

Error-related negativity (ERN) and sustained threat: Conceptual framework and empirical evaluation in an adolescent sample

ANNA WEINBERG,^a ALEXANDRIA MEYER,^b EMILY HALE-RUDE,^b GREG PERLMAN,^c ROMAN KOTOV,^c DANIEL N. KLEIN,^b AND GREG HAJCAK^b

^aDepartment of Psychology, McGill University, Montréal, Quebec, Canada

^bDepartment of Psychology, Stony Brook University, Stony Brook, New York, USA

^cDepartment of Psychiatry, Stony Brook University, Stony Brook, New York, USA

Abstract

The error-related negativity (ERN) currently appears as a physiological measure in relation to three Research Domain Criteria (RDoC) constructs: Cognitive Control, Sustained Threat, and Reward Learning. We propose a conceptual model in which variance in the ERN reflects individual differences in the degree to which errors are evaluated as threatening. We also discuss evidence for the placement of the ERN in the “Sustained Threat” construct, as well as evidence that the ERN may more specifically reflect sensitivity to *endogenous* threat. Following this, we present data from a sample of 515 adolescent females demonstrating a larger ERN in relation to self-reported checking behaviors, but only in older adolescents, suggesting that sensitivity to internal threat and the ERN-checking relationship may follow a developmental course as adolescents develop behavioral control. In contrast, depressive symptoms were linked to a smaller ERN, and this association was invariant with respect to age. Collectively, these data suggest that the magnitude of the ERN is sensitive both to specific anxiety-related processes and depression, in opposing directions that may reflect variation in internal threat sensitivity. We discuss directions for future research, as well as ways in which findings for the ERN complement and challenge aspects of the current RDoC matrix.

Descriptors: Anxiety, Emotion, Cognitive control, Adolescents, ERPs

The Research Domain Criteria (RDoC) project aims to construct a scientific understanding of psychopathology in terms of well-defined neural circuits. The brain is an organ that is exquisitely sensitive to detecting threats and rewards. It mobilizes the body to approach potential opportunities and avoid possible threats; these fundamental functions of the central nervous system are reflected in many RDoC constructs within the Positive and Negative Valence Systems domains, respectively. Indeed, three threat-related constructs are currently specified within the Negative Valence System domain of RDoC: Acute Threat (i.e., fear), Potential Threat (i.e., anxiety), and Sustained Threat (i.e., chronic stress).

The error-related negativity (ERN) currently appears as a physiological measure of the “Sustained Threat” construct; it is also listed as a measure relevant to both the “Performance Monitoring” construct of the Cognitive Systems domain, and the “Reward Learning” construct of the Positive Valence System domain. The conceptual link between

the ERN and both performance monitoring and learning constructs is clear—after all, the ERN reflects error detection, and the ability to detect mistakes enables us to learn from them (Sutton & Barto, 1998; Thorndike, 1927). But why is the ERN included as a unit of analysis in the “Sustained Threat” construct? What do psychopathology studies focusing on the ERN reveal? And what specific dimensions of function and dysfunction are reflected by variation in the ERN?

In the current article, we address these and related questions by focusing on the ERN in both within- and between-subjects studies evaluating how variation in the ERN fits within broader nomological networks. We focus on how the ERN might be integrated within the RDoC Negative Valence System domain, and discuss how ERN data might further inform the RDoC framework and research initiative. We aim to illustrate how variables at the physiological level of analysis might be used to suggest refinements to the RDoC matrix and thereby contribute to a neuroscientifically informed science of psychopathology. Consistent with the broader RDoC enterprise, we consider the crucial role of both development and environmental experience, along with heritable propensities, in shaping the ERN and its relationship to individual differences. To illustrate the role of such influences, we present data from a large sample of adolescent females ($N = 550$), examining the emerging relationship across adolescence between the ERN and empirically defined phenotypes related to internalizing psychopathology.

This study was supported by National Institute of Mental Health grant MH093479 awarded to Roman Kotov. We gratefully thank all the adolescent participants and their parents for generously contributing their time and energy to the ADEPT project.

Address correspondence to: Anna Weinberg, Department of Psychology, McGill University, Montréal, Québec, H3A 1B1, Canada. E-mail: anna.weinberg@mcgill.ca

Biobehavioral Processes Underlying the ERN

The ERN is a fronto-centrally maximal negative deflection in the event-related potential (ERP) that differentiates erroneous from correct responses within 100 ms of response onset (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Coles, Meyer, & Donchin, 1995). The anterior cingulate cortex (ACC) appears to be the primary neural generator of the ERN, as suggested by evidence from multiple lines of research (Brázdil, Roman, Daniel, & Rektor, 2005; Dehaene, Posner, & Tucker, 1994; Debener et al., 2005; Hoffmann & Falkenstein, 2010; Miltner et al., 2003). Yet, in keeping with the focus of RDoC, it may be more accurate to say that the generation of the ERN reflects the activity of a neural *network* involved in error processing. For instance, the ACC also has dense interconnections to both limbic and prefrontal areas (Bush, Luu, & Posner, 2000), each of which also likely contributes to the amplitude of the ERN. Because adaptive processing of errors depends upon active maintenance of task instruction and goals, the lateral prefrontal cortex (PFC) plays a critical role in the error-monitoring network and generation of the ERN (e.g., Gehring, Himle, & Knight, 2000; Kiehl, Liddle, & Hopfinger, 2000; Ullsperger & von Cramon, 2006). The activity of the ACC is also driven by input from dopaminergic (DA) neurons in the midbrain (Bush et al., 2000), and one prominent theory of the ERN suggests it represents DA disinhibition of the ACC when the basal ganglia evaluate outcomes of actions as “worse than expected” (e.g., Holroyd & Coles, 2002; Nieuwenhuis et al., 2002, 2004). DA functioning does appear to influence the magnitude of the ERN: Both tonic and phasic levels of DA influence the magnitude of the ERN (de Bruijn, Hulstijn, Verkes, Ruijt, & Sabbe, 2004; Manoach & Agam, 2013), and genetic polymorphisms governing DA neurotransmission can also influence error processing in both healthy and neuropsychiatric populations (for an overview, see Manoach & Agam, 2013).

The ERN, performance monitoring, and cognitive control.

The ERN is certainly implicated in cognitive control. Without the ability to rapidly detect errors, it would not be possible to remedy them, or to adaptively regulate behaviors in a changing environment (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Holroyd & Coles, 2002). Several competing within-subjects theories of the functional significance of the ERN agree that the ERN functions as a kind of alarm following error commission—a call to increase cognitive control and make behavioral adjustments (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Gehring, Goss, Coles, Meyer, & Donchin, 1993; Holroyd & Coles, 2002; Holroyd & Yeung, 2012). Consistent with this, behavioral adaptations are frequently observed following errors. For instance, errors are often rapidly corrected (Rabbitt, 1966), even when participants are explicitly instructed not to make corrections (Fiehler, Ullsperger, & Von Cramon, 2005; Ullsperger & von Cramon, 2006). There is also the phenomenon of posterror slowing, entailing the tendency to slow down on correct trials following errors, presumably to reassert control over behavior (Allain, Burle, Hasbroucq, & Vidal, 2009; Rabbitt, 1966).

