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Attentional Control Moderates Relations Between Negative Affect and Neural Correlates of Action Monitoring in Adolescence

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This study examined the moderating role of attentional control on relations between negative affect and action monitoring event related potentials (ERPs) (error-related negativity (ERN) and N2) in a group of healthy adolescents (9 to 17 years old). These ERPs were recorded while participants completed a modified flanker task. Participants also completed the negative affect subscale of the Positive and Negative Affect Schedule for Children (PANAS–C) and the attentional control subscale of the Early Adolescent Temperament Questionnaire–Revised (EATQ–R). Regression analyses revealed negative affect by attentional control interactions, suggesting that youth high in attentional control and high in negative affect show increased N2 amplitude and a trend toward increased ERN amplitude. These findings are discussed with regard to the interface of attention and emotion processes that are implicated in action monitoring and relevance to the study of self-regulation during adolescence.

The ability to monitor and regulate our actions, particularly when faced with emotionally salient events, represents an important set of skills that influence decision-making and goal-oriented behavior. These skills undergo important developmental changes in adolescence and depend, in part, on the maturation of a network of prefrontal and subcortical neural regions (Dahl, 2004; Steinberg, 2005; Steinberg, 2007). One of these neural regions, the anterior cingulate cortex (ACC), is a structure in the medial wall of the prefrontal cortex that is considered as a transitional cortex interfacing emotion, cognition, and action (Devinsky & Luciano, 1993; Devinsky, Morrell, & Vogt, 1995; Vogt & Pandya, 1987). The ACC has been found to be implicated in action monitoring, which is an aspect of self-regulation that integrates emotion, cognition, and behavior.

Action monitoring refers to the ability to monitor and control self-initiated actions, which involves error detection and conflict monitoring. In recent years, a number of studies have capitalized on the temporal resolution of event related potentials (ERPs) to measure the timing of action monitoring processes. They have identified two medial-frontal ERPs that index electrophysio-

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logical correlates of action monitoring: the error-related negativity (ERN) and the N2 (Dehaene, Posner, & Tucker, 1994; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Coles, Meyer, & Donchin, 1995; Gehring, Goss, Coles, Meyer, & Donchin, 1993; van Veen & Carter, 2002b). Source localization studies have found that these action monitoring ERPs have neural generators in the ACC.

Recent work has begun to document how these action monitoring ERPs change across development and to what extent they may be sensitive to individual differences, particularly those related to affect. For instance, some research studies indicate that these ERPs undergo important changes in adolescence (Davies, Segalowitz, & Gavin, 2004; Ladouceur, Dahl, & Carter, 2007) and that they may be sensitive to varying levels of negative affect (Hajcak, McDonald, & Simons, 2003; Hajcak, McDonald, & Simons, 2004). Given that adolescence is a key developmental period during which there are important maturational changes in neural systems underlying the monitoring and regulation of behavior, examining how differences in the level of negative affect might impact these ERPs associated with action monitoring in adolescents can advance our understanding of the neural mechanisms underlying self-regulation and its development.

The ERN is a response-locked sharp negative deflection occurring between 50–150 msec after the execution of an incorrect response. The N2 is a negative-going ERP that is evoked approximately 250 msec following stimulus onset in correct high-conflict trials. Both ERPs have been assessed in cognitive tasks that elicit conflict such as the Eriksen flanker task (Eriksen & Eriksen, 1974). Traditionally, the N2 has been associated with response inhibition (e.g., Falkenstein, Hoormann, & Hohnsbein, 1999; Garavan, Ross, Murphy, Roche, & Stein, 2002; Kok, 1986; Pfefferbaum, Ford, Weller, & Kopell, 1985). The interpretation of the N2 as reflecting response inhibition stems from findings from multiple studies reporting an N2 using a Go No-Go task, frequently used to assess inhibitory control. Using the Go No-Go, the N2 can be detected approximately 200–300 msec following stimulus onset and is usually greater in No-Go than Go trials (Eimer, 1993; Fallgatter & Strik, 1999). Several source localization studies have suggested that the neural generators of the Go No-Go N2 to be in the vicinity of the inferior and lateral prefrontal cortex (Kiefer, Marzinzik, Weisbrod, Scherg, & Spitzer, 1998; Lavric, Pizzagalli, & Forstmeier, 2004). Others, however, have implicated both the prefrontal cortex and the ACC as plausible loci of the N2 (Bokura, Yamaguchi, & Kabayashi, 2001), suggesting that the ACC may play a monitoring role whereas the PFC may be involved in response inhibition per se. As such, the N2 has been considered, along with the ERN, as an ERP associated with action monitoring processes (Ladouceur et al., 2007; Lavric et al., 2004; van Veen & Carter, 2002a; Yeung & Cohen, 2006). Indeed, further support for this view stems from the fact that ERN and N2 amplitudes are maximally distributed at fronto-central sites (Gehring et al., 1993) and that both have neural generators in the vicinity of the dorsal region of the ACC (e.g., Herrmann, Rommler, Ehlis, Heidrich, & Fallgatter, 2004; van Veen & Carter, 2002a; Yeung, Botvinick, & Cohen, 2004). Moreover, developmental studies have demonstrated that the ERN and N2 may undergo similar developmental changes in childhood and adolescence, both reaching adult amplitude levels in mid-to-late adolescence (Davies et al., 2004; Ladouceur, Dahl, & Carter, 2004; Ladouceur et al., 2007). Thus, focusing on both the ERN and the N2 and to what extent they may be sensitive to individual differences within the same study has the potential of providing further insight into the neural mechanisms of action monitoring.

