people demonstrated a relatively stable ERN. These results suggest that insecurely attached people become generally hyper-vigilant to negative outcomes after the insecurity threat. In other words, attachment moderates the affective aspects of performance monitoring, albeit without moderating actual behavioral performance.

[3]Reported average ERN amplitude scores differ from the apparent peaks in the group average waveforms from Figure 1 primarily due to the influence of noise and variability in peak latency across subjects (Luck, 2005). Importantly, peak measures, such as the values used here, have been found to be highly reliable (Weinberg and Hajcak, 2011).

[4]Despite the reduced sample size, we explored pre- to post-threat ERN differences among the insecure typologies. The pre-threat-ERN and post-threat-ERN at Cz and FCz were entered into a similar between (attachment: secure *vs* fearful *vs* dismissive *vs* preoccupied) within (pre-threat MSIT *vs* post-threat MSIT) repeated measures ANOVA analysis. Results showed that a significant pre- to post-threat ERN increase was found for both fearful; at Cz $F(1, 52) = 27.98$, $P < 0.001$, $\eta^2_p = 0.35$; at FCz, $F(1, 52) = 22.49$, $P < 0.001$, $\eta^2_p = 0.31$; and for preoccupied individuals; at Cz, $F(1, 52) = 6.38$, $P < 0.05$, $\eta^2_p = 0.11$; at FCz, $F(1, 52) = 5.43$, $P < 0.05$, $\eta^2_p = 0.10$. However, dismissive people showed only a marginal increase in ERN at Cz, $F(1, 52) = 3.56$, $P < 0.07$, $\eta^2_p = 0.07$; and no increase at FCz, $F(1, 52) = 1.16$, $P > 0.2$. These results, albeit hampered by the small n, suggest that dismissive people resemble their secure counterparts and may also be able to mute distress caused by the threat, consistent with their known ability to suppress unwanted emotions (Shaver and Mikulincer, 2007).

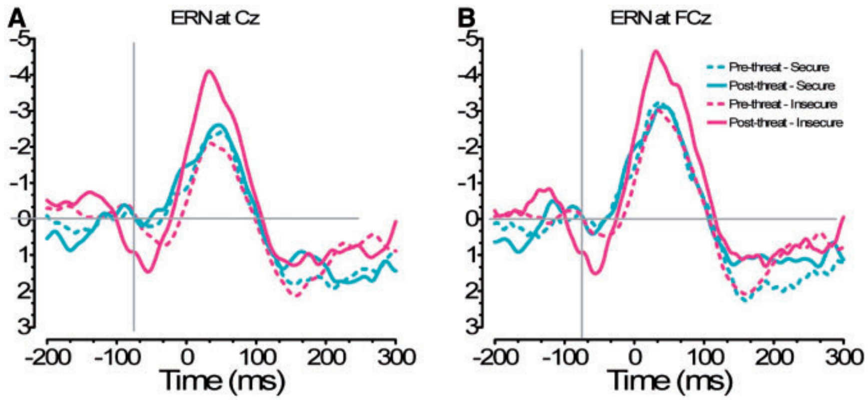

Fig. 1 Pre- and post-threat MSIT error-related potentials at electrode (**A**) Cz and electrode (**B**) FCz for secure and insecure individuals.

These results are an important addition to an incipient literature on the neural instantiation of attachment security (see Coan, 2010). Recall that the ERN has been reliably localized to the ACC—a cortical structure that is sensitive to aversive outcomes and activates avoidance-related processes (Shackman *et al*., 2011). These results suggest that secure people may evidence lower levels of threat-induced psychophysiological arousal and defensiveness due to lower ACC reactivity to threats.

How might attachment security mute ACC reactivity?

Secure attachment has been associated with a number of neurophysiological processes related to ACC activation and affect regulation. First, secure attachment has been found to predict higher levels of the neuropeptide oxytocin in humans (Tops *et al*., 2007). Though its function is still debated (see Chen *et al*., 2011 and De Dreu *et al*., 2011), oxytocin is strongly implicated in affiliation, and like attachment security, oxytocinergic processes appear to develop with positive experiences of social support (Carter, 1998). Oxytocin has also been demonstrated to be anxiolytic, modulating activation in the amygdala, the hypothalamic–pituitary–adrenal axis, and the ACC (Carter, 1998; Kirsch *et al*., 2005; Tops *et al*., 2007; Baumgartner *et al*., 2008; Petrovic *et al*., 2008). For example, intranasal administration of oxytocin suppresses cortisol and reduces subjective anxiety (Heinrichs *et al*., 2003). Thus, ERN amplitude in secure individuals may have been muted through oxytocinergic processes.

Secure attachment has also been associated with heightened orbitofrontal activation during emotion regulation (Gillath *et al*., 2005). The orbitofrontal cortex (OFC) is known to inhibit other cortical and subcortical areas, including the amygdala and the ACC, during the regulation of negative affect (Amat *et al*., 2005; Johnstone *et al*., 2007). OFC inhibitory processes also develop over a history of successful affect regulation experiences and help 'inoculate' people from future stressors (Amat *et al*., 2005; Quirk and Beer, 2006). Recall the fMRI study in which more securely attached individuals show reduced ACC activation to negative relationship scenarios (Gillath *et al*., 2005). Intriguingly, secure people in this study also showed heightened activation in the OFC after the same negative relational scripts. The current results extend this correlational evidence by showing that secure people react to poignant threats with reduced neural alarm and, presumably, less ACC activation. Together, these findings suggest that secure individuals may have muted ACC activation through OFC inhibitory processes.