However, cognitive control relies on both evaluative and regulatory processes (Holroyd & Yeung, 2012; Larson, Clayson, & Clawson, 2014; Shackman et al., 2011), and we would argue that the ERN reflects *evaluative* rather than regulatory neural activity. Evaluative activity serves to signal the *need* for cognitive control, but it does not necessarily *implement* cognitive control. Consistent with this view, variation in the ERN is typically associated only weakly with control-related variables highlighted in the RDoC

matrix. For instance, although posterror slowing and other behavioral adaptations are evident across studies, the association between the magnitude of the ERN and the degree to which cognitive control is engaged is not clear. Only a few studies have investigated the intraindividual coupling of ERN magnitude and behavioral measures, and some have found that error trials beginning with a larger ERN can be characterized by increased posterror slowing (Debener et al., 2005; Gehring et al., 1993; see, however, Weinberg, Riesel, & Hajcak, 2012). A recent meta-analysis of studies of nonclinical levels of trait anxiety also suggests that some individuals with larger ERNs can show increased posterror slowing (Cavanagh & Shackman, 2014). On the other hand, many between-groups studies in clinical populations have reported that the group with the larger ERN typically does not demonstrate better performance (see, e.g., Weinberg, Riesel, et al., 2012 for a review).

We would argue that the ERN functions as a very early warning sign that behavioral adjustment is necessary. This is consistent with models of the ACC, which hold that an important role of the ACC is to integrate information about punishment to guide behavior (Shackman et al., 2011). In our view, the ERN is an early evaluator signal that is then followed by a cascade of downstream processes, including increased activation of the dorsolateral prefrontal cortex (DLPFC; Kerns et al., 2004; van Veen, 2006), increased activation of the amygdala (Pourtois et al., 2010), and engagement of task-relevant motor and sensory areas (Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; King, Korb, von Cramon, & Ullsperger, 2010; Ullsperger, King, & Von Cramon, 2008; see Figure 1). Thus, the connection between evaluation (i.e., ERN) and compensation (i.e., posterror behavioral adjustments) is indirect. As a result, the association between the ERN and performance adjustments would depend on intermediate processes, and a larger ERN would not necessarily lead to better control.

ERN and endogenous threat. Rather than reflecting the degree of instantiated cognitive control, we believe that the magnitude of the ERN varies according to within- and between-subject variables that impact the *evaluation* of errors. More specifically, we suggest that variability in the magnitude of the ERN more directly reflects the degree to which errors are evaluated as threatening (Weinberg, Riesel, & Hajcak, 2012). Consistent with this, the physiological response to errors resembles in many ways the body’s response to other types of threat (e.g., Critchley, Tang, Glaser, Butterworth, & Dolan, 2005; Hajcak & Foti, 2008; Hajcak, McDonald, & Simons, 2003b.; Lindström, Mattsson-Mårn, Golkar, & Olsson, 2013). Moreover, manipulations that make errors more threatening—as when errors are punished—increase the magnitude of the ERN (Chiu & Deldin, 2007; Ganushchak & Schiller, 2008; Hajcak, Moser, Yeung, & Simons, 2005; Riesel, Weinberg, Endrass, Kathmann, & Hajcak, 2012). However, we do not consider the ERN a valenced or affective response in and of itself. Rather, we believe the ERN reflects an early evaluative signal, which can be influenced by contextual and individual difference factors that modulate the value of errors—thus making it sensitive to affective factors. This evaluative signal kicks off a dynamic process which rapidly mobilizes defensive systems, as well as additional cognitive processing, and signals the need to respond adaptively. According to this perspective, increased cognitive control evident in behavioral measures would be just one type of adaptive response following error detection. The host of physiological changes following errors signaling the initiation of a defensive response may be another.

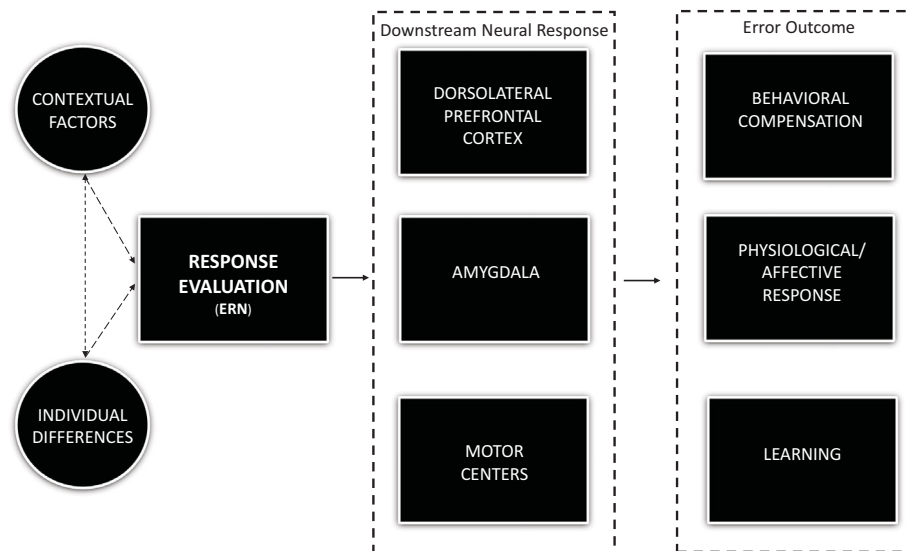


Figure 1. Our model of the evaluative and compensatory components of the error-monitoring process. As we have argued, the ERN reflects an evaluative stage in executive control over behaviors. The magnitude and direction of this evaluative response is sensitive to both contextual factors and individual differences. This evaluative signal then triggers downstream processes, including activation of the dorsolateral prefrontal cortex (DLPFC), amygdala, and motor and sensory areas of the brain, activation of which may or may not lead to adaptive behavioral adjustments. While not depicted in this figure, contextual factors and individual differences likely also influence each step of the downstream process, and may also directly influence compensatory behaviors.

However, errors represent a rather unique type of threat. While errors can undoubtedly threaten an individual's safety (e.g., a momentary lapse in attention or a motor slip while driving a car can be catastrophic), unlike snakes, spiders, and stimuli that signal impending aversive experiences, errors are *endogenous threats*—their source is internal, and errors do not demand the same degree of environmental vigilance. Instead, prevention of errors requires more of an internal focus, a vigilance concerning one's own behaviors (e.g., Müller, Möller, Rodriguez-Fornells, & Münte, 2005). At the moment, the RDoC matrix focuses exclusively on external threat. But there are good reasons to focus on sensitivity to *endogenous threat*¹ as a distinct construct that may be highly relevant to psychopathology. For instance, interoceptive sensitivity is a key element of panic disorder (Domschke, Stevens, Pfleiderer, & Gerlach, 2010; Ehlers & Breuer, 1992; Hamm, Richter, & Pané-Farré, 2014). Likewise, scrutiny of bodily sensations is a characteristic of hypochondriasis (Rawal, Collishaw, Thapar, & Rice, 2013). Furthermore, social anxiety is frequently characterized by maladaptive self-monitoring and self-defeating attention to one's own thoughts, behaviors, and physical sensations (Clark & Wells, 1995). Sensitivity to internal threat may therefore be an important avenue of research for RDoC as the matrix is evaluated and refined. We propose here that errors are one form of internal threat, and

1. We would note here that we believe the distinction between endogenous and exogenous threat is primarily a function of the source of the threat—not necessarily a function of their neural or physiological instantiation. Endogenous threats are likely as varied in their neural representation, and in the manner by which they activate core defensive circuitry and fear-output responses, as exogenous threats. Similarly, we believe that individual differences in sensitivity to errors resemble sensitivity to other types of threat: errors are aversive to most people (like snakes), perhaps as a consequence of learning experiences, but for a subset of individuals in the population, they are more catastrophic. We posit that this hypersensitivity to errors, like hypersensitivity to snakes, is a result of heritable temperamental differences which are then exacerbated through aversive experiences (e.g., harsh punishment following mistakes) that make errors more consequential, costly, and fearsome.

that variability in the ERN reflects the degree to which these internal threats are evaluated as aversive.