Indeed, although the focus of the research regarding the functional significance of the ERN and N2 has largely been on the cognitive processes indexed by these components, there are a growing

number of studies describing the influence of motivation, affect, and other emotion-laden factors on these components. For example, Luu, Collins, and Tucker (2000) reported significant correlations between negative affect and ERN amplitudes in college students (Luu, Collins, & Tucker, 2000). Specifically, ERN amplitudes were greater in college students who were high on self-reported negative affect. These findings, however, applied only to the first quartile of the trials of the task used to assess ERN. In order to further substantiate the relationship between negative affect and ERN amplitudes, Hajcak et al. (2004) used a between-group design to compare ERN amplitudes and other error-related psychophysiological measures (e.g., skin conductance response (SCR)) in subjects that were either high or low in self-reported negative affect, using the Positive and Negative Affect Scale (PANAS) (Watson, Clark, & Tellegen, 1988). As a secondary aim, they also compared the same variables in sub-groups of high-negative affect with different levels of positive affect. These authors found, consistent with Luu et al. (2000), that subjects high in self-reported negative affect exhibited increased ERN amplitude as well as increased error-related responses on other psychophysiological indices, including SCR. Furthermore, they found that within the negative affect group, levels of positive affect did not have a moderating effect on these error-related psychophysiological indices (Hajcak et al., 2004).

Hajcak et al.'s (2004) findings are consistent with findings of increased error-related brain activity associated with anxiety and depression (Gehring, Himle, & Nisenson, 2000; Hajcak et al., 2003; Hajcak & Simons, 2002; Johannes et al., 2002; Johannes et al., 2001; Ladouceur, Dahl, Birmaher, Axelson, & Ryan, 2006; Luu et al., 2000). For instance, Hajcak, McDonald, and Simons (2003) found that college undergraduate students who scored high on general anxiety and worry self-report measures tended to have increased ERN amplitudes (Hajcak et al., 2003). Other authors have also found increased ERN amplitude in children and adults diagnosed with OCD as well as children diagnosed with an anxiety disorder (Johannes et al., 2001; Ladouceur et al., 2006; Santesso, Segalowitz, & Schmidt, 2006). With regard to depression, Tucker et al. (2003) documented increased ERN amplitude in individuals diagnosed with clinical depression (Tucker, Luu, Frishkoff, Quiring, & Poulsen, 2003). Other studies, however, did not observe such a relation between ERN amplitude and depression (Ruchsow et al., 2004) or found that depression was associated with decreased ERN amplitude (Ruchsow et al., 2006). Differences in the clinical characteristics of the samples and methodological procedures may account for the discrepancy in these findings. Nevertheless, some have argued that the increased ERN is not a function of either anxiety or depression per se, but could reflect an underlying characteristic of high negative affect present in both disorders (Hajcak et al., 2004; Tucker, Derryberry, & Luu, 2000).

Although fewer studies have been conducted with the N2, there is some evidence linking N2 with negative emotional evaluation (Lewis, Lamm, Segalowitz, Stieben, & Zelazo, 2006; Lewis, Todd, & Honsberger, 2007). For instance, Lewis and colleagues examined medial-frontal ERPs, including the ERN as well as the frontal N2—or inhibitory N2 thought to index inhibitory control mechanisms. In two recent studies, they reported increased N2 amplitudes to angry compared to happy faces in a group of 4–6-year-old children (Lewis et al., 2007; Todd, Lewis, Meusel, & Zelazo, 2008). They also reported that negative mood induction (created by the loss of earned points) was associated with increased N2 amplitude in a modified Go No-Go task in normal 13–16-year-old children (Lewis et al., 2006).

In sum, there is mounting evidence suggesting that medial-frontal ERPs associated with action monitoring processes, such as the ERN and N2, are larger in the presence of negative emotion. One possible explanation for the changes in the amplitude of these ERPs is that they may index af-

fective responses to conflict or error commission. This explanation, however, precludes the role of emotion in modulating attention to emotionally salient events.

Another, perhaps more plausible explanation is that negative emotions may increase the *saliency* of conflict and errors and in this way contribute to greater mobilization of attentional resources dedicated toward monitoring conflict or errors. Such an increase of attentional resources should be associated with greater activity of the dorsal ACC and translate into an increase in ERN and N2 amplitudes. Changes in these ERPs in the context of emotional information or emotional states (e.g., monitoring of self-initiated actions while perceiving threatening information or experiencing strong emotions) may reflect changes in action monitoring processes that in turn influence self-regulation of behavior (e.g., Larson et al., 2006; Lewis et al., 2006; Wiswede, Münte, Goschke, & Rüsseler, 2009). For instance, high levels of negative affect may alter the threshold dedicated to detecting conflict or errors and as a consequence, signal the need to modify behavior in ways that may be maladaptive given a particular context. Given that attentional control plays an important role in the modulation of attention toward or away from emotionally salient information (Derryberry & Reed, 2002), it is possible that it may be involved in moderating the effects of negative affect on action monitoring processes.

