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Emotion Down-Regulation Diminishes Cognitive Control: A Neurophysiological Investigation

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Traditional models of cognitive control have explained performance monitoring as a "cold" cognitive process, devoid of emotion. In contrast to this dominant view, a growing body of clinical and experimental research indicates that cognitive control and its neural substrates, in particular the error-related negativity (ERN), are moderated by affective and motivational factors, reflecting the aversive experience of response conflict and errors. To add to this growing line of research, here we use the classic emotion regulation paradigm—a manipulation that promotes the cognitive reappraisal of emotion during task performance—to test the extent to which affective variation in the ERN is subject to emotion reappraisal, and also to explore how emotional regulation of the ERN might influence behavioral performance. In a within-subjects design, 41 university students completed 3 identical rounds of a go/no-go task while electroencephalography was recorded. Reappraisal instructions were manipulated so that participants either down-regulated or up-regulated emotional involvement, or completed the task normally, without engaging any reappraisal strategy (control). Results showed attenuated ERN amplitudes when participants down-regulated their emotional experience. In addition, a mediation analysis revealed that the association between reappraisal style and attenuated ERN was mediated by changes in reported emotion ratings. An indirect effects model also revealed that down-regulation predicted sensitivity of error-monitoring processes (difference ERN), which, in turn, predicted poorer task performance. Taken together, these results suggest that the ERN appears to have a strong affective component that is associated with indices of cognitive control and behavioral monitoring.

Keywords: emotion regulation, self-control, performance monitoring, error-related negativity

The efficient pursuit of our everyday goals depends critically upon our capacity to detect and resolve spontaneously occurring challenges to performance. As part of guiding ongoing behavior, efficient performance monitoring predicts individual differences in adaptive life outcomes across a variety of social, personality, and affective domains, including academic attainment (Hirsh & Inzlicht, 2010; Johns, Inzlicht, & Schmader, 2008), the restriction of racially prejudiced behaviors (Amodio et al., 2008; Payne, Shimizu, & Jacoby, 2005), and the regulation of negative emotions (Compton et al., 2008). Although it has been shown that performance monitoring is associated with a number of positive outcomes, the precise nature of these control functions is currently disputed. In recent years, considerable debate has centered on the extent to which affective processes drive evaluative and executive aspects of cognitive control (Botvinick, 2007; Inzlicht & Al-Khindi, 2012; Legault & Inzlicht, 2013). In the current study, we demonstrate that conflict monitoring functions are not devoid of emotion, but that they also possess inherent affective qualities. Through the use of the explicit emotion-regulation paradigm, we offer evidence that affective experience is a component of conflict detection and performance monitoring functions.

Performance Monitoring

Over the past two decades, considerable research has investigated the neural substrates of cognitive control. One widely studied electrophysiological correlate of performance monitoring is an event-related potential (ERP) called the error-related negativity (ERN or Ne; Falkenstein, Hohnsbien, Hoormann, & Blanke, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The ERN reflects a negative deflection in response-locked electroencephalographic (EEG) activity which demonstrates maximal amplitude at fronto-central electrode sites, 80 ms–100 ms after error commission. Converging evidence from ERP source localization techniques (Dehaene, Posner, & Tucker, 1994; Gehring, Himle, & Nisenson, 2000; van Veen & Carter, 2002), functional neuroimaging (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; van Veen & Carter, 2002), and intracerebral EEG recordings (Pourtois et al., 2010) propose the anterior cingulate cortex (ACC) as the

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most likely neural generator of this early neurophysiological response to errors. As the ERN is present in a variety of cognitive tasks (Riesel, Weinberg, Endrass, Meyer, & Hajcak, 2013), across multiple stimulus presentation and response modalities (Endrass, Reuter, & Kathmann, 2007; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Holroyd, Dien, & Coles, 1998), the component is widely assumed to reflect the operation of a generic, multimodal, performance monitoring system.

Cognitive neuroscience approaches have traditionally led the theoretical framing of the ERN. Importantly, these cognitive accounts view the ERN as a correlate of executive functions responsible for the strategic regulation of cognition and performance. Botvinick, Braver, Barch, Carter, Barch, and Cohen (2001) postulated that the ERN reflects conflict monitoring functions that reside within the ACC. Under this framework, high response conflict occurs after errors due to the transient coactivation of opposing response channels representing the committed error and the task-appropriate, correct response (Gehring & Fencsik, 2001; Yeung, Botvinick, & Cohen, 2004). This conflict monitoring hypothesis further suggests that executive aspects of cognitive control are up-regulated as a function of the conflict strength computed by the ACC. An alternative model (Holroyd & Coles, 2002) proposes that the ERN reflects reinforcement learning processes, driven by functional interactions between the ACC and the mesencephalic dopamine system. According to this view, the ERN reflects a discrepancy between a desired or expected outcome (i.e., a correct response) and the actual outcome (i.e., an error response). Consequently, the ERN reflects an early neurocognitive indicator that ongoing events are evaluated as “worse” than expected (Holroyd & Coles, 2002; Stahl, 2010). In turn, these reinforcement learning signals train the ACC to select the appropriate “motor controller” to guide future performance (Holroyd & Coles, 2002). Importantly, although the conflict monitoring and reinforcement learning models provide divergent accounts of the precise computational basis of the ERN (see Gehring, Liu, Orr, & Carp, 2012 for a review), these cognitive models mutually assume that the ERN reflects performance monitoring processes while failing to consider the more central role of emotion.

Affective Modulation of the ERN and Control

In addition to preceding increased cognitive control, errors are aversive events (Hajcak & Foti, 2008), which are associated with subjective experiences of distress (Spunt, Lieberman, Cohen, & Eisenberger, 2012). The aversive quality of errors is supported by multiple psychophysiological phenomena triggered by error commission, such as increased skin conductance (Hajcak, McDonald, & Simons, 2003; O’Connell et al., 2007), potentiated startle response (e.g., Hajcak & Foti, 2008; Riesel, Weinberg, Moran, & Hajcak, 2013), and contraction of the corregator supercilii (frowning) muscle (Lindström, Mattson-Mårn, Golkar, & Olsson, 2013). Furthermore, intracranial local field potential recordings in humans reveal error-related activity in the ACC, but also in deeper limbic structures commonly associated with affective processing, such as the amygdala (Brázdil et al., 2002; Pourtois et al., 2010), suggesting that error-monitoring involves the integration of both affective and cognitive information processing (Pourtois et al., 2010; Bush, Luu, & Posner, 2000). What’s more, both contemporary and historic perspectives of ACC function have emphasized the sensitivity of this neural structure to both cognitive control and negative affect/arousal (Ballantine, Cassidy, Flanagan, & Marino, 1967; Corkin & Hebben, 1981; Rainville, Duncan, Price, Carrier, & Bushnell, 1997; Shackman et al., 2011). A recent neuroimaging meta-analysis indicates that largely overlapping portions of the ACC track the seemingly heterogeneous processes related to negative affect, cognitive control, and pain (Shackman et al., 2011). These findings, along with others that advocate for the integration of emotion and cognition (e.g., Zelazo & Cunningham, 2007), provide further evidence that affective properties play an important role in cognitive processes like performance monitoring and behavioral control. Building off of the theoretical integration of emotion and cognition, these studies indicate that error commission produces a psychophysiological profile consistent with a negative affective event (see Gross, 1998; Lindström et al., 2013; Pourtois et al., 2010; Spunt et al., 2012).