Individual Differences in the ERN: From Diagnoses to Dimensions of Psychopathology

In addition to the evidence reviewed above, the placement of the ERN in the Negative Valence Systems domain no doubt has to do with a large and growing body of research on between-subject variability in the ERN. If the magnitude of the ERN reflects in part the degree to which errors are aversive, then it stands to reason that the ERN will vary according to individual difference variables that affect the degree to which errors are processed as catastrophic events (see Figure 1). From the perspective of clinical science, interest in individual differences in the ERN was fueled by a paper by Gehring and Knight (2000), who found that patients with obsessive-compulsive disorder (OCD) were characterized by an increased ERN compared to healthy controls. Evidence for an enhanced ERN in OCD has since been replicated at least 20 times (see, e.g., Weinberg, Dieterich, & Riesel, 2015, for a review). Indeed, the link appears to be so robust that many have argued that the enhanced ERN might be a viable endophenotype for OCD (Hajcak, Franklin, Foa, & Simons, 2008; Manoach & Agam, 2013; Olvet & Hajcak, 2008; Riesel, Endrass, Kaufmann, & Kathmann, 2011; Taylor, 2012).

However, the enhanced ERN is not unique to OCD, a fact that illustrates the need for and impetus behind the RDoC framework. If nominally distinct disorders share common patterns of neural response, this suggests that the boundaries between them are not as firm as a categorical system implies. In fact, an enhanced ERN has also been observed in individuals with generalized anxiety disorder (GAD; Carrasco, Hong, et al., 2013; Ladouceur, Dahl, Birmaher, Axelson, & Ryan, 2006; Weinberg, Klein, & Hajcak, 2012; Weinberg, Kotov, & Proudfit, 2015; Weinberg, Olvet, & Hajcak, 2010; Xiao et al., 2011; Zambrano-Vazquez & Allen, 2014) as well as

social anxiety disorder (SAD; Endrass, Riesel, Kathmann, & Buhlmann, 2014). Similarly, an enhanced ERN has been observed in individuals with subclinical symptoms of OCD (e.g., Hajcak et al., 2002; Kaczurkin et al., 2013), as well as in individuals reporting high levels of worry (e.g., Hajcak et al., 2003a; Moser, Moran, & Jendrusina, 2012), and negative affect (NA; e.g., Hajcak, McDonald, & Simons, 2004).

However, an enhanced ERN is not observed across *all* anxiety disorders: Individuals with simple phobias (Hajcak, McDonald, & Simons, 2003a; Moser, Hajcak, & Simons, 2005) and posttraumatic stress disorder (PTSD) appear to display an ERN comparable to healthy controls (Rabinak et al., 2013). These data likely reflect the fact that anxiety is not a monolithic construct. Whereas external threat may be more salient for phobias and single-trauma PTSD, erroneous action may be more threatening to GAD, SAD, and OCD. Additionally, although GAD, SAD, and OCD share an enhanced ERN, they are assigned to two separate classes in the *Diagnostic and Statistical Manual of Mental Disorders, 5th edition* (DSM-5), suggesting the activity of these neural systems often does not respect diagnostic boundaries, and further highlighting the need for studies that look beyond diagnoses.

Moreover, individuals with depression, who are clinically often characterized by perfectionism and maladaptive concern over errors, as well as high NA, do *not* always show an enhanced ERN (see, however, Chiu & Deldin, 2007; Holmes & Pizzagalli, 2008, 2010). In fact, in several studies the ERN in depression has appeared comparable in magnitude to controls (Olivet, Klein, & Hajcak, 2010; Ruchow et al., 2004; Schrijvers et al., 2009; Weinberg, Klein, et al., 2012; Weinberg et al., 2015), or reduced relative to controls (Ladouceur et al., 2012; Schoenberg, 2014; Schrijvers et al., 2008). There is also evidence that comorbid depression can moderate the association between the ERN and some forms of anxiety (Weinberg, Klein, et al., 2012; Weinberg et al., 2015). Previously (Weinberg, Klein, et al., 2012; Weinberg et al., 2015), we have attributed evidence for an attenuated ERN in depression to motivational disengagement and consequently reduced threat sensitivity (Bylsma, Morris, & Rottenberg, 2008; Lang & McTeague, 2009; McTeague & Lang, 2012; Rottenberg, Gross, & Gotlib, 2005). These data further suggest the presence of two opposing influences on the ERN: symptoms related to internal threat sensitivity, which are associated with an enhanced ERN, and symptoms of depression, which may obviate or suppress the former association.

ERN and cross-diagnostic phenotypes. Data indicating similarities in the ERN across seemingly disparate disorders, and differences in the ERN across ostensibly similar disorders, beg the question of what symptoms and impairment are linked to the ERN *across diagnoses*. In other words, what is the nature of the function and dysfunction that variability in the ERN relates to? We and others have attempted to address this question by examining the ERN in relation to transdiagnostic phenotypes. To date, evidence suggests that anxious apprehension (i.e., cognitive symptoms of anxiety) specifically relates to the enhanced ERN, while physiological symptoms of acute fear response (e.g., shaky hands, shortness of breath, pain in chest) or depression (e.g., anhedonia, sad mood) do not (Moser et al., 2012; Moser, Moran, Schroder, Donnellan, & Yeung, 2013; Weinberg et al., 2010; Zambrano-Vazquez & Allen, 2014).

However, anxious apprehension itself encompasses multiple components (e.g., Berenbaum, Bredemeier, & Thompson, 2008; Olatunji et al., 2010), and the ERN does not appear to relate

equally to all of them. Some have argued that the specific mental behavior to which the ERN relates is worry (e.g., Moser et al., 2013). While trait worry does appear to be associated with an enhanced ERN (Hajcak et al., 2003a; Weinberg, Klein, et al., 2012; Weinberg et al., 2010), it is not clear if this is a direct association, or if it instead reflects the association between worry and other phenotypes common in anxiety disorders. In addition, in many factor analytic studies, worry appears as a quintessential distress marker, a common core of anxiety and depression, much like negative affectivity (Watson, 2009; Watson, O'Hara, & Stuart, 2008). Moreover, although worry is not a formal criterion for a DSM-IV diagnosis of major depressive disorder (MDD), there is evidence that it is commonly elevated in individuals with this diagnosis (Andrews & Borkovec, 1988; Starcevic, 1995). Yet the ERN shows greater specificity. As noted above, an enhanced ERN is not evident across all anxiety disorders, nor is it consistently evident in clinical or subclinical depression; in fact, depression and anxiety symptoms may actually have opposing effects on the ERN (for a review, see Weinberg, Dieterich, et al., 2015). Thus, worry appears to be a less specific phenotype than the ERN. Recent structural modeling studies of emotional disorders have identified a variety of narrower symptom dimensions with strong discriminant validity and more specific associations to diagnostic categories (Watson, 2009; Watson et al., 2012)—these empirically derived phenotypes may facilitate the identification of more precise emotional reactions, cognitive styles, or behaviors associated with the enhanced ERN.