Attentional control, as assessed within a temperament system framework (Rothbart & Sheese, 2007), is considered an important aspect of effortful control—a dimension of temperament referring to the ability to inhibit a dominant (habitual) response to perform a subdominant one (Rothbart, Ellis, Rueda, & Posner, 2003). It includes both attention focusing, or the ability to pay attention to a task over time without being distracted, and attention shifting, which is concerned with flexibility in attention that permits voluntary shifts from one stimulus to another (Derryberry & Reed, 2002; Posner & Rothbart, 2000).

Recent studies have found inverse relations between negative affect (or emotionality) and attentional control. For instance, several studies have demonstrated that performance on cognitive tasks (e.g., slower reaction times) is altered when subjects are presented threat-related stimuli or distracters thought to be anxiety inducing (for a review, see Vasey & MacLeod, 2001). Derryberry et al. (2002) found that such an attentional bias to threat-related stimuli was greater in anxious adults who were low in attentional control. Similar findings were reported in children (Derryberry & Reed, 2002). Lonigan, Lonigan, Vasey, Phillips, & Hazen (2004) found that children with high levels of negative affectivity, a temperament risk factor for anxiety disorder, and lower levels of attentional control exhibit a stronger attentional bias toward threat (Lonigan et al., 2004). Lower levels of attentional control also have been associated with higher levels of internalizing symptoms and threat interpretations distortions in children (Muris & Ollendick, 2005).

The aim of the present study was to examine relations between negative affect, attentional control, and medial-frontal ERPs associated action monitoring processes, namely the ERN and N2, in a group of healthy adolescents. Based on previous research demonstrating positive relations between negative affect and ERN and N2 amplitudes and inverse relations between negative affect and attentional control, we predicted that attentional control may play a moderating role in the relations between negative affect and ERN and N2 amplitudes. In other words, we predicted that participants high in negative affect and low in attentional control would exhibit greater ERNs and N2s while performing a cognitive task. As discussed earlier, if negative affect increases the emotional saliency of conflict or errors, then subjects who are low in attentional control would be less able to modulate attentional resources allocated to processing conflict or errors, and as such would exhibit greater medial-frontal ERPs. Conversely, we predicted that subjects high in negative af-

fect and high in attentional control would exhibit lower-amplitude ERNs and N2s because such subjects would be able to better modulate attention to conflict or errors.

METHOD

Participants

The study comprised 40 adolescents ranging in age from 9 to 17 years. Of these, 10 participants were excluded because they did not have complete data sets (i.e., complete self-report and EEG data). In addition, 1 participant was excluded from both ERN and N2 analyses because of a high level of artifact in more than 50% of the EEG data. This yielded a total of 29 participants who were included in the N2 analyses (mean age = 12.4, *SD* = 1.86; 10 girls). Of these, 13 were not included in ERN analyses because they either had too few errors or too few good error EEG segments (i.e., less than 20) thus yielding a total of 16 participants who were included in the ERN analyses (mean age = 13, *SD* = 1.97; 6 girls). Participants were screened for neurological and psychiatric disorders, and for visual acuity. All participants were native English speakers. The University of Pittsburgh Institutional Review Board approved the study. Participants under 18 years of age and their parents were required to sign assent and informed consent forms, respectively.

Self-Report Measures

Early Adolescent Temperament Questionnaire (EATQ–R; Ellis & Rothbart, 2001). The EATQ–R is a questionnaire designed to assess temperament in children and adolescents based on the temperament model developed by Rothbart and colleagues (Rothbart & Bates, 1998). It includes the following scales: activation control, affiliation, attention, fear, frustration, high intensity pleasure, inhibitory control, pleasure sensitivity. Each item is rated on a five-point scale ranging from 1 = hardly ever true to 5 = almost always true. The EATQ–R has been reported to have good reliability (Ellis & Rothbart, 2001). The data presented here focus on ratings of attentional control as measured by the child self-report attention subscale, which reflects the capacity to focus attention as well as to shift attention when desired.

Positive and Negative Affect Schedule–Child Version (PANAS–C) (Laurent et al., 1999). The PANAS-C consists of 30 items scored on a scale of 1 (very slightly or not at all) to 5 (extremely) assessing the extent to which a variety of emotional words reflect how participants have been feeling during the past few weeks. Half of the items assess positive affect (PA) and half, negative affect (NA). Laurent et al. (1999) reported adequate reliability for the negative affect and positive affect scales (.92–.94) of the PANAS–C. The data presented here focus on ratings from the negative affect scale of the PANAS–C.

Task

EEG measures were taken while participants performed an arrow version of the Eriksen flanker task with congruent (i.e., →→→→→ and ←←←←←) and incongruent (i.e., ←←→←← and →→←→→) conditions (Eriksen & Eriksen, 1974). The five-arrow stimulus arrays were presented using E-prime (Psychological Software Tools, Pittsburgh, PA). Each trial started with the

presentation of a central fixation cross "+." Following the fixation cross, one of the four stimulus arrays (→→→→→, ←←←←←, ←←→←←, →→←→→) appeared on the computer screen. The probability of occurrence of each stimulus array was .25. Participants were asked to respond by pressing a button on a button box using their left index finger if the central arrow pointed to the left and their right index finger if the central arrow pointed to the right. In order to enhance the effect of the flankers with regard to priming incorrect responses in the incongruent condition, the flanker stimuli appeared 100 msec prior to the target stimulus, which appeared in the same location as the fixation cross. Flankers and the central arrow remained on the screen until a response was made after which they disappeared simultaneously and a fixation cross appeared, which indicated the intertrial interval. The intertrial interval was randomized between 500 and 1,500 msec. Each block of trials began with a fixation cross having a duration of 3,000 msec.