In further support of an affective conceptualization of the ERN, there is strong evidence that the component is modulated by both state and trait emotional factors. First, larger ERNs have been reported in anxious psychopathologies, such as obsessive–compulsive disorder (OCD, Gehring, Himle, & Nisenson, 2000) and generalized anxiety disorder (GAD, Weinberg, Olvet, & Hajcak, 2010; Weinberg, Klein, & Hajcak, 2012), postulating that errors are particularly threatening for such cohorts (Hajcak, 2012). Similarly, enhanced ERNs have also been observed among nonpatient groups, such as those high in anxious anticipation (Moser, Moran, & Jendrusina, 2012), trait-anxiety (Aarts & Pourtois, 2010), trait negative affect (Luu, Collins, & Tucker, 2000; Hajcak, McDonald, & Simons, 2003, 2004; Santesso, Bogdan, Birk, Goetz, Holmes, & Pizzagalli, 2012; Yasuda, Atsushi, Miyawaki, Kumano, & Kuboki, 2004), neuroticism (Eisenberger et al., 2005; Olvet & Hajcak, 2012; Pailing & Segalowitz, 2004), and obsessive–compulsive personality symptoms (Hajcak & Simons, 2002), indicating that error-related threat sensitivity is also a feature of subclinical samples. Second, state increases in the ERN have been observed in task contexts where errors are punished (Potts, 2011; Riesel, Weinberg, Endrass, Kathmann, & Hajcak, 2012), when performance is explicitly evaluated by an experimenter (Hajcak, Moser, Yeung, & Simons, 2005), when performance contexts include derogatory external feedback (Wiswede, Münte, & Rüsseler, 2009a), or when negatively valenced pictures are presented between trials of a flanker task (Wiswede, Münte, & Rüsseler, 2009b). Not all studies, however, find these effects. Larson, Baldwin, Good, and Fair (2006), for example, found an increase in ERN amplitude when pleasant pictures, but not negative ones, were superimposed between task trials; Clayson, Clawson, and Larson (2012) found that, despite changes in emotion ratings, manipulating state affect had little influence on ERN amplitude, and Larson, Gray, Clayson, Jones, and Kirwan (2013) found that valence and arousal did not differentiate ERN amplitude, although difference wave ERN (ERN minus CRN) was related to arousal but not valence. In light of these findings, several authors have proposed that the ERN tracks the affective or motivational significance of errors and is modulated by both contextual and dispositional factors (Amodio, Master, Yee, & Taylor, 2008; Gehring & Willoughby, 2002; Hajcak & Foti, 2008; Luu, Collins, & Tucker, 2000; Riesel et al., 2012). Important for current concerns, however, the evidence of the affective and motivational variation in ERN amplitude is still currently mixed and little is known about how exactly these emotion properties relate to instrumental behaviors of cognitive control and performance monitoring (e.g., Shackman et al., 2011).

Thus, several questions remain, and accounting for the specific role of affective processes in cognitive control is a significant challenge to ongoing research. It is currently unclear, for example, if emotion—in particular, negative affect—reflects an epiphenomenal experience of a conflict detection process, or if affect itself plays a key role in the initiation of control (cf., Yeung et al., 2004). An instrumental view of "on-task" emotion has recently been iterated by several authors. The affect alarm model proposes that the affective sting experienced during conflict and errors act as a distress signal, warning that instrumental control is needed (Bartholow et al., 2005; Inzlicht & Al-Khindi, 2012; Hobson, Inzlicht, & Al-Khindi, 2013). Similarly, Botvinick (2007) proposed that the ACC might conduct a cost-benefit analysis of ongoing information processing, with conflict registering as one potential cost, which is then met with the up-regulation of cognitive control. What is also less known is the distinction between incidental and integral affect and the differentiated effects they may have on the neurophysiological and behavioral correlates of performance monitoring. The majority of studies looking at the link between emotion, ERN, and cognitive control do so by manipulating an incidental discrete emotion, like when participants undergo a negative or positive mood induction while viewing valenced images (e.g., Larson, Gray, Clayson, Jones, & Kirwan, 2013; Wiswede, Münte, & Rüsseler, 2009b). However, the effects of integral-based affect are less known. The negative emotion states that are integrally related to the task itself naturally arise when dealing with conflict detection and error commission, and, as research has shown, can often map onto feelings of anxiety (Inzlicht & Al-Khindi, 2012) and frustration (Spunt et al., 2012). Given this important distinction, it stands to reason that integral, on-task affect—separate from incidental, discrete emotion states—has a unique effect on performance monitoring processes. Thus, the aim of the current study is to test whether ERN amplitude and behavioral control can be altered when manipulating the appraisal of people's task-related negative affective responses through emotion regulation.

Emotion Regulation

Pioneering theoretical advances from the psychoanalytical (Breuer & Freud, 1957; Freud, 1946) and stress/coping traditions (Lazarus, 1966) led to the empirical and formal investigation of emotion regulation (Gross, 1998). A broad process model of emotion regulation distinguishes between antecedent- and response-focused regulation strategies (Gross, 2002). Antecedent-focused strategies occur before the emotional response, and most notably take the shape of cognitive reappraisal. In contrast, response-focused strategies happen after the emotional response has unfolded, typically manifesting as suppression behaviors (Gross, 1998). Importantly, the two responses have different affective trajectories and selective psychophysiological experiences (Gross, 2002). The emotional reappraisal strategies, as compared with suppression responses, attenuate adverse cognitive, affective, and physiological consequences of emotional experience, and as such are generally viewed as the more adaptive form of emotion regulation (Gross, 1998; Gross, 2002; Gross & Thompson, 2007; Ochsner & Gross, 2005).