In a recent study of individuals with MDD, GAD, and OCD, in which we used empirically derived symptom dimensions, we found that although GAD and OCD were associated with larger amplitudes of the ERN, self-reported worry was not related to the magnitude of the ERN (Weinberg, Kotov, et al., 2015). And in fact, individuals with a diagnosis of depression, who were characterized by levels of self-reported worry comparable to those of individuals with a diagnosis of GAD or OCD, did not differ from controls in terms of the magnitude of the ERN. Instead, the symptom dimension that appeared to relate to the ERN across all of these diagnoses (as well as healthy controls) was checking. Checking captures the extent to which people engage in inspection of their own behaviors in order to reduce anxiety about potential catastrophe (e.g., checking to see if I turned the stove off to prevent a gas explosion; checking to see if I locked the doors to prevent the entry of a murderer). These data are consistent with evidence that excessive concern over errors is associated with increased checking behaviors (Frost & Hartl, 1996; Frost, Marten, Lahart, & Rosenblate, 1990), as well as evidence that checking is elevated in both GAD and OCD (Kawamura, Hunt, Frost, & DiBartolo, 2001; Schut, Castonguay, & Borkovec, 2001). These results may be helpful in explaining the similar findings of increased ERN in both OCD and GAD. But the results of this study are also very consistent with the aims of RDoC. They demonstrate a transdiagnostic association between a pathological behavioral response (i.e., checking) and a well-defined neural process (i.e., the ERN).

It is worth noting here that despite its strong associations with OCD, checking is also a transdiagnostic construct. Consistent with previous studies (Parrish & Radomsky, 2010; Watson et al., 2012), the highest levels of checking in the study by Weinberg, Kotov, & Proudfit (2015) were evident for individuals with OCD, but checking was also elevated in GAD and MDD without comorbid OCD. This begs the question of why the ERN was not also enhanced in the depressed group. We found that across all diagnoses, symptoms typical of severe depression were associated with a *decreased* ERN (Weinberg, Kotov, & Proudfit, 2015; see also Schrijvers et al.,

2008). Furthermore, these data suggest that the magnitude of the ERN may reflect the balance of these two opposing phenotypes: checking, which is associated with an increased ERN, and depression, which is associated with a decreased ERN. It is likely that many RDoC measures will relate to multiple phenotypes relevant to psychopathology. Parsing these sometimes-opposing influences may therefore require large cross-diagnostic studies, as well as simultaneous consideration of multiple phenotypes to allow suppressor effects to emerge. One purpose of the analyses reported below was to examine the opposing influences of checking and depression in a large adolescent sample, using empirically derived phenotypes.

ERN, Development, Environment, and Risk for Psychopathology

The effects of checking and depression described above were observed in already-affected and often chronically ill adults. From this, it is difficult to say whether the enhanced ERN might represent a “scar” resulting from years of active symptoms, or whether it might contribute to the initial occurrence of psychopathology. If the ERN is just a scar, then it could still be useful as a marker of variation in different phenotypes, and might have prognostic implications for course or treatment response. However, if the ERN is instead a stable, trait-like vulnerability marker that predates observable psychopathology, then it may be useful for the identification of at-risk individuals, as well as intervention and prevention efforts.

While developmental and environmental aspects of psychopathology are not included in the formal RDoC matrix, they are still considered critical elements of RDoC-funded research, and RDoC research focused on specific brain circuits and functions is in a strong position to facilitate research on vulnerable, not-yet affected populations (see, e.g., [Kozak & Cuthbert, 2016](#)).

The ERN is well suited to advance this research approach. As discussed above, the ERN appears to be trait-like ([Larson, Baldwin, Good, & Fair, 2010](#); [Meyer, Bress, & Proudfit, 2014](#); [Olvet & Hajcak, 2009](#); [Segalowitz et al., 2010](#); [Weinberg & Hajcak, 2011](#)). In addition, there is evidence that variation in the ERN is familial ([Carrasco, Harbin, et al., 2013](#); [Euser, Evans, Greaves-Lord, Huizink, & Franken, 2013](#); [McLoughlin et al., 2009](#); [Riesel et al., 2011](#); [Simmonite et al., 2012](#)), and that its magnitude is subject to substantial genetic influence ([Anokhin, Golosheykin, & Heath, 2008](#)). ERN response has also been linked to specific genetic polymorphisms ([Althaus et al., 2009](#); [Fallgatter et al., 2004](#); [Meyer, Klein, et al., 2012](#); [Mueller, Makeig, Stemmler, Hennig, & Wacker, 2011](#); [Olvet, Hatchwell, & Hajcak, 2010](#)). Thus, the ERN appears to be a viable candidate for a stable heritable neural marker of vulnerability to psychopathology.

Moreover, there is evidence that the ERN relates to developmental processes of risk that emerge across development. For instance, behavioral inhibition (BI) assessed in early childhood predicts a larger ERN in adolescence ([McDermott et al., 2009](#)). Recently, we have also demonstrated that an enhanced ERN at age 6 prospectively predicts the onset of new anxiety disorders at age 9, even after controlling for baseline levels of anxiety and maternal history of anxiety ([Meyer, Proudfit, Torpey-Newman, Kujawa, & Klein, 2015](#)). However, there is increasing evidence that the magnitude of this trait-like response can also be influenced by context and experience. For instance, harsh and punitive parenting styles can lead to an enhanced ERN in children ([Brooker & Buss, 2014](#); [Meyer, Proudfit, Bufferd, et al., 2015](#)), and these data suggest a

potential mechanism for the development of the ERN-anxiety association. It is possible that learning experiences that make the consequences of errors more catastrophic (i.e., harsh or critical parenting) increase self-monitoring, sensitize individuals to the commission of errors, and potentiate the ERN—and that these effects may place individuals at risk for anxiety disorders.

There are several considerations in developmental studies on the ERN and anxiety. Among these is the fact that important developmental changes occur in ACC function and structure from childhood to adulthood ([Casey et al., 1997](#)), particularly within the period of adolescence ([Crone, 2014](#)). Similarly, the ERN appears to increase with age, and may not reach adult levels until the late-teen years ([Davies, Segalowitz, & Gavin, 2004](#)), suggesting the need to account for developmental factors associated with adolescence in the emergence of the ERN-anxiety association.

Another important consideration is that different trajectories may exist for clinical and subclinical levels of anxiety. For example, there is evidence that the association between an enhanced ERN and subclinical levels of trait anxiety does not emerge until adolescence ([Meyer, Weinberg, Klein, & Hajcak, 2012](#)). In younger children, heightened trait anxiety may instead relate to a blunted ERN ([Meyer, Weinberg, et al., 2012](#); [Moser, Durbin, Patrick, & Schmidt, 2015](#)). Additionally, a blunted ERN has been observed among young, nonanxious children of mothers with anxiety disorders ([Torpey et al., 2013](#)). In contrast, a link between *clinical* levels of anxiety and an enhanced ERN can be observed well before adolescence ([Meyer, Hajcak, et al., 2013](#)). For instance, there is evidence that the ERN is enhanced in children with OCD ([Hajcak et al., 2008](#)) and in heterogeneous groups of clinically anxious children ([Ladouceur et al., 2006](#); [Meyer, Hajcak, et al., 2013](#)). One possible explanation for these apparently contradictory findings is that children and youth with normative levels of anxiety are more concerned with external threat, whereas sensitivity to internal threat is underdeveloped; on the other hand, clinical levels of anxiety in children may already be associated with increased self-monitoring and excessive concern over internal threats such as errors (e.g., [Meyer, Hajcak, et al., 2013](#)). The development of the ERN-anxiety association may reflect developmental changes in error evaluation as children become more sensitive to the potential value of their own mistakes as sources of internal threat ([Copeland, Angold, Shanahan, & Costello, 2014](#); [Spence, Rapee, McDonald, & Ingram, 2001](#)). But these data further highlight a need to focus on specific phenotypes rather than diagnoses to integrate literature on the ERN across development. Indeed, such dimensional phenotypes show substantially higher temporal stability than diagnoses ([Markon, Chmielewski, & Miller, 2011](#); [Shea et al., 2002](#)). Specifically, previous work on the development of the ERN-anxiety association has not used empirically derived phenotypes to the same extent that adult studies have ([Moser et al., 2013](#)).