Procedure

Participants were seated at a distance of approximately 0.5 m from the monitor. After a description of the experiment, participants were given detailed task instructions. They were told that they were going to see a series of trials with five arrows appearing on the computer screen and that they had to press the left button with their left index finger if the arrow in the middle pointed to the left and press the right button with their right index finger if the arrow in the middle pointed to the right. They were also told to respond as quickly and as accurately as possible. To ensure that participants remained motivated through out the task, they were told at the beginning of the task that they could win a "cash bonus" if they performed extremely well on this task (all were told that they did very well and received an extra $5). After hearing the instructions read by the experimenter, participants were asked to repeat them back to the experimenter to ensure that they understood the instructions. They then proceeded to complete one block of 60 practice trials. The experimenter monitored participants' performance during the practice block and provided appropriate feedback.

Following the electrode net application, the experimenter asked participants to try not to move, grind their teeth, or blink too much. If they felt the need to blink, they could do so while the fixation cross was on the screen. Before starting the task, the experimenter reminded participants of the instructions and answered any questions. After a short practice session, participants received five blocks of 120 trials with each block initiated by the participant. Participants were permitted to rest between blocks. The percentage of correct responses was computed between blocks informing the experimenter of the participants' performance; this information was used to guide the experimenter in providing feedback to participants. It was not made available to participants. If the percentage of correct responses was above .95, the experimenter reminded participants to be accurate but to go faster. If the percentage of correct responses was below .80, the experimenter reminded participants to go fast but to be more accurate. Participants filled out the self-report measures after completing the flanker task. Once testing was completed, participants were briefed on the purpose of the experiment.

EEG Data Acquisition and Processing

The electroencephalogram (EEG) was recorded using a 128-channel Geodesic Sensor Net and sampled at 250 Hz, using EGI software (Electrical Geodesic, Inc., Eugene, OR). EEG was re-

corded with a 0.1–100 Hz bandpass filter (3 dB attenuation) and digitized using a 12 bit A/D converter. Data acquisition was started after all impedances for all EEG channels were reduced to below 50 kΩ. During data acquisition, all channels were referenced to channel 129 (Cz) and later re-referenced, prior to data analyses, against an average reference (Bertrand, Perrin, & Pernier, 1985; Tucker, Liotti, Potts, Russell, & Posner, 1993). Impedances were measured prior to and following EEG recording. Channels that had impedances above 100 kΩ at the end of the recording session were noted and visually inspected during the data processing phase.

EEG data processing involved the following steps. EEG data were digitally filtered using a 0.3–30 Hz bandpass filter. For the ERN, the EEG was segmented into epochs from 400 msec before to 800 msec after response onset and divided according to correct and error trials. For the N2, the EEG was segmented into epochs from 400 msec before to 800 msec after stimulus onset and divided according to congruent and incongruent correct trials. Segments that had reaction times lower than 100 msec and higher than 2,000 msec were not included. Artifacts were screened with automatic detection methods using NetStation software (Electrical Geodesics, Inc.). Artifact rejection criteria were defined as 70 μV for eye blinks or eye movements. A segment was marked bad if it contained more than 10 bad channels. A channel was marked bad in one of three conditions: (1) when the fast average amplitude exceeded 100 μV; (2) differential average amplitude exceeded 200 μV; or (3) the channel showed zero variance. In addition, channels were excluded if they contained more that 20% bad channels across the entire recording and interpolated using spherical spline interpolation including all channels of the spherical surface of the head (Perrin, Bertrand, & Pernier, 1987). The percentage of good segments that were included in individual averages was 60 (*SD* = 16) for the ERN and 64 (*SD* = 19) for the N2.

EEG Data Reduction and Analyses

To quantify the response-locked ERN, averages were computed separately for correct and erroneous trials. Trials with reaction times less than 100 msec or greater than 2,000 msec were excluded. The data were then baseline corrected, which involved subtracting from each data point after response onset the average activity in the 100-msec window (–150 to –50 msec) prior to response onset. The ERN was scored as the largest negative deflection with a medial-frontocentral topography between 0–120 msec following response onset. To quantify the stimulus-locked N2, averages were computed separately for correct congruent and incongruent trials. For the N2, baseline correction involved subtracting from each data point after stimulus onset the average activity in the 100-msec window prior to stimulus onset. The N2 was scored as the largest negative deflection with a medial-frontocentral topography between 250–370 msec following the onset of the central arrow on correct trials (see Figure 1).