In light of cognitive reappraisal's capacity to alter the emotional experience, and given the association between emotion and the ERN, we wondered if cognitive reappraisal—the deliberate up- and down-regulation of one's emotions—can differentially influence ERN amplitude. If this shows to be the case, it would provide further evidence for the influence of affective processes on the ERN, and performance monitoring more generally. The current study borrows from a recent neuroimaging study by Ichikawa et al. (2011) in which they found that emotion reappraisal of error-specific negative affect led to the selective recruitment of midcingulate brain regions, which, in turn, predicted subsequent errors during a cognitive control task. To our knowledge, however, this is the only study to date which has looked the effect of reappraisal of integral negative affect on cognitive control. The question remains of whether the specific temporal dynamics of error-monitoring, as captured by EEG and the ERN component specifically, are similarly influenced by the appraisal of task-related emotion processing. Thus, the aim of the present study was to test the following related hypotheses: (a) the ERN can be modulated by conscious, emotion reappraisal strategies, such that down-regulating one's emotions will lead to a dampened ERN amplitude while up-regulating one's emotions will lead to a heightened ERN amplitude; and (b) the ERN modulations impacted by reappraisal strategy will subsequently impact behavioral correlates of cognitive control; that is, a dampened ERN amplitude will be related to poorer cognitive control (i.e., more errors) while a heightened ERN will be related to improved control. We hypothesized that performance monitoring possesses certain affective qualities and that the ability to monitor effectively can be altered by the increased or decreased experience of emotions. At present, no EEG study has directly manipulated task-related negative affect through emotion reappraisal regulation strategies during a cognitive control task. The goal for the current study, therefore, is to formally investigate the link between integral negative affect and the neural and behavioral markers of performance monitoring.

Method

Participants and Procedures

Forty-eight introductory psychology students at the University of Toronto Scarborough participated for course credit. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. We decided, a priori, to terminate data collection at the end of the term provided that we had upward of 40 participants at that point (a sample size that is not unlike previous studies with similar methodological and repeated measures designs; e.g., Krompinger, Moser, & Simons, 2008). Seven participants were excluded from all analyses due to computer/hardware malfunction ($n = 5$), too few errors ($n = 1$), or high EEG artifact rates ($>$35% artifacts; $n = 1$). This left us with a sample of 41 participants (29 females, 12 males; mean age = 19 years, $SD = 1.64$ years). Participants were told that the purpose of the study was to investigate the role of emotion and personality on cognitive performance.

Emotion regulation manipulations. Explicit emotion reappraisal strategies were manipulated using a within-subjects design consisting of three conditions: down-regulation, up-regulation, and a control. The order of condition was counterbalanced across participants. Following traditional emotion regulation paradigm manipulations (e.g., Gross, 1998), participants were given the following instructions:

> For the next part of the task, we ask that you adopt a detached attitude as you complete the task. Think about the task in a cold, emotion-free, analytical way. View the task from a third-person perspective. Try to remove and disengage yourself from the task as much as possible.

In the up-regulation condition, the instructions were as follows:

> For the next part of the task, we ask that you adopt an involved attitude as you complete the task. Immerse yourself in the task; really feel all the emotions going through you as you complete the task. Think of the task as being personally very important to you, as being vital for your self-identity.

Last, in the control condition, participants were asked to complete the task as they normally would, without any further instructions. The instructions were a specific form of reappraisal and differed from traditional positive/negative reappraisal that is often used in the emotion regulation literature. Specifically, participants were asked to engage in emotional detachment during down-regulation and personal emotional involvement during up-regulation (see Gross, 1998). Furthermore, the context in which the reappraisal instructions were given differs from previous studies where, for instance, participants are given specific instructions to reappraise their emotions in direct response to a particular event like positive or negative valenced images (Hajcak & Nieuwenhuis, 2006) or errors (Ichikawa et al., 2011). Contrasted with these studies, the current reappraisal instructions did not explicitly mention the target of reappraisal (i.e., commission of errors). Rather, participants were asked to reappraise any emotions throughout the duration of the task. By using these nonspecific reappraisal instructions, our aim was to have participants down- and up-regulate their affective states as they naturally arose during their performance, so that, in effect, any efforts of reappraisal were aimed directly at the integral sources of task-related negative affect.

Go/no-go task. In all three conditions, participants completed an identical go/no-go task. Participants were instructed to press a button if they saw a "go" stimulus (i.e., the letter M) and to refrain from pushing the button if they saw a "no-go" stimulus (i.e., the letter W). On each trial, a fixation cross was presented in the middle of the screen for 300 ms–700 ms, followed by either a "go" or "no-go" stimulus for 100 ms. Participants were given a maximum time of 500 ms to respond on each trial. Within each condition, participants completed four blocks, each consisting of 40 "go" trials and 10 "no-go" trials. Trials were presented randomly within blocks. For each condition, participants' average reaction time (RT) for go and no-go (i.e., errors of commission) responses were measured; the number of errors of commission and the number of errors of omission (i.e., failing to respond on a go trial) were also measured.

Self-reported emotional involvement. In order to measure participants' fluctuating emotional experiences across the different types of reappraisal strategies, participants were asked after each condition to rate on a 7-point Likert scale how involved they were, ranging from *detached* to *involved*, and also how emotional they were, ranging from *full of emotion* to *emotionless.* The second rating checks were scaled in the reverse in order to insure that participants were paying close attention; they were reverse scored during analyses. A higher score therefore indicated being more involved and emotional. The two checks had a low internal consistency, Cronbach's $\alpha = .572$, therefore, independent analyses were conducted on each scale.

Neurophysiological Recording

Continuous EEG was recorded during the go/no-go task using a stretch Lycra cap embedded with 32 tin electrodes (Electro-Cap International, Eaton, OH). Recordings used average ear and a forehead channels as reference and ground, respectively. The continuous EEG was digitized using a sample rate of 512 Hz, and electrode impedances were maintained below 5 kΩ during recording. Offline, EEG was analyzed with Brain Vision Analyzer 2.0 (Brain Products GmbH, Munich, Germany). EEG data was corrected for vertical electro-oculogram artifacts (Gratton, Coles, & Donchin, 1983) and digitally filtered offline between 0.1 and 30 Hz (FFT implemented, 24 dB, zero phase-shift Butterworth filter). The signal was corrected using a 200 ms baseline which commenced 200 ms before the response. An automatic procedure was employed to detect and reject artifacts. The criteria applied were a voltage step of more than 25 μV between sample points, a voltage difference of 150 μV within 150 ms intervals, voltages above 85 μV and below −85 μV, and a maximum voltage difference of less than 0.50 μV within 100 ms intervals. These intervals were rejected from individual channels in each trial. An epoch was defined as 200 ms before and 800 ms after the response. Data for these epochs were averaged within participants independently for correct and incorrect trials, and then grand-averaged within the respective emotion regulation conditions. Error and correct-related brain activity was defined as the mean amplitude between 0 ms and 100 ms postresponse at the frontocentral electrode, FCz. We opted to use a mean amplitude measure for the ERPs as such measures provide more reliable ERP measurements than peak amplitudes (Luck, 2005). ERN calculations were based on no fewer than five artifact-free error trials (Olvet & Hajcak, 2009). In light of recent evidence pointing to the weak internal consistency of the go/no-go task in ERN calculations (Meyer, Bress, & Proudfit, in press), it is important to note that the average total number of error trials that were used in the ERN averaging were well above five ($M = 16.6$; $SD = 6.7$).