The Current Study

The present study focused on neural response to errors in a large sample of adolescent females between the ages of 13.5 and 15.5. We sampled from this age group because there is evidence that the association between normative symptoms of anxiety and enhanced ERN response becomes stronger in this age range ([Meyer, Weinberg, et al., 2012](#)). Thus, this age group was selected to assess potential developmental influences on the emergence of the anxiety-ERN association.

Consistent with the principles of RDoC, we examined associations with empirically defined transdiagnostic symptom dimensions

related to anxious apprehension and depression, across all 550 individuals within our sample. In an attempt to refine the anxiety-ERN association, we first examined specific associations between symptoms of anxiety and the ERN. Consistent with previous research (Weinberg, Kotov, & Proudfit, 2015), we expected that checking would be associated with an enhanced ERN across all individuals, but that other symptoms of anxiety would not. Following this, we examined potential opposing effects of depression symptoms, which we expected would be associated with a decreased ERN. Finally, we examined developmental differences in the association between the ERN and both checking and depression.

Method

Participants

A total of 550 never-depressed adolescent girls and their biological parents participated in the Adolescent Development of Emotions and Personality Traits (ADEPT) project, a longitudinal study of personality and risk for depression among never-depressed adolescent females. Some participants were excluded based on poor quality EEG data ($n = 19$), incomplete self-report measures ($n = 7$), if their accuracy level in the task was less than 60% ($n = 7$), or if they committed fewer than 6 errors ($n = 2$), leaving a total of 515 participants. Our final sample included girls between the ages of 13.5–15.5 ($M = 14.39$, $SD = 0.63$) with an ethnic/racial breakdown that was 81.2% Caucasian, 4.6% Black, 8.3% Latino, 2.5% Asian, 0.2% Native American, and 3.1% “Other.”

Participants were recruited from the community using a commercial mailing list of homes containing a daughter in the targeted age range, and through word of mouth, local referral sources (e.g., school districts), online classifieds, and advertisements in the community. Families were financially compensated for their participation. Participants were included in the study sample if they were fluent in English, able to read and comprehend questionnaires, and had a biological parent able to participate in the study. Exclusion criteria were lifetime history of a major depressive episode or dysthymia, or the presence of intellectual disabilities (as indicated by school placement). All tasks and procedures were approved by Stony Brook University’s Internal Review Board.

Symptoms

Current depression and anxiety symptoms were assessed in adolescents using the expanded Inventory of Depression and Anxiety Symptoms (IDAS-II; Watson et al., 2012). The IDAS-II is a 99-item factor-analytically derived self-report inventory of empirically distinct dimensions of depression and anxiety symptoms. Each item assesses symptoms over the past 2 weeks on a five-point Likert scale ranging from 1 (Not at all) to 5 (Extremely). The IDAS-II has demonstrated good internal consistency, test–retest reliability, and convergent and discriminant validity with diagnoses and self-report measures (Watson et al., 2012). The present study focused on the following IDAS-II subscales: general depression (20 items), $\alpha = .91$; panic (8 items), $\alpha = .86$; social anxiety (6 items), $\alpha = .86$; claustrophobia (5 items), $\alpha = .87$; traumatic intrusions (4 items), $\alpha = .80$; traumatic avoidance (4 items), $\alpha = .85$; checking (3 items), $\alpha = .82$; ordering (5 items), $\alpha = .76$; and cleaning (7 items), $\alpha = .86$, as they tap dimensions of interest. Subscales were scored as a mean of all items included in that scale, rather than the sum as in Watson and colleagues (2012).

Task and Procedure

Participants completed an arrowhead version of the flanker task (Eriksen & Eriksen, 1974) while their EEG activity was recorded. On each trial of the task, participants were shown a row of five arrowheads and were instructed to indicate the direction the center arrow was pointing by responding with the left and right mouse button. Half of all trials were compatible (“<<<<<<” or “>>>>>”) and half were incompatible (“<<>><<” or “>><<>>”); the order of compatible and incompatible trials was randomized. Participants completed a practice block to ensure they understood the task, which was readministered if necessary until they performed above 60% accuracy. Both speed and accuracy were emphasized during task instruction and throughout the experiment. After each block of trials, participants received one of three types of performance feedback: If performance was 75% correct or lower, the message “Please try to be more accurate” was displayed; if accuracy was above 90%, participants were told “Please try to respond faster”; finally, if performance was between 75% and 90% correct, the message “You’re doing a great job” was displayed.

Psychophysiological Recording, Data Reduction, and Analysis

Continuous EEG activity was collected using an elastic cap and the ActiveTwo BioSemi system (BioSemi, Amsterdam, the Netherlands). Thirty-four Ag/AgCl-tipped electrodes were used based on the international 10/20 system (including FCz and Iz) as well as two electrodes placed on the left and right mastoids. The electrooculogram generated from eye movements and eye blinks was recorded using four facial electrodes: horizontal eye movements were measured via two electrodes placed approximately 1 cm outside the outer canthus of the left and right eyes, and vertical eye movements and blinks were measured via two electrodes placed approximately 1 cm above and below the right eye. The EEG signal was preamplified at the electrode to improve the signal-to-noise ratio by the BioSemi ActiveTwo system. The data were digitized at a 24-bit resolution with a sampling rate of 512 Hz using a low-pass fifth-order sinc filter with a half-power cutoff of 102.4 Hz. Each active electrode was measured online with respect to a common mode sense active electrode producing a monopolar (nondifferential) channel.

Data processing was performed offline with Brain Vision Analyzer (Brain Products, Gilching, Germany). All data were referenced to the average of the left and right mastoids and band-pass filtered from 0.1 to 30 Hz. Eye blink and ocular corrections were conducted using a standard regression-based algorithm (Gratton, Coles, & Donchin, 1983). A semiautomatic procedure was used to detect and reject artifacts. The criteria applied were a voltage step of more than 50.0 μV between sample points, a voltage difference of 300.0 μV within a trial, and a maximum voltage difference of less than 0.50 μV within a 100 ms interval. Intervals were rejected from individual channels in each trial, and visual inspection of the data was then conducted to detect and reject remaining artifacts.

The recorded EEG activity was segmented relative to both error and correct responses, beginning 500 ms before a response and continuing 1,000 ms following a response (i.e., 1,500 ms epochs). Error and correct trials were then separately averaged. The mean activity in a 200-ms window from -500 to -300 ms prior to response onset served as the baseline and was subtracted from each data point. The ERN was quantified on error trials as the average

activity in a 50 ms window surrounding the peak of the ERN (i.e., most negative point between -25 and 75 ms of committing an error) at scalp site FCz, where error-related brain activity was maximal. In addition, the correct response negativity (CRN) was evaluated for the same time window and sites on correct trials. All analyses focused on the Δ ERN (i.e., the ERN minus CRN) due to the fact that this measure is thought to disentangle neural response to errors from generic response monitoring processes common to both error and correct trials reflected in the CRN (Simons, 2010).

Behavioral measures included both the number of error trials for each subject, and accuracy expressed as a percentage of trials with correct responses. Average reaction times (RTs) on error and correct trials were also calculated separately. Posterror RT was also evaluated to examine posterror behavior. Trials were removed from analysis if reaction times were faster than 200 ms or slower than 1,000 ms.