Statistical Analysis

Statistical analyses were performed on the behavioral and ERP measures using SPSS (version 16.0). Specifically, behavioral measures were analyzed using a repeated measures ANOVA model with trial type (congruent, incongruent) and response type (correct, error) as within-subject variables. Greenhouse-Geisser correction was applied upon any violations of the assumption of sphericity. Follow-up analyses included univariate analyses of variance and t-tests with Bonferonni correction. Outlying reaction time data points less than 100 msec or greater than 2,000

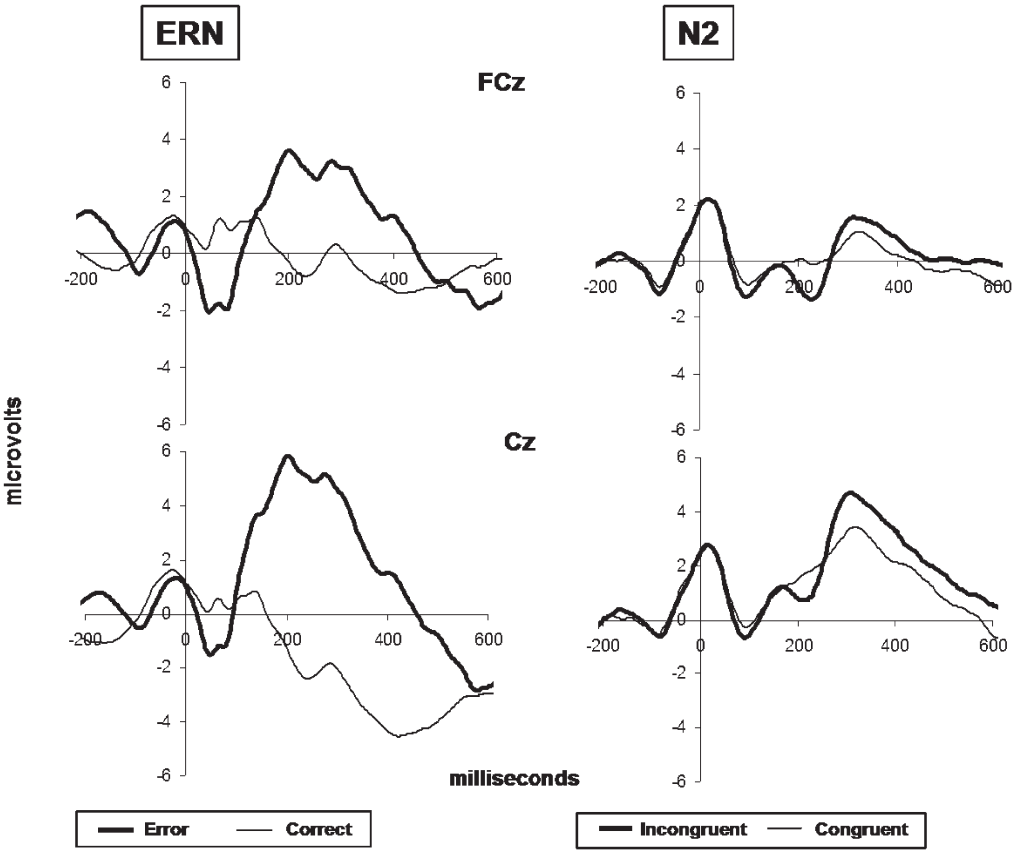

FIGURE 1 Grand averaged response-locked error-related negativity (ERN) and stimulus-locked (N2) waveforms at the FCz and Cz electrode sites.

msec were filtered out. Descriptive analyses were performed on the behavioral data and presented (see Table 1). Difference waveforms were calculated for the ERN and N2. For the ERN, each point of the correct trial was subtracted from the error trial response-locked waveform. For the N2, each point of the correct congruent trial was subtracted from the correct incongruent trial stimulus-locked waveform. We then calculated the adaptive mean for each of the difference waveforms (over the 0–120 msec post-response window for the ERN and the 250–370 msec following the onset of the central arrow on correct trials for the N2). One sample *t*-tests were computed to examine whether the adaptive means were significantly different from zero. Furthermore, means and correlations between the predictor variables and the dependent variables were calculated. Regression analyses were used to test whether attentional control moderated the relations between negative affect and the action monitoring ERPs (i.e., ERN and N2). All variables included in the regression model were centered and interaction terms were created by multiplying the centered variables (negative affect × attentional control). Because prior studies have documented age differences in ERN and N2 amplitude (Davies et al., 2004; Ladouceur et al., 2007), age was used as a covariate.

TABLE 1
Means and Standard Deviations on Behavioral Performance Measures

Variables	*Mean (SD)*
Reaction Time	
Overall	489.42 (105.85)
Correct	466.05 (97.10)[a]
Incorrect	365.76 (90.32)[a]
Congruent	455.17 (96.60)
Incongruent	523.67 (117.16)
Post-error slowing	22.91 (49.8)
Percentage of Errors	
Overall	8.10 (4.23)
Congruent	2.48 (2.28)
Incongruent	13.72 (7.04)

$N = 29$; *SD*: Standard deviations; [a]Scores based on subset with error-related negativity data ($N = 16$).

Separate analyses were conducted to assess the interactions between negative affect and attentional control on each dependent variable (ERN and N2) controlling for age. Age was entered first into the model, followed by negative affect and attentional control. Finally, an interaction between negative affect and attentional control was created and entered into the model. All analyses were conducted on the restricted (main effects only) and full (main effects and interactions) models. Post-hoc probing was conducted to interpret interactions only for models yielding a significant change in R^2 with the inclusion of interaction terms (Cohen, Cohen, West, & Aiken, 2003).

RESULTS

Behavioral Data

Table 1 presents mean reaction time and accuracy measures. There was a significant trial type main effect for reaction time, $F(1, 28) = 104.62$, $p < .001$, indicating, as expected, that participants had slower reaction times on incongruent than congruent trials. There was also a significant response type main effect, $F(1, 15) = 170.49$, $p < .001$, indicating, as expected, that participants had faster reaction times on incorrect than correct trials. Furthermore, they committed significantly more errors on incongruent than congruent trials, $F(1, 15) = 105.78$, $p < .001$, and had significantly slower reaction times on correct trials following error trials than on correct trials following correct trials, $F(1, 28) = 6.14$, $p < .01$. Finally, bivariate correlations between the overall percentage of errors and correct RTs ($r(16) = –.22$), and the percentage of errors and incorrect RTs ($r(16) = –.25$) indicated that there were no overall speed–accuracy trade-offs.