Attachment processes have also been related to the brain's endogenous opioid system (Nelson and Panksepp, 1998). In particular, opioids tend to be released in response to social contact and bonding, inhibiting pain and distress. Genetic variation in the μ-opioid receptor gene (OPRM1) has been linked to attachment security (Barr *et al*., 2008). Securely attached individuals may thus have functionally higher levels of opioid activity due to their perceptions of secure social bonds, thereby reducing the potency of any personal threats that they encounter. Indeed, individuals with μ-opioid receptor alleles promoting more sensitive opioid systems tend to demonstrate less ACC activity following social rejection (Way *et al*., 2009).

Finally, securely attached people may regulate distress by activating approach-motivated processes. Secure people tend to adopt approach motivated strategies to deal with distress (Mikulincer and Florian, 1998) and recent research suggests that approach motivation uniquely mutes distress. For example, distress-inducing events cause reactive approach motivation (Nash *et al*., 2011) and approach motivation predicts decreased ERN amplitude (Nash *et al*., 2012).[5]

These potential neural mechanisms need not be exclusive and could form the neurobiological instantiation of Bowlby's attachment system (see Johnstone *et al*., 2007, for a similar neural system of affect regulation among the non-depressed). Future research could examine whether oxytocinergic, OFC, opioid and approach motivation processes act on the ACC and interact with attachment security.

LIMITATIONS AND FUTURE DIRECTIONS

We note certain opportunities to extend these results. Past research suggests that anxious people may show the strongest reaction to aversive events given their tendency to become hyper-vigilant in stressful situations, whereas avoidant-dismissive individuals could mirror secure people given their skills at suppressing stressful cognitions and emotions (Shaver and Mikulincer, 2007; DeWall *et al*., 2012). Exploratory analyses (see note 4) hinted that this was indeed the case, as dismissive people, like secure individuals, did not show a significant ERN increase after threat. On the other hand, avoidant individuals do evidence increased autonomic reactivity and fail at

[5]Intriguingly, increased ACC activation has also been associated with better emotion regulation (Ochsner *et al*., 2002; Hariri *et al*., 2003). Plausibly, then, secure people could have evidenced a larger ERN increase to threat than evidenced by insecure people as secure people are better at emotion regulation. However, this alternative hypothesis would have been inconsistent with the effect of distress on ERN amplitude (Hajcak and Foti, 2008) and the psychological and physiological evidence demonstrating that secure people are unperturbed by distress (Quirin *et al*., 2008). Thus, we expected and found that secure people would evidence a stable ERN to threat. This is consistent with the ACC's role in signalling the need for regulation rather than engaging in regulation itself (Shackman *et al*., 2011). Finally, it is possible that the stable ERN seen among secure people could have been a downstream result of muted amygdala activation as the amygdala is important for the generation and expression of affect and shares rich reciprocal connections with the ACC (Ghashghaei *et al*., 2007). Future studies will be needed to examine this possibility.

suppression when cognitively taxed. Thus, we are hesitant to make any claims regarding dismissive individuals given the small sample size. Future research should probe differences in neural reactivity among participants with insecure styles after cognitively taxing manipulations, perhaps utilizing different measures of attachment security.

Another potential limitation is that the pre–post design makes it difficult to rule out the possibilities that mere duration or task repetition caused the ERN increase rather than the insecurity threat. It is unclear why task duration or repetition would increase ERN only among insecure people, however. The ERN also reliably decreases over time or number of trials (Olvet and Hajcak, 2008), in direct contrast to the increased ERN among insecure participants in this study. We do note that although the effectiveness of the insecurity threat was not directly measured in the current study, it did specifically cause anxious distress in our pilot study and the ERN is sensitive to distress. Thus, the most parsimonious interpretation of our result is that the increased ERN amplitude reflects distress caused by the threat. Future research could supplement the current findings by incorporating a between-subjects design.

It is also noteworthy that ERN amplitude was increased by distress for the insecure group but this heightened sensitivity to errors did not translate into actual performance gains. This suggests that, for the insecure, error sensitivity does not necessarily lead to improved performance or control (see Inzlicht and Al-Khindi, 2012, for a similar dissociation between the ERN and performance). ERN amplitude predicted post-error slowing only for secure people and only after the insecurity threat. This is particularly notable given that secure people did not show any significant changes in ERN and post-error slowing was reduced for both groups. Though the ERN has been found to predict post-error slowing (e.g. Gehring *et al.*, 1993), other research has failed to demonstrate such a relation (e.g. Hajcak *et al.*, 2003b). Consistent with the current results, correlations between the ERN and performance may be dependent upon both individual and situational variables (Weinberg *et al.*, 2012). Future research should continue to explore when and for whom the ERN predicts control and performance.

Finally, the current research leaves it as an open question whether secure people are initially buffered from distress (i.e. they simply do not find the threat to be bothersome), or whether they quickly reduce distress. Secure people may be reacting in some way immediately after experiencing distress that allows them to rapidly regulate their emotional state (e.g. activating the attachment system, see Mikulincer and Florian, 1998). Future research could explore how attachment security impacts the specific temporal sequence of affect regulation and neural reactivity to distress.

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