All statistical analyses were conducted using SPSS (version 22.0) General Linear Model software. Pearson coefficients were used to examine zero-order correlations between Δ ERN and all IDAS symptom dimension scores. Associations between Δ ERN and IDAS anxiety subscales were also analyzed using multiple linear regression analyses, as was the relationship between the Δ ERN and the IDAS General Depression scale. In each of these analyses, age was included as a covariate. To examine the potential moderating role of age on the relationship between Δ ERN and both checking and depression, we utilized a nonparametric bootstrapping method (SPSS Macro from Preacher & Hayes, 2004).

Results

Behavioral Data

Overall response accuracy was 86.6%, $SD = 6.10$, which increased with age, $r = .14$, $p < .01$. Participants responded faster on error, $M = 357.80$ ms, $SD = 56.73$, compared to correct trials, $M = 446.30$ ms, $SD = 62.22$, $F(1, 502) = 2,386.43$, $p < .001$, $\eta_p^2 = .83$. Reaction times on trials following an error, $M = 456.00$ ms, $SD = 77.58$, were slower than RTs following correct trials, $M = 431.56$ ms, $SD = 61.41$, $F(1, 502) = 213.38$, $p < .001$, $\eta_p^2 = .30$. Consistent with previous studies, participants were faster on error trials and posterror RTs were slower. However, behavioral response variables did not correlate with any of the IDAS symptom measures (all $ps > .06$).

Error-Related Brain Activity

The ERN, $M = -1.54$, $SD = 5.11$ was larger (i.e., more negative) than the CRN, $M = 1.12$, $SD = 4.07$, $F(1, 514) = 242.77$, $p < .001$, $\eta_p^2 = .32$. Table 1 shows the correlations, means, and standard deviations for error-related brain activity and all IDAS scales of interest. In a simultaneous multiple regression analysis of the eight anxiety-relevant subscales of the IDAS (Panic, Social Anxiety, Claustrophobia, Traumatic Intrusions, Traumatic Avoidance, Checking, Ordering, and Cleaning), controlling for age, only checking was significantly associated with an enhanced Δ ERN and thus we retained it for further analysis (see Table 2).² A follow-up regression analysis including symptoms of both depres-

sion and checking was significant, $F(2, 512) = 5.32$, $p < .001$, with symptoms of depression and checking showing opposing associations with Δ ERN magnitude, such that symptoms of depression related to reduced Δ ERN, and checking symptoms related to enhanced Δ ERN (see Figure 2 and Table 3).

Development

Zero-order correlations suggested that age was not related to any of the anxiety subscales or to symptoms of depression (all $ps > .20$). Consistent with previous work, the magnitude of the Δ ERN increased with age (Table 1). To examine the potential moderating role of development on the relationship between Δ ERN and both checking and depression, we utilized a nonparametric bootstrapping method (SPSS Macro from Preacher & Hayes, 2004). In the first model, we examined the potential interaction between checking and age in predicting Δ ERN while controlling for symptoms of depression. Again, we found opposing main effects of checking and depression on the Δ ERN, $t = 2.01$, $p < .05$, and $t = 3.15$, $p < .01$, respectively. Additionally, there was a significant interaction between age and checking symptoms, $t = -2.12$, $p < .05$ (see Figure 3). Among older girls, checking was related to an increased Δ ERN, $t = -2.94$, $p < .01$; however, checking was unrelated to the Δ ERN magnitude among younger girls, $t = -.53$, $p = .59$. In the second model, we tested for an interaction between depressive symptoms and age in predicting Δ ERN while controlling for checking symptoms. While checking symptoms still predicted Δ ERN magnitude, $t = -2.06$, $p < .05$, the interaction between age and depression was not significant, $t = -1.30$, $p = .20$, nor was the main effect of depression in this model, $t = 1.45$, $p = .15$.

Discussion

Using empirically derived phenotypes measured within a large sample, the present study demonstrated that checking behaviors related to a larger (i.e., more negative) ERN, and depressive symptoms related to a smaller (i.e., less negative) ERN. These results are consistent with evidence from an adult clinical sample (Weinberg, Kotov, & Proudfit, 2015), and indicate that the ERN may be useful in tracking normative variation in transdiagnostic phenomena (i.e., checking and depression symptoms) across adolescence.³ They further demonstrate that the magnitude of the ERN appears to be sensitive to multiple phenotypes, potentially acting in opposing directions (e.g., Weinberg, Klein, et al., 2012; Weinberg, Kotov, & Proudfit, 2015).

Moreover, developmental findings indicated that age related to a larger ERN, and that age moderated the association between checking and the ERN: A larger ERN was related to checking behaviors only in older adolescents. These results are consistent with previous work demonstrating that the capacity for internal performance monitoring increases from childhood to adolescence (see, e.g., Crone, 2014 for a review), as well as with evidence that the association between symptoms of anxiety and the ERN changes over the course of development (e.g., Meyer, Weinberg, et al., 2012). Importantly, the increased association between ERN and

2. Neither the CRN nor the ERN alone related to any of the anxiety subscales or symptoms of depression, all $ps > .10$. Furthermore, in regressions predicting ERN or CRN alone (instead of Δ ERN), none of the anxiety subscales were significantly related to neural activity, all $ps > .10$.

3. "Depressive symptoms" is a broader, more diffuse clinical-outcome dimension than "checking." From the perspective of RDoC, it will be desirable in future research of this kind to parse depressive symptomatology into narrower symptom subdimensions (e.g., anhedonia, rumination, psychomotor deficits).

Table 1. Correlation Table Depicting Associations Between the ΔERN (Error-Related Negativity Minus Correct-Related Negativity), Age, and Subscales of the Inventory of Depression and Anxiety Symptoms (IDAS)

	1	2	3	4	5	6	7	8	9	10	11	Mean	SD
1. ΔERN	–											– 2.66	3.88
2. Age	–.12**	–										14.39	.63
3. Depression	.10*	–.01	–									1.65	.62
4. Panic	.07	–.04	.77**	–								1.34	.55
5. Social Anxiety	.09	–.03	.71**	.61**	–							1.77	.87
6. Claustrophobia	.04	–.08	.52**	.49**	.51**	–						1.37	.71
7. Traumatic Intrusions	.04	–.04	.72**	.73**	.57**	.49**	–					1.41	.70
8. Traumatic Avoidance	.06	–.01	.49**	.41**	.45**	.51**	.55**	–				1.82	.95
9. Checking	–.02	–.05	.52**	.51**	.53**	.45**	.45**	.45**	–			1.82	.97
10. Ordering	.03	–.03	.38**	.32**	.42**	.41**	.33**	.38**	.64**	–		1.74	.79
11. Cleaning	.00	–.07	.42**	.36**	.43**	.54**	.38**	.47**	.52**	.57**	–	1.45	.67

Note. Means and standard deviations are shown using IDAS scores. * indicates $p < .05$, ** indicates $p < .01$.

checking with age was unique—that is, no moderating effect of age was found for the association between depression and the ERN.

The results of the current study provide further evidence for the utility of the ERN within the context of the RDoC framework. Specifically, our findings indicate that a well-characterized neural index of error monitoring (i.e., ERN) is conceptually proximal to a specific maladaptive behavior (i.e., checking), as opposed to a more distal heterogeneous diagnostic category determined by clinical consensus in the absence of biological considerations. Furthermore, checking behaviors are evident across multiple diagnostic categories (Parrish & Radomsky, 2010; Watson et al., 2012; Weinberg, Kotov, & Proudfit, 2015), suggesting that the ERN may index checking as a transdiagnostic symptom variable.