Event Related Potentials

One-sample *t*-tests were computed to test whether the adaptive means for the ERN and N2 waveforms at the medial-frontocentral electrode sites were significantly different from zero. The ERN

difference waveform was significantly different from zero at FCz, t (15) = –5.95, $p < .001$, and Cz, t (15) = –3.48, $p < .01$. The N2 difference waveform was also significantly different from zero at the FCz, t (28) = -3.22, $p < .01$, and Cz, t (28) = –2.44, $p < .05$. Because the effects were greater at FCz site, adaptive means and standard deviations are reported for the ERN in Table 2 and for the N2 in Table 3. Moreover, adaptive means at FCz were entered into the regression model.

Correlation Analyses

Tables 2 to 3 also present zero-order correlations of the key variables in the study. Negative affect was significantly positively correlated with N2 amplitude. It appeared to be also positively correlated with ERN, but this effect was a trend (Table 2). Negative affect was also negatively correlated with attentional control, but only for N2 (Table 3).

Regression Model

Error-related negativity (ERN). Regression analysis with ERN as the dependent variable and negative affect as the predictor can be found in Table 4. The full model, assessing attentional control as the moderator, reflected a trend in the change in R^2 compared to the restricted model, with 41% of the variance explained, $F(1, 11) = 4.39$, $p = .06$. Because of the strength of the relationship, we nevertheless explored the main effects and interactions and found a trend for a negative affect by attentional control interaction effect, t (11) = –2.10, $p = .06$. We examined the simple

TABLE 2
Descriptive Statistics and Correlations for Indicator Variables for ERN (FCz) (N = 16)

	ERN	*Attentional Control*	*Negative Affect*
ERN	—		
EATQ–R Attention	–.18	—	
PANAS–C (Neg)	.40^{+}	–.32	—
Mean	–3.24	3.39	1.60
Standard Deviation	2.21	0.81	0.44

$^{+}p < .10$; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$. ERN = error-related negativity;
EATQ–R = Early Adolescent Temperament Questionnaire–Revised; PANAS–C = Positive and Negative Affect Schedule–Child Version.

TABLE 3
Descriptive Statistics and Zero-Order Correlations for Indicator Variables for N2 (FCz) ($N = 29$)

	N2	*Attentional Control*	*Negative Affect*
N2	—		
EATQ–R Attention	–.08	—	
PANAS–C (Neg)	.40*	–.46**	—
Mean	–1.02	3.42	1.60
Standard Deviation	1.71	0.79	0.61

$^{+}p < .10$; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$. EATQ–R = Early Adolescent Temperament Questionnaire–Revised; PANAS–C = Positive and Negative Affect Schedule–Child Version.

TABLE 4
Regression Analyses of Negative Affect and Attentional Control on ERN

	B	*SE (B)*	R^2	R^2 *Change*	*F Change*	*P Change*
I. Restricted Model			0.17			
Age	.14	.32				
Negative Affect	.43	.30				
Attentional Control	–.10	.29				
I. Full Model			0.41	0.24	4.40^{+}	0.06
Age	.04	.28				
Negative Affect	.06	.32				
Attentional Control	–.21	.27				
Negative Affect × Attention Control	$-.59^{+}$	.28				

$^{+}p < .10$; $*p < .05$; $**p < .01$; $***p < .001$. ERN = error-related negativity.

effects of negative affect at 1 standard deviation above, below, and at the mean of attentional control as recommended by Aiken and West (2001). Estimated regression lines for each of these levels of attentional control are presented in Figure 2. Results suggest that attentional control might moderate the relations between negative affect and ERN amplitude in that children with higher levels of negative affect and attentional control tended to have more negative ERN amplitude.

N2. Regression analysis with N2 as the dependent variable and negative affect as the predictor can be found in Table 5. The full model, assessing attentional control as the moderator, re-

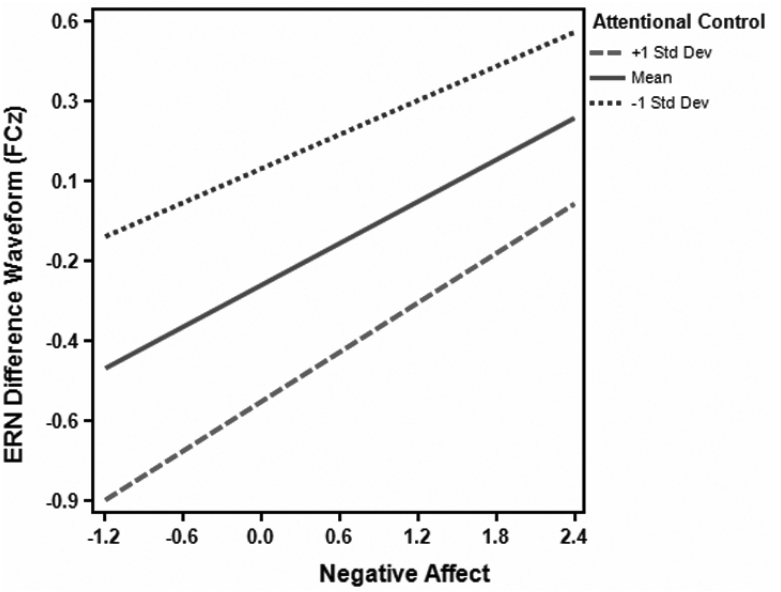

FIGURE 2 Attentional control tends to moderate relations between negative affect and error-related negativity (ERN). Participants high in negative affect and attentional control tend to have greater ERN.