Results

Self-Reported Emotional Involvement: Manipulation Check

Analyses revealed that self-report levels of involvement and emotional feelings during task performance reflected the changing reappraisal strategies (see Table 1). A 3-way repeated measures ANOVA with rated level of task involvement as the dependent variable revealed a significant main effect, $F(2, 40) = 47.04$, $p < .001$, $\eta_p^2 = .547$, such that participants' involvement ratings differed for each reappraisal condition. Post hoc pairwise comparisons revealed that compared with the control round ($M = 4.56$, $SD = 1.81$), participants' involvement ratings were significantly less during the down-regulation round ($M = 2.78$, $SD = 1.68$), $F(1, 40) = 29.09$, $p < .001$, $\eta_p^2 = .427$; and significantly more

Table 1

Means (SD) for Manipulation Checks (Reported Involvement and Emotional Feeling), Cognitive Performance on the Go/No-Go Task, and Electroencephalography (EEG) Measures

Dependent variable	Down-regulation	Up-regulation	Control
Level of involvement	2.78_{a} (1.68)	5.85_{b} (1.46)	4.56_{c} (1.81)
Emotional feeling	2.70_{a} (1.28)	4.80_{b} (1.58)	3.60_{c} (1.63)
Omission error rate (%)	14.95_{a} (12.10)	12.75_{a} (11.11)	14.99_{a} (12.13)
Commission error rate (%)	41.61_{a} (17.02)	40.53_{a} (17.62)	42.50_{a} (16.67)
Total number of commission errors	16.8_{a} (6.60)	16.2_{a} (7.04)	17_{a} (6.68)
Overall accuracy rate (%)	79.7_{a} (13.05)	81.7_{a} (12.41)	79.5_{a} (13.05)
Reaction time correct	206.20_{a} (41.34)	201.89_{a} (37.35)	203.56_{a} (40.11)
Reaction time error	148.94_{a} (23.49)	147.08_{a} (23.91)	148.14_{a} (31.77)
Error-related negativity (ERN)	-3.23_{a} (4.61)	-4.15_{b} (5.55)	-4.68_{b} (5.39)
Correct-related negativity (CRN)	2.14_{a} (2.47)	3.37_{b} (2.54)	2.80_{a} (2.61)
ΔERN (ERN-CRN)	-5.34_{a} (4.48)	-7.53_{b} (5.46)	-7.47_{b} (5.45)

Note. Means across rows with different subscripts differ significantly at $p < .05$ (two tailed).

during the up-regulation round ($M = 5.85$, $SD = 1.46$), $F(1, 40) = 18.51$, $p < .001$, $\eta_p^2 = .322$.

Similarly, a 3-way repeated measures ANOVA with rated emotional feelings as the dependent variable revealed a significant main effect, $F(2, 40) = 23.96$, $p < .001$, $\eta_p^2 = .381$, such that participants' emotional ratings differed for each reappraisal condition. Post hoc pairwise comparisons revealed that compared with the control round ($M = 3.60$, $SD = 1.63$), participants' emotion ratings were significantly less during the down-regulation round ($M = 2.70$, $SD = 1.28$), $F(1, 40) = 10.06$, $p = .003$, $\eta_p^2 = .205$; and significantly more during the up-regulation round ($M = 4.80$, $SD = 1.58$), $F(1, 40) = 47.91$, $p < .001$, $\eta_p^2 = .551$. Together, this suggests that participants' self-reported emotion and level of involvement reflected our manipulation instructions to down-regulate, up-regulate, or perform the task normally (i.e., control) across the experiment.

Go/No-Go Task Performance

The behavioral data revealed that reappraisal strategies had no direct effects on performance (see Table 1). The average percent correct for go trials was 85.1% in the control condition, 85.1% in the down-regulation condition, and 87.3% in the up-regulation condition. The average percent correct for no-go trials was 57.5% for the control, 58.4% for the down-regulation, and 59.5% for the up-regulation. A 3 (reappraisal strategy: down-regulation vs. up-regulation vs. control) × 2 (response: error vs. correct) repeated measures analysis of variance (ANOVA) with RT as the dependent variable revealed a significant main effect of response, $F(2, 40) = 263.87$, $p < .001$, $\eta_p^2 = .867$, such that RTs on error trials, regardless of reappraisal condition, was significantly faster than RTs on correct trials. A 3 (reappraisal strategy: down-regulation vs. up-regulation vs. control) × 2 (error type: omission vs. commission) repeated measures ANOVA with error rate as the dependent variable revealed a significant main effect of error type, $F(1, 40) = 83.12$, $p < .001$, $\eta_p^2 = .670$, such that participants, again regardless of reappraisal strategy, committed significantly more commission than omission errors. No other main effects of interactions were significant ($p > .10$).

The ERN

A 2 (response type: error vs. correct) × 3 (reappraisal condition: down-regulation vs. up-regulation vs. control) repeated measures ANOVA revealed a significant main effect of response type, $F(1, 40) = 103.11$, $p < .001$, $\eta_p^2 = .72$, indicating that there is an increased negative going ERP in response to errors ($M = -4.89$ μV, $SD = 5.20$) versus correct responses ($M = 2.76$ μV, $SD = 5.20$; see Figure 1). Importantly, the main effect of response type was subsumed under a significant interaction with reappraisal strategy, $F(1, 40) = 5.034$, $p = .03$, $\eta_p^2 = .112$.

Analyses of simple main effects for *correct* response type revealed that CRN amplitude in the up-regulation condition ($M = 3.37$, $SD = 2.54$) was significantly larger (i.e., more positive) than the CRN amplitude in both the control condition ($M = 2.80$ μV, $SD = 2.61$), $F(1, 40) = 4.73$, $p = .04$, $\eta_p^2 = .106$, and the down-regulation condition ($M = 2.14$ μV, $SD = 2.47$), $F(1, 40) = 12.77$, $p < .01$, $\eta_p^2 = .242$. The difference between down-regulation and control was marginally significant, $F(1, 40) = 3.27$, $p = .08$, $\eta_p^2 = .076$. Analyses of simple main effects for *error* response type revealed that ERN amplitude in the down-regulation reappraisal condition ($M = -3.22$ μV, $SD = 4.61$) was significantly smaller (i.e., less negative) than the ERN amplitude in the control condition ($M = -4.67$ μV, $SD = 5.38$), $F(1, 40) = 4.213$, $p = 0.04$, $\eta_p^2 = .095$. However, there was not a difference between the up-regulation ERN ($M = -4.15$ μV, $SD = 5.54$) and the control ERN, $F(1, 40) = 0.517$, $p = 0.476$, $\eta_p^2 = 0.013$; nor was the difference between the down- and up-regulation ERN significant, $F(1, 40) = 1.917$, $p = .174$, $\eta_p^2 = .046$.