ERN, Development, and Risk for Psychopathology

The results of this article also suggest the importance of conducting developmental investigations within the framework of RDoC. The moderating role of age on the ERN-checking association is consistent with work demonstrating that the association between the ERN and trait anxiety changes as children transition into adolescence (Meyer, Weinberg, et al., 2012). These results are also helpful in demonstrating specificity in another way, by suggesting that the ERN is not an index of a general liability for internalizing psychopathology (Bress, Meyer, & Hajcak, 2013). Instead, our findings indicate that symptoms of depression exerted an opposing influence on the magnitude of the ERN. This suggests that depression and some types of anxiety are at least partially distinguishable in terms of patterns of neural response, and that variation in the ERN may be useful in tracking unique trajectories of these pathologies. These data also highlight the need for more prospective developmental studies to determine whether the association between checking and the ERN gets stronger over time.

Additionally, there is evidence that the ERN-anxiety association may differ between subclinical and clinical levels of anxiety. For instance, while normative levels of anxiety in children have been associated with a blunted ERN (Meyer, Weinberg, et al., 2012; Moser et al., 2015; Torpey et al., 2013), there is also evidence that enhancement of ERN is already evident in children with clinically significant levels of anxiety (Hajcak et al., 2008; Ladouceur et al., 2006; Meyer, Hajcak, et al., 2013). Moreover, we have recently demonstrated that an enhanced ERN at age 6 predicts a new diagnosis of an anxiety disorder at age 9 (Meyer, Proudfit, Torpey-Newman, et al., 2014). One possibility is that there are meaningful anxiety thresholds, above which the association with the ERN is

relatively stable across development, and may represent a risk marker for early-onset dysfunction. In other words, children with clinically relevant levels of anxiety may already be engaging in more performance monitoring and increased scrutiny of their behaviors as a source of endogenous threat. Below this threshold, child and parent report of anxiety may capture a more general type of distress. Combined, these results suggest multiple developmental pathways to the expression of anxious pathologies.

It is also possible that identifying specific, and empirically derived, anxious phenotypes, such as checking, might be useful in explaining these differences. Future studies encompassing a broader range of ages, as well as levels of dysfunction, will be needed to explore this. Additionally, the data we present here are cross-sectional. However, these participants are returning to the lab for additional visits, which will allow us to track the emergence and progression of symptoms over time. One critical future direction will be to examine whether the construct of sensitivity to endogenous threat, as measured by checking behaviors and the ERN, provides information about course, severity, and risk for anxiety-related pathologies.

And finally, adolescence is a developmental period during which it may be particularly important to consider the contribution of multiple RDoC systems, as well as their interactions, to the expression of psychopathology. This developmental period is marked not only by continued (albeit uneven) maturation of both cortical and subcortical regions, but also tremendous development and flux in the connections and communications between these regions (Casey, Duhoux, & Cohen, 2010; Casey, Jones, & Hare,

Table 2. Results of a Simultaneous Multiple Regression Examining the Unique Effects of All Anxiety Subscales of the Inventory of Depression and Anxiety Symptoms (IDAS) on the ΔERN (Error-Related Negativity Minus Correct-Related Negativity)

	β	t	p
Age*	–.12	–2.65	<.01
Panic	.05	.67	.51
Social Anxiety	.10	1.54	.12
Claustrophobia	.01	.09	.93
Traumatic Intrusions	–.05	–.74	.46
Traumatic Avoidance	.08	1.29	.20
Checking *	–.15	–2.30	<.05
Ordering	.09	1.38	.17
Cleaning	–.05	–.77	.44
Overall model R		.18	
Overall model R ²		.03	

Note. * indicates $p < .05$, ** indicates $p < .01$.

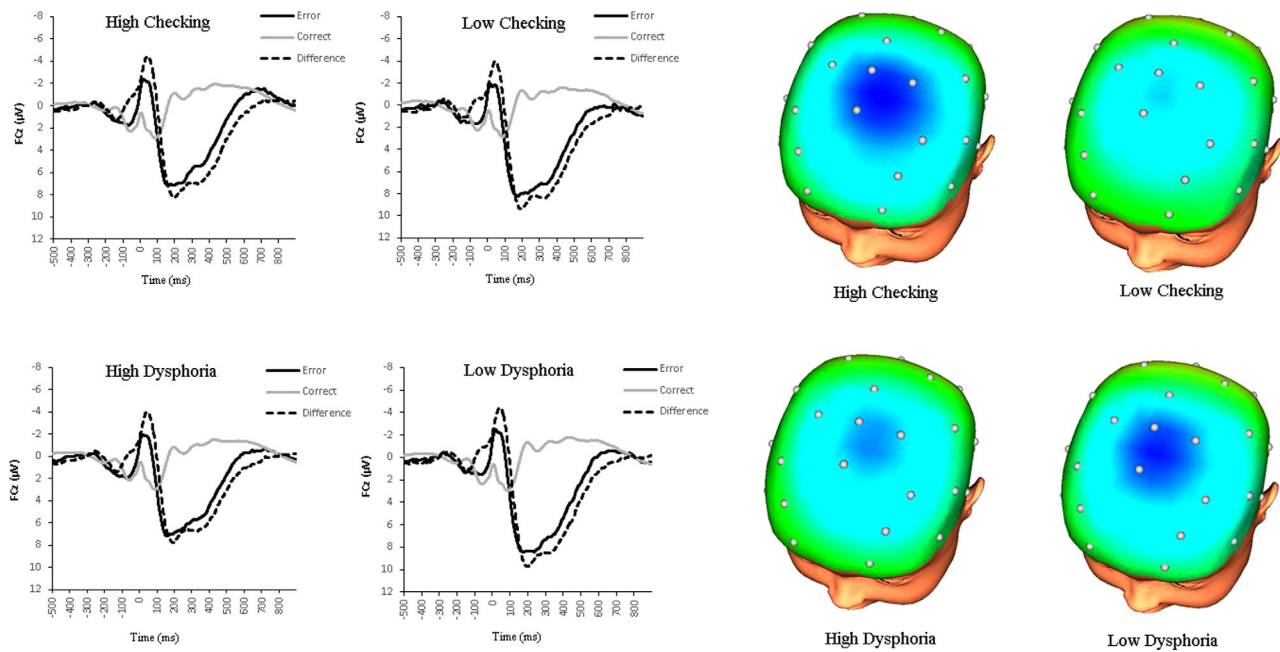


Figure 2. Response-locked event-related potentials (ERP) waveforms at electrode site FCz, during the flanker task. Also depicted are the topographic maps depicting differences (in μV) between error and correct responses in the time range of the error-related negativity (ERN) (-25 to 75 ms). For the purpose of presentation, we created high and low checking groups based on quartiles, using a residual approach.

2008). In order to understand individual differences in this transitional period, it may be critical to consider the relative influence of evaluative and regulatory systems (Casey et al., 2010; Casey et al., 2008) as these circuits and structures develop.

Limitations

While the current study drew from a large and well-characterized sample, and used a well-validated experimental paradigm, there are also limitations that should be noted. For example, the sample was composed only of females. There is a wealth of evidence suggesting sex differences in the development of anxiety in children and adolescents (Chaplin, Gillham, & Seligman, 2009; Lewinsohn, Gotlib, Lewinsohn, Seeley, & Allen, 1998). Sex differences in the magnitude of the ERN have also been observed (Larson, South, & Clayson, 2011), and there is some evidence that the ERN-anxiety coupling may be stronger in females (Moran, Taylor, & Moser, 2012). Given these considerations, it will be important to replicate these results in males. Future studies might also examine the association with additional facets of anxious apprehension (e.g., worry,

intolerance of uncertainty) to clarify the specificity of the association with checking.