TABLE 5
Regression Analyses of Negative Affect and Attentional Control on N2

	B	*SE (B)*	R^2	R^2 *Change*	*F Change*	*P Change*
I. Restricted Model			0.17			
Age	0.01	.19				
Negative Affect	0.46	0.21				
Attentional Control	0.13	0.21				
I. Full Model			0.42	0.25	10.41^{**}	0.004
Age	–0.07	0.16				
Negative Affect	–0.14	0.26				
Attentional Control	–.04	0.18				
Negative Affect × Attentional Control	$–0.74^{**}$	0.23				

$^{+}p < .10$; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

flected a significant change in R^2 compared to the restricted model with 42% of the variance explained, $F(1, 24) = 10.41$, $p < .005$. While there was a significant main effect for negative affect in the restricted model, $t(24) = 2.23$, $p < .05$, in the full model, this was subsumed under a significant negative affect by attentional control interaction, $t(24) = –3.23$, $p < .005$. We examined the simple effects of negative affect at 1 standard deviation above, below, and at the mean of attentional control as recommended by Aiken and West (1991). Estimated regression lines for each of these levels of attentional control are presented in Figure 3. Here, attentional control moderated the relations between negative affect and N2 amplitude. Children with higher levels of negative affect and attentional control had more negative N2 amplitude.

DISCUSSION

In this study, we had predicted that adolescents high in negative affect and low in attentional control would exhibit larger ERNs and N2s. This prediction was based on the reasoning that if negative affect increases the emotional saliency of conflict or errors (by mobilizing attentional resources), then adolescents who are low in attentional control might be less able to modulate attentional resources necessary to processing conflict or errors, and therefore would exhibit greater medial-frontal ERPs. Instead, we found that adolescents high in negative affect and high in attentional control exhibited greater N2 amplitudes. A trend was found for ERN indicating that adolescents high in negative affect and high in attentional control might exhibit greater ERN amplitudes. It is possible that our results for the ERN did not reach statistical significance due to the smaller sample size for these analyses.

Because of the developmental changes in ERN and N2 (Davies et al., 2004; Ladouceur et al., 2007), age was entered into the model but it did not impact the relations between the predictor variables and action monitoring ERPs. Furthermore, behavioral data replicated earlier findings with faster reaction times on error trials than on correct trials and faster reactions and less errors on congruent than incongruent trials. As in previous studies using this task with adolescents, we also observed slower reaction times on correct trials following error trials (i.e., post-error slowing) (Davies et al., 2004; Ladouceur et al., 2004, 2007).

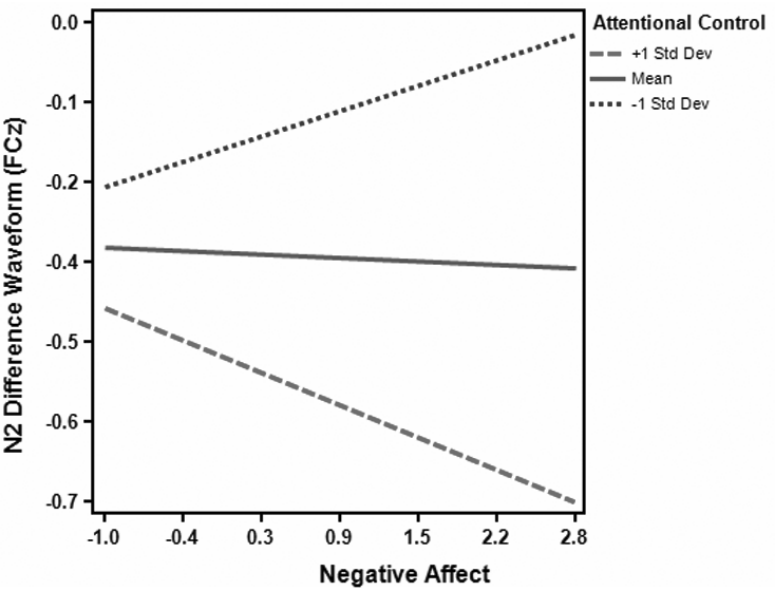

FIGURE 3 Attentional control moderates relations between negative affect and N2. Participants high in negative affect and attentional control have greater N2.

These findings suggest that both cognitive and affective processes are important to the goal of understanding individual variations in ERN and N2 amplitudes. Yet, there remains a good deal of uncertainty as to the details of how these processes interact in relation to action monitoring. There is some value in considering different theoretical approaches that have been used in the adult literature to interpret the functional role of these action monitoring ERPs in order to elucidate how the interaction of cognitive and affective processes might be associated with changes in ERN and N2.