Analyses using the difference wave approach were also conducted in order to avoid issues of interpretability of raw ERP components (Luck, 2005). A repeated measures ANOVA with the difference wave scores (error amplitude *minus* correct amplitude, ΔERN) as the dependent variable revealed a significant main effect of strategy, $F(2, 40) = 5.034$, $p = .02$, $\eta_p^2 = .130$, suggesting a difference in ΔERN across reappraisal strategies (see panel D in Figure 1). Mirroring our findings from the traditional ERP analyses, pairwise comparisons revealed that the ΔERN in the down-regulation condition ($M = -5.47$ μV, $SD = 4.56$) was significantly less negative than that observed in both the control

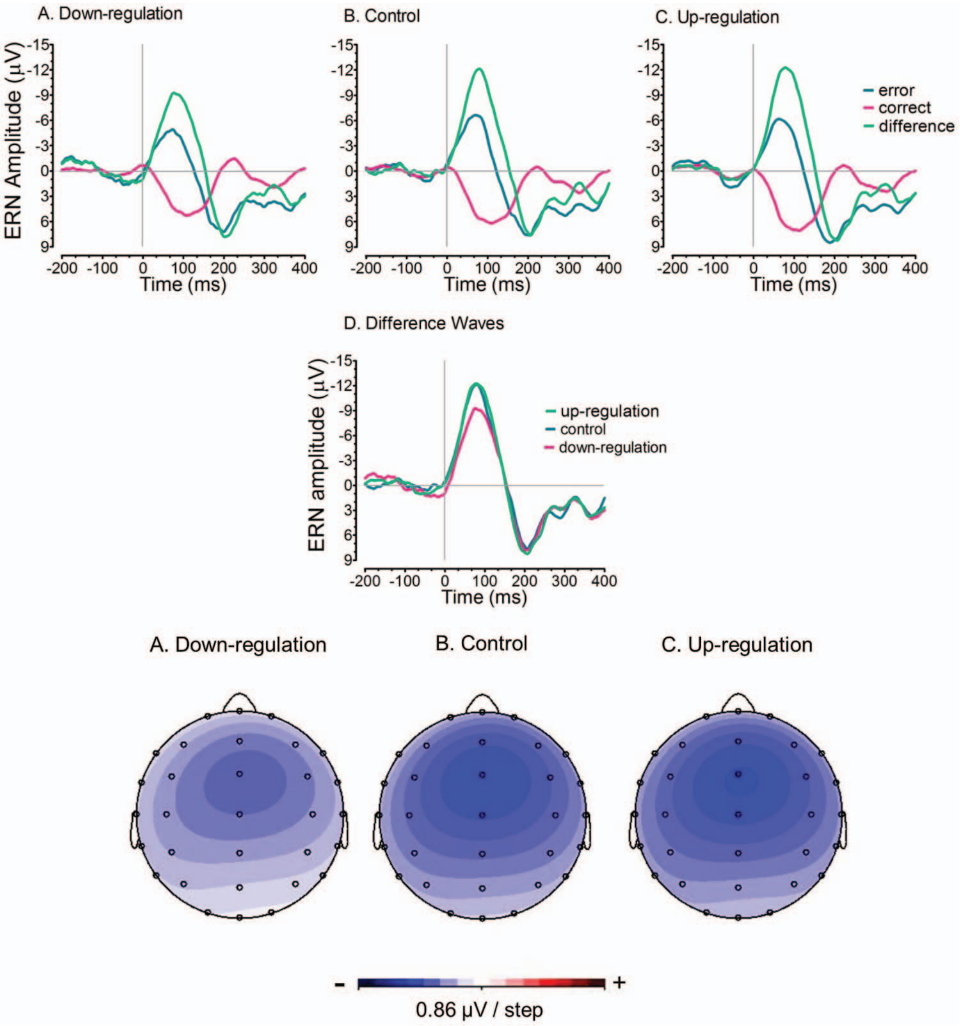

Figure 1. Upper panels: Response-locked waveform amplitude at FCz following correct and incorrect responses on the go/no-go task for the (A) down-regulation reappraisal, (B) control no-reappraisal, (C) up-regulation reappraisal (D), and the difference wave for each. Lower panels: Spline maps depict the scalp distribution of the ΔERN (mean activity 0 ms–100 ms) for the (A) down-regulation, (B) control, and (C) up-regulation conditions.

condition ($M = -7.54$ μV, $SD = 5.45$), $F(1, 40) = 5.96$, $p = .019$, $\eta_p^2 = .130$; and up-regulation condition ($M = 7.53$ μV, $SD = 5.46$), $F(1, 40) = 8.34$, $p = .006$, $\eta_p^2 = .173$. However, no significant difference was found between the control and up-regulation conditions, $F(1, 40) < 1$, $p = .942$,), $\eta_p^2 = .000$.

These results provide partial support for our hypotheses: We found that in response to errors, the down-regulation strategy led to a dampened ERN; however, the up-regulation strategy did not lead to an increased ERN amplitude. This suggests that emotion regulation reappraisal strategies affect ERN amplitude, but only when participants selectively down-regulated their emotions during task performance.

Mediating the Effect of Reappraisal Condition on Error-Monitoring

To test the relationship between condition (down-regulation, up-regulation, and control) and error monitoring activity (i.e., ΔERN, ERN, and CRN) as mediated by participants' emotion and involvement ratings, we used a multicategorical mediation model (Preacher & Hayes, 2008, in press). We used bootstrap analysis with 5,000 samples to obtain parameter estimates for the specific indirect effects. Table 2 presents the 95% bias-corrected confidence intervals for the indirect effects of emotion ratings and involvement ratings on the relationship between condition and ΔERN. A confidence interval that does not contain zero indicates a statistically significant indirect effect, and, consequently, mediation (Preacher & Hayes, 2008). The confidence intervals for specific indirect effects indicate that emotion ratings mediated the relationship between both down-regulation and up-regulation reappraisal and ΔERN; involvement ratings did not act as a significant mediator in either case (see Figure 2). Furthermore, the effects were not significant when ERN and CRN were included in the model. When included alone, neither error- nor correct-related performance monitoring processing was predictive of the effects;