For example, according to the "conflict monitoring" theory, both the ERN and N2 are believed to index conflict monitoring processes. The ERN is thought to reflect an evaluative process that serves to detect conflict or "crosstalk" between executed incorrect response and activation of correct response through ongoing stimulus evaluation (for a review, see Yeung et al., 2004). The stimulus-locked N2 is also thought to reflect an evaluative process that serves to detect conflict or "crosstalk" but it is between correctly executed responses and pre-potent response tendencies. Given that both the ERN and N2 have neural generators in the same region of the ACC, it is thought that these may reflect similar cortical mechanisms (Kopp, Rist, & Mattler, 1996) or more general conflict monitoring processes (Donkers & van Boxtel, 2004). According to this view, sensitivity of detecting conflict is determined by a certain threshold level (Botvinick, Cohen, & Carter, 2004; Carter et al., 1998). The threshold level can increase or decrease depending on various factors such as how many attentional resources are being allocated to monitoring performance. For example, ERN amplitudes are more negative when subjects focus attention on performance accuracy (Gehring et al., 1993) or are made to feel self-conscious about their performance (Hajcak, Moser, Yeung, & Simons, 2005). Accordingly, it is possible that, in the current study, high levels of negative affect combined with a tendency to focus attention on goal-directed activi-

ties may have translated into increased sensitivity in detecting conflict (i.e., lower threshold level) and consequently larger ERN and N2 amplitudes.

If we consider an alternative theoretical perspective—the view that errors or the possibility of making an error, such as when participants process stimuli containing incongruent information, are emotionally salient—then it is possible that the greater capacity to focus attention can become a liability when negative affect is high. For instance, Pérez-Edgar and Fox (2007) recently reported that children whose mother rated them as being high in attentional control had significantly slower reaction times to social negative words when performing an emotional Stroop task. These findings were contrary to their predictions that children low in attentional control would exhibit stronger attentional biases when processing social negative words (Pérez-Edgar & Fox, 2007). The authors interpreted these findings as possibly indicating that, when faced with varying levels of threat, children rated high in attentional control may rely more heavily on a certain cognitive strategy reflecting a well-developed selective attention system. If we extend this interpretation to findings in the current study, it is possible that adolescents rated high in attentional control *and* high in negative affect may tend to over-focus on errors or the possibility of making errors or over-rely on a conflict evaluation system that prioritizes ongoing conflict information. Accordingly, a "well-primed" attentional system, as that of adolescents rated high in attentional control, may become a liability if it brings into greater focus the commission of errors or response conflict.

Such a liability could also be explained according to the "processing-efficiency hypothesis" (Eysenck, Derakshan, Santos, & Calvo, 2007). According to this hypothesis, anxious individuals are thought to require greater activation of brain systems supporting cognitive control processes (e.g., ACC, dorsolateral prefrontal cortex) in order to maintain equivalent performance than non-anxious individuals. In the current study, we measured self-rated levels of negative affect, which consists of items reflecting negative affect, including feelings of anxiety. According to the "processing-efficiency hypothesis," high levels of anxiety could intrude on the normal cognitive processes by taking up attentional resources due to excessive worry or rumination intended to dispel dysphoric emotions (Borkovec & Roemer, 1995). However, in an effort to maintain a standard level of performance on the task, subjects may exert a compensatory enhancement of cognitive effort in order to regulate the effects of anxiety on cognition. Such an enhanced effort could contribute to increased neural activity in the ACC. In the current study, the increased neural activity in the ACC could be associated with action monitoring processes and translate to greater N2, and possibly greater ERN amplitudes.

It is also important to consider these findings with the broader goals of understanding the development of self-regulation in adolescence. Examining changes in ERPs associated with action-monitoring represents one promising approach to investigating the neural mechanisms of self-regulation. Our findings suggest that action monitoring involves a set of complex interactions between cognitive and affective processes that undergo important maturational changes extending into adolescence. Negative affect appears to interact with cognitive control of attention in ways that can influence neural systems that contribute to self-regulation of behavior and real-life decision making. Such findings also has implications in advancing our understanding of the neural systems implicated in the regulation of emotion-related behavior as well as our understanding of these systems in both normal development and developmental psychopathology (Phillips, Ladouceur, & Drevets, 2008). Clearly, there is a need for larger studies and perhaps better measures of attention and emotion.

There are also other limitations to this study that could be addressed in future research. For instance, replicating this study with a larger sample is necessary, particularly with regard to examining more closely the relations between negative affect, attentional control and their interaction on ERN. Also, given recent evidence of changes in emotional reactivity associated with puberty (Dahl & Spear, 2004; Steinberg, 2007), recruiting adolescents within a narrower age-range but varying in the level of pubertal maturation would enable us to examine more specifically the effects of other developmental factors such as puberty. It is possible that the influence of negative affect on the saliency of errors, for example, might be greater as adolescents enter into puberty. Furthermore, both negative affect and attentional control measures were derived from self-report questionnaires. Finding other ways to manipulate affect (e.g., mood induction) and measure attentional control (e.g., computerized paradigms) would enable us to further examine how attention–emotion interactions are implicated in action monitoring processes.

To summarize, we have demonstrated that interactions between negative affect and attentional control predict increased amplitudes of action monitoring ERPs, particularly N2, in a group of healthy adolescents. These findings are contradictory to our predictions that high attentional control would attenuate relations between high negative affect and ERN and N2 amplitudes. Nevertheless, these findings represent an initial attempt to explore the role of attention–emotion processes in modulating action monitoring ERPs and its implications for understanding mechanisms underlying self-regulation in adolescence.

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