Table 2
Results of the Multicategorical Mediation Analysis: Emotion Ratings as a Mediator of the Effects of Down-Regulation and Up-Regulation Reappraisal on ΔERN

	SE b	95% bias-corrected confidence interval
Indirect effects through emotion ratings		
Up-regulation condition	52.73	[−190.91, −1.36]*
Down-regulation condition	39.75	[3.64, 147.01]*
Indirect effects through involvement ratings		
Up-regulation condition	47.30	[−215.19, 3.17]
Down-regulation condition	62.21	[−1.08, 166.66]

* $p < .05$.

only difference-wave activity, ΔERN, was affected by mediation. This aligns well with ERP research practices which argue that difference-waves can be helpful in isolating and drawing inferences from waveform components as they have lower signal-to-noise ratio than those of the original ERP waveforms (Luck, 2005). Taken together then, the emotion and involvement ratings, though similar in how they were affected by condition manipulation, seem to be tapping into different constructs. Indeed, the mediation analyses show that emotion and involvement ratings differentially predict modulations in error-monitoring processes. In support of our hypotheses, this shows that emotion or affect in particular—rather than involvement or engagement—is what is driving the observed modulations in error-monitoring and ERN amplitude.

Indirect Effects of Emotion Reappraisal and Performance Monitoring on Cognitive Control

To test our second hypothesis, that reappraisal-based modulations in ERN amplitude affect cognitive performance, we conducted multiple indirect effects tests. We tested the models to see whether there would be an effect of emotion experience, as a function of reappraisal, on cognitive control *through* error-monitoring processes (i.e., ERN, CRN, and ΔERN; Preacher & Hayes, 2004). The two main models that we tested differed only in terms of their initial predictor variable; the first including the categorical variable of reappraisal condition (i.e., down-regulation, up-regulation, and control) and the second, as a more direct test, including the continuous variable of emotion/involvement ratings. Before proceeding, it is important to highlight the distinction between the statistical terms *mediated effect* and *indirect effect* (Holmbeck, 1997). In a mediation effect, the assumption is that the total effect X on Y be significant initially; there is no such requirement in the testing of an indirect effect. For the present analyses therefore, an indirect effects test was justified despite the absence of an initial total effect of reappraisal condition/emotion ratings on error rates (Hayes, 2009; Preacher & Hayes, 2004). For contrasting views on the requirement that the total effect be significant, see Collins, Graham, and Flaherty (1998) and Shrout and Bolger (2002).

For the first model (reappraisal condition as our predictor variable) we used an indirect effects test for a multicategorical independent variable (in this case, the reappraisal strategy: down-regulation, up-regulation, and control; Preacher & Hayes, 2008). Similar to the mediation analysis above, the significance of the relative indirect effects was tested using bootstrap analysis with 5,000 samples to obtain parameter estimates. A confidence interval that does not include zero indicates a statistically significant indirect effect (Preacher & Hayes, 2008; see Table 3). We fit the data to our model separately for the intervening variables, ERN, CRN, and ΔERN. The results show nonsignificant indirect effects for condition on task performance through ERN (down-regulation: [−0.24, 1.86]; up-regulation: [−0.94, 1.41]), as well as through CRN (down-regulation: [−1.09, 0.09]; up-regulation: [−0.12, 1.05]). The third test of our model, however, revealed a significant

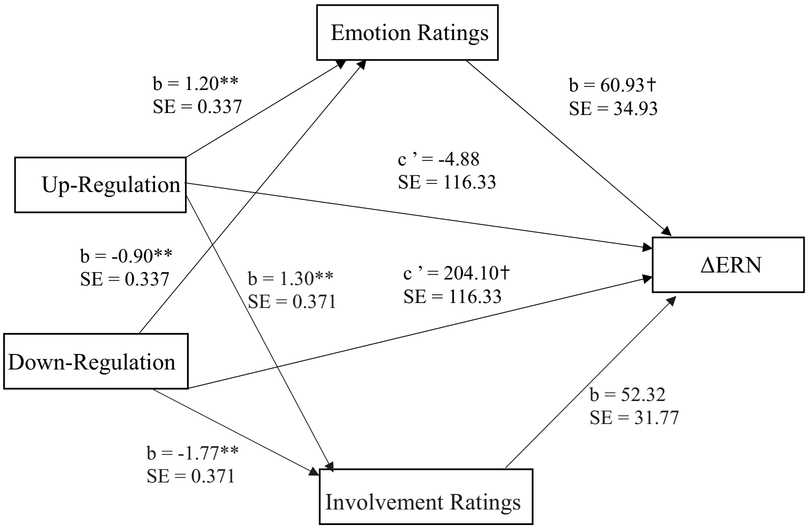

Figure 2. A multicategorical mediation model of emotion ratings as a mediator of the relation between reappraisal condition (down- and up-regulate) and difference-wave ERN. Unstandardized regression coefficients (and the associated standard errors) from a bootstrap procedure are provided along the paths. Darker outlines indicate significant indirect effects and, consequently, mediation (* $p < .05$. ** $p < .01$.).

Table 3
Results of the Indirect Effects Test With a Multicategorical Independent Variable of Condition: The Indirect Effect of Reappraisal Condition on Cognitive Control Through ΔERN

Relative indirect effect through ΔERN	*SE* b	95% bias-corrected confidence interval
Up-regulation condition	0.502	[−1.09, 0.91]
Down-regulation condition	0.504	[0.05, 2.09]*

* $p < .05$.

indirect effect when including ΔERN in the model: The down-regulation condition, specifically, was positively related to ΔERN, which, in turn, was positively related to the number of errors during task performance (0.05, 2.09). The indirect effect for up-regulation was not significant (−1.10, 0.91). Figure 3 illustrates the results of our analyses. Similar to the earlier mediation analysis, these findings suggest that the composite ERP difference waveform is a stronger model predictor and, thus, a more suitable metric to use (Luck, 2005). The results from these analyses show that down-regulation predicted a dampened ΔERN, which, in turn, led to reduced accuracy on the go/no-go. Down-regulating emotion in a test of cognitive control, in other words, predicted worse cognitive control, albeit indirectly and through diminished performance monitoring, as assessed by ΔERN. Similar to the above findings there was no such effect for up-regulation.

In the second model we collapsed across condition assignment to test the indirect effect of emotion and involvement ratings on task performance through error-monitoring using multilevel structural equation modeling (Preacher, Zyphur, & Zhang, 2010). We tested separate models using emotion/involvement ratings and ERN, CRN, and ΔERN as our X and M predictors, respectively. Contrary to our hypotheses, all of the models tested were not significant. These findings are expected, however, given the null effects of the up-regulation condition in our original repeated measures analyses.

Taken together, the indirect effects tests reveal that emotion reappraisal, specifically the down-regulation strategy, affects cognitive control on a go/no-go task but does so indirectly *through* dampening amplitude of ΔERN. Although we find no such indirect effect for emotion/involvement ratings—when collapsing across reappraisal condition—the significant condition effect is partial evidence in support of the hypothesis that integral negative affect, as manipulated by reappraisal during task performance, is related to both the neural and behavioral indices of cognitive control.

Discussion

The current study is one of the first to demonstrate that antecedent-focused emotion reappraisal strategies influence neurophysiological and behavioral indices of error-related cognitive control. By asking participants to engage in emotional reappraisal strategies, our study investigated how top-down cognitive processes of reappraisal color online emotional responding during a cognitive control task. This manipulation allowed us to focus in on interactions between affective processing and performance monitoring. Interestingly, when participants performed an inhibitory control task with a detached, nonemotional mindset (down-regulation), performance monitoring processes differentiated less between error and correct trials (reduced ERN and ΔERN), relative to control or up-regulation instructions. Furthermore, self-reported emotionality (but not subjective involvement) mediated the relationship between reappraisal condition and ΔERN. Importantly, these findings provide novel support for emerging affective accounts of the ERN (Inzlicht & Al-Khindi, 2012). Most importantly, we also found evidence supporting a link between affect, monitoring, and behavioral control (no-go error rate); that is, reappraisal condition impacted inhibitory control (error-rates) indirectly through neural performance monitoring (ΔERN).

In light of our present findings, it is important to consider *why* instructions to down-regulate emotional involvement during task performance would selectively impact upon early (<100 ms) error-related brain activity. We suggest that by deliberately approaching the go/no-go task in a detached, nonemotional manner, participants achieved a relatively sustained state of reduced affective reactivity. And, as erroneous actions are rapidly evaluated as negative events (Aarts et al., 2012; Aarts et al., 2013; Hajcak & Foti, 2008; Lindström et al., 2013; Pourtois et al., 2010), this diminished emotional responding likely dampened neural monitoring mechanisms to the transient distress associated with erroneous actions. Specifically, the data from our study suggests that the ERN is not only a neural indicator of cognitive processing; but also has properties of emotion that can be modulated by the same regulatory strategies known to influence negative emotional experience in other contexts (e.g., Gross, 2002). Interestingly, this finding complements recent reports that manipulations which *reduce* negative arousal during performance, such as acute alcohol administration (Bartholow, Henry, Lust, Saults, & Wood, 2012) or the misattribution of arousal (Inzlicht & Al-Khindi, 2012), also attenuate the ERN.

By not explicitly accounting for emotion-cognition interactions, extant cognitive neuroscience models of control (e.g., Botvinick et al., 2001; Holroyd & Coles, 2002) are unable to fully explain the observed associations between emotion regulation, brain, and behavior. Specifically, our findings stress the role of emotional experience in behavioral regulation: When participants down-regulated their emotions—removing the full range of possible experienced emotions—they reported feeling less emotion reactivity and performance monitoring was less efficient (reduced ERN),

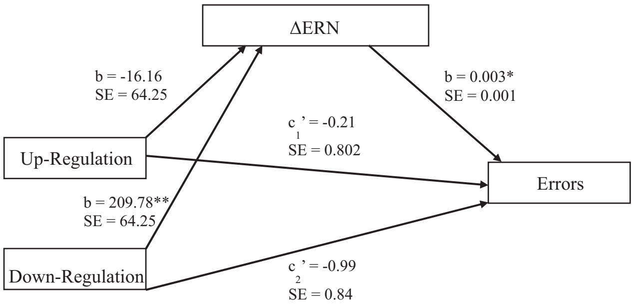

Figure 3. An indirect effects model showing the indirect effect of condition assignment (reappraisal strategy) on cognitive control (i.e., number of errors) through difference waveform (ΔERN). Unstandardized regression coefficients (and the associated standard errors) from a bootstrap procedure are provided along the paths (* $p < .05$. ** $p < .01$.).

which, in turn, was associated with poorer task performance. This pattern of results is best accounted for by recent proposals that the aversive experience of response-conflict or errors alerts individuals to challenges, and, in turn, this distress energizes cognitive control efforts to avoid future negative outcomes (Botvinick, 2007; Inzlicht & Legault, 2012; Schmeichel & Inzlicht, 2013). Consequently, when the emotional pang of error commission is reduced during emotion down-regulation, the saliency of this "affective alarm" signal (Inzlicht & Legault, in press) is diminished, making the individual less likely to engage corrective control processes (Bartholow et al., 2012; Inzlicht & Al-Khindi, 2012). Although we stress the importance of affect for control, we are also mindful of the inherent difficulty in partitioning psychological phenomena, at either a conceptual or neural level, into strictly "cognitive" or "affective" processes (e.g., Etkin et al., 2011; Gray, 2004; Shackman et al., 2011). We do not wish to create a false dichotomy between a purely "affective" or "cognitive" theory of the ERN and executive control. Instead, we hope that the current study adds to the growing line of evidence to suggest that emotional and cognitive processes are highly integrated, with affective experience playing a central role in cognitive control and the strategic regulation of motivated behavior (Gray, 2004).

In further relation to the behavioral correlates of control, and consistent with previous research (e.g., Inzlicht & Gutsell, 2007), our findings suggest that the ERN predicts particular performance outcomes (i.e., overall accuracy). Although widely hypothesized (e.g., Botvinick et al., 2001; Holroyd & Coles, 2002; Yeung et al., 2004), such a direct relationship between increased ERN amplitude and improved cognitive performance is not always found (Weinberg, Riesel, and Hajcak, 2012). In light of these mixed results, Weinberg, Riesel, and Hajcak (2012) recently hypothesized that improved task performance may constitute but one potential adaptive consequence of performance monitoring. Alternatively, the uncertain threat associated with error commission might also trigger the mobilization of defensive responses, particularly for groups that experience errors as being particularly concerning (see also Hajcak, 2012; Proudfit, Inzlicht, & Mennin, 2013). Consequently, the coupling between ERN amplitude and task performance is potentially moderated by a number state or trait factors. Given that the relationship between the ERN and control has been shown to be moderated by variables such as intrinsic motivation (Bartholow et al., 2012; Legault, Al-Khindi, & Inzlicht, 2012) and the correct attribution of negative affect (Inzlicht & Al-Khindi, 2012), it may be interesting to see whether differences in trait emotion regulation—that is, people's natural disposition to employ one strategy over another—will also act as one such moderator (e.g., Drabant, McRae, Manuck, Hariri, & Gross, 2009).

Our findings may also have implications for clinical research. As reviewed previously, increased ERN amplitudes have been consistently observed in several affective psychopathologies, often without concomitant changes in behavioral performance between clinical participants and healthy controls (Holmes & Pizzagalli, 2008; Olvet & Hajcak, 2008; Weinberg et al., 2012). Furthermore, although substantial variation in ERN amplitude appears to be stable and trait-like among groups with internalizing psychopathologies (Olvet & Hajcak, 2008; Proudfit, Inzlicht, & Mennin, 2013; Weinberg et al., 2012), state-related changes in error-monitoring have been reported for anxious (Riesel et al., 2012) and neurotic (Olvet & Hajcak, 2012) individuals. Therefore, investigating the relationship between emotion regulation and performance monitoring in clinical groups would provide an interesting avenue for future research and clinical application. More specifically, these psychopathologies are associated with poor emotional response systems, in addition to the inefficient use of adaptive emotion regulation strategies (Davidson, 2004; Mather et al., 2004), with interventions such as cognitive–behavioral therapy aiming to encourage the framing of more realistic cognitive appraisals (for a review see Butler, Chapman, Forman, & Beck, 2006). And so, ongoing research should continue to explore whether increased ERN amplitudes in anxious pathologies are immutable (i.e., resistant to conscious cognitive regulation) or if reappraisal strategies are capable of attenuating these heightened neurophysiological error-monitoring processes. Importantly, as hyperactive performance monitoring is commonly observed in anxiety without behavioral dysfunction (Hajcak, 2012; Weinberg et al., 2012), one might predict that any possible ERN reductions resulting from reappraisal in such groups could occur without producing detrimental effects for behavioral performance. Of course, more research is needed in order to understand the exact association between heightened error-monitoring/affective reactivity and the ERN.

It is important to consider the current findings within the broader framework of the process model of emotion regulation and to address their limitations (cf., Gross, 1998). First, in contrast to the effects of down-regulation, up-regulation of emotion had no observable effects on neural or behavioral markers of cognitive control. Given the proposed relationship between affect and performance monitoring, it is important to consider why focusing on emotional experience did not increase ERN amplitude. One possibility is that there exists an upper limit to how much negative emotion individuals experience during a nonvalenced, cognitive control task. Thus, failure to find an effect of up-regulation on the ERN may be due to an upward boundary condition or ceiling effect. In line with our results, other studies have also failed to find neural effects of up-regulation strategies (Krompinger, Moser, & Simons, 2008; Moser et al., 2006), despite an increase in people's self-reported emotion ratings (Ochsner et al., 2004). Another possibility could be due to our methodological design and the fact that the up-regulation reappraisal condition did not specifically instruct participants to increase only *negative* affect during task performance. In other words participants may have been equally as likely to amplify their positive affect in response to effective task performance as they would have been to increase their negative affect in response poorer task performance (i.e., error commission); thus reducing the overall likelihood of the up-regulation manipulation influencing ERN amplitude. Future studies will benefit from using clean experimental manipulations in order to tease apart the up-regulation of positive and negative emotions during task performance.

Furthermore, as multiple forms of emotion reappraisal have been identified in the literature (e.g., Gross, 1998; Gross & Thompson, 2007), it is unclear which specific strategies were employed during up- and down-regulation in the present study. Importantly, although we welcome future research that aims to more precisely determine the influence of distinct reappraisal strategies on performance monitoring, careful consideration of our regulation instructions can shed further light on the present findings. Specifically, as our down-regulation instructions emphasized performing the task with a detached, nonemotional mindset, it is possible that participants engaged down-regulation strategies involving a degree of mental distraction. At first glance, it might be argued that such disengagement provides an alternative, nonemotional explanation of our results. In effect, by deliberately removing focus from the task, participants may have employed less performance monitoring (i.e., ERN) through general attentional disengagement, rather than through the explicit reappraisal of emotional experience. Countering these concerns, however, it should first be noted that mental distraction and emotion regulation are not mutually exclusive concepts. More specifically, distraction—as a unique form of emotion regulation—has been found to activate similar neural circuitry as reappraisal and to also lead to decreased reports of negative affect (e.g., Kanske et al., 2011). In further support of the central role of emotion regulation in our ERN results, the mediation analysis (see Figure 2) indicated that self-reported affective experience (but not subjective involvement/engagement) mediated the relationship between reappraisal condition and ΔERN. Critically, these findings suggest that down-regulation attenuated performance monitoring by dampening "hot" information processing rather than attentional disengagement more generally. Yet given the possibility of these alternative explanations, future research will benefit from exploring the different forms of reappraisal strategies and their differential effects on neuro-affective markers like the ERN. The current study, for instance, concentrated on antecedent focused reappraisal strategies, and so it may be interesting to see if response-related emotion regulation, such as suppression, also impacts performance monitoring in a similar manner. Such findings would provide additional support for our hypothesis that error-related affective experience is modulated by other emotion-based processes.

Finally, it may be suggested that cognitive demands induced by reappraisal also influenced the observed data pattern. More specifically, cognitive load was perhaps increased when participants deliberately altered their emotional experience, resulting in reduced cognitive capacity during the regulation conditions, relative to control. Importantly, as interactions between cognitive capacity and the ERN have recently been subjected to increased consideration (cf., Moser et al., 2013), it is important to assess the possible influence of attentional load on the present results. In order for a capacity explanation to adequately account for the current findings, there would need to be asymmetrical effects between reappraisal styles, given the null effect in the up-regulation condition. Current theory, however, does not align with this interpretation. The production-monitoring hypothesis (Kalisch et al., 2005; Kalisch et al., 2006), for example, suggests that the prefrontal areas that generate and maintain positive working memory contents during down-regulation are also needed to actively maintain negative working memory contents during up-regulation. According to this theory then, if attentional load were the likely operating mechanism, we would expect to see similar attenuations in ERN amplitude in both down-regulation *and* up-regulation. In short, the asymmetrical effects of attentional load on ERN amplitude deviate from previous theory, and therefore, provide a less compelling explanation of the present findings. Nevertheless, more research is needed in order to explicitly test how changes in cognitive capacity modulate ERN amplitude and whether such factors are impacted by emotion processing and regulation strategies.

Conclusions

The influence of the cognitive down-regulation of emotion on neurophysiological and behavioral correlates of cognitive control, as observed in the current study, demonstrates the importance of affect in performance monitoring processes. These findings cannot be accounted for by the principle cognitive neuroscience models of cognitive control, which do not explicitly address the role of affect in cognitive performance. Using emotion regulation strategies as a way to manipulate levels of emotional involvement and intensity, we were able to show that certain fluctuations in affective experiences can modulate the ERN, which, in turn, predicts changes in cognitive performance. It is our hope that these findings will contribute to a more complete account of performance monitoring—an account which appreciates the central role of emotion in executive functioning.

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