Additionally, the current analyses were cross-sectional, and the age range in this sample was somewhat narrow. Future studies might utilize longitudinal data across a broader age range. Nonetheless, given the need to specify a target age range, the ages represented in the present sample are likely particularly important to the development of the checking-ERN association (Meyer, Weinberg, et al., 2012). Finally, the current study used a community sample, rather than a clinical sample. Reduced variance in some measures of psychopathology might make it difficult to detect associations, and those detected likely are underestimated. We would note, however, that the results of this investigation mirror those from an adult patient sample (Weinberg, Kotov, & Proudfit, 2015). Moreover, the use of an adolescent sample permitted the investigation of developmental questions.

Conclusions and Future Directions

We have argued that variation in the ERN reflects individual differences in the degree to which errors are evaluated as salient or

Table 3. Results of a Simultaneous Multiple Regression Examining the Unique Effects of the Inventory of Depression and Anxiety Symptoms (IDAS) Subscales of Checking and Depression on the ΔERN (Error-Related Negativity Minus Correct-Related Negativity)

	β	t	P
Age**	.27	-2.73	<.01
Checking *	-.10	-2.03	<.05
Depression **	.15	2.93	<.01
Overall model R^2		.17	
Overall model R^2		.03	

Note. * indicates $p < .05$, ** indicates $p < .01$.

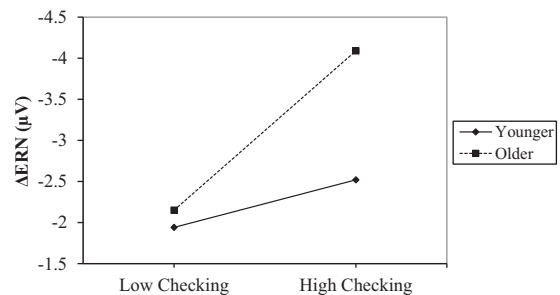


Figure 3. The interaction of age and checking behaviors measured in the Inventory of Depression and Anxiety Symptoms (IDAS). As depicted, the association between checking behaviors and the error-related negativity (ERN) only became evident at older ages.

catastrophic, and that the nature of this evaluation likely emerges via the interplay between genetic propensity and individual learning history across development. To the extent that the ERN reflects variability in sensitivity to errors, as a type of endogenous threat, it may be more aptly designated as an indicator of “Sustained Threat” than Acute Threat. Pathological checking could be a behavioral manifestation of “Sustained Threat,” and the shared variance with the ERN may reflect some portion of this construct. The evidence that we present for an attenuated ERN with increasing depression may also reflect individual differences in threat sensitivity: depression and symptoms of depression have often been associated with a blunted response to threat (Bylsma et al., 2008; Lang & McTeague, 2009; McTeague & Lang, 2012; Rottenberg et al., 2005). Other indices of “Sustained Threat” included in the RDoC matrix are attentional bias toward threat, dysregulated hypothalamic–pituitary–adrenal axis, punishment sensitivity, avoidance, and perseverative behaviors. Here and elsewhere, we have demonstrated a link between the ERN and perseverative checking. An enhanced ERN has also been linked to increased self-reported punishment sensitivity (Boksem, Tops, Kostermans, & De Cremer, 2008). Combined, these data suggest that several of the measures included in the “Sustained Threat” construct relate to one another meaningfully, and may effectively capture some portion of variance in this construct.

However, studies like the current one may also be useful in refining the RDoC matrix itself, which is explicitly a work in progress. For instance, the associations among alternative manifest measures of “Sustained Threat” tend to be modest (e.g., Nelson, Patrick, & Bernat, 2011; Patrick et al., 2013), as was the case in the present sample. **Kozak and Cuthbert (2016)** address the difficulties associated with making inferences from moderate levels of covariation; error related to method variance will likely continue to be a challenge facing studies that seek to use multiple alternative methods of measurement (e.g., self-report, ERP, fMRI) to capture latent phenomena. In addition, refining these nomological networks will be critical as the field continues to evaluate the potential distinctions among constructs within RDoC’s Negative Valence System.

We have argued that variability in the ERN reflects individual differences in sensitivity to errors, as endogenous threat. It is possible that the distinction between internal and external sources of threat should be reflected in distinct RDoC constructs. Many anxiety disorders are characterized by sensitivity to endogenous threat (Clark & Wells, 1995; Domschke et al., 2010; Ehlers & Breuer, 1992; Hamm et al., 2014). It will be important to understand whether processing these distinct types of threat engages overlap-

ping or distinct circuits, and whether symptoms and pathologies that emerge from these sensitivities are distinct from one another.

Apart from the need to clarify the position of the ERN within the broad Negative Valence System, there remains the question of what it means for a marker to appear within three different RDoC domains. As we have argued, it is likely the case that cognitive control and motivational factors are integrated functions in the context of performance monitoring. This is consistent with the way that the RDoC work groups characterized the construct of cognition, as noted by **Kozak and Cuthbert (2016)**. We have argued that cognitive control has both evaluative and regulatory components, and that *individual differences* in the ERN largely reflect variability in the extent to which errors are evaluated as threatening. Explicit recognition of the interplay among domains may be critical to understanding RDoC’s dimensional model. More specifically, it will be important to determine the extent to which dysfunction in evaluative systems and dysfunction in executive systems are causally related.

In short, it will be necessary to continue to explore the extent to which the constructs within RDoC dimensions, and even the superordinate dimensions themselves, reflect the activity of independent or overlapping systems. One approach that may be helpful in refining the constructs is to begin with the construction of an empirically based taxonomy of psychological phenotypes (e.g., Krueger & Markon, ; Watson, 2005). Associations with other units of analysis could then be examined, allowing the observed correspondence between biology and psychology to define a construct (Patrick et al., 2013). RDoC domains, in this light, would be emergent entities from distinct patterns of correspondence between psychology and biology.

The present results suggest the value of the ERN in tracking the ways in which dysfunction of multiple domains interact to influence psychological and neurobiological functioning, as well as the development of dysfunction. But these data also have the potential to begin to refine the matrix itself. It seems clear from these data that RDoC dimensions do not operate independently, are sensitive to multiple phenotypes in potentially opposing directions, and that observed psychopathology likely emerges from interactions among them. This may be particularly important when considering developmental trajectories. And finally, it may be important to examine whether, when, and how dysfunction in evaluative systems is causally related to dysfunction in executive systems. Future RDoC studies looking across multiple units of analysis, and including both internalizing and externalizing psychopathology, might more ably consider the ways in which variations in threat sensitivity and cognitive control combine to influence abnormal behaviors.

References

- Allain, S., Burle, B., Hasbroucq, T., & Vidal, F. (2009). Sequential adjustments before and after partial errors. *Psychonomic Bulletin Review*, *16*, 356. doi: 10.3758/PBR.16.2.356
- Althaus, M., Groen, Y., Wijers, A. A., Mulder, L. J., Minderaa, R. B., Kema, I. P., ... & Hoekstra, P. J. (2009). Differential effects of 5-HTTLPR and DRD2/ANKK1 polymorphisms on electrocortical measures of error and feedback processing in children. *Clinical Neurophysiology*, *120*, 93–107. doi: 10.1016/j.clinph.2008.10.012
- Andrews, V. H., & Borkovec, T. (1988). The differential effects of inductions of worry, somatic anxiety, and depression on emotional experience. *Journal of Behavior Therapy and Experimental Psychiatry*, *19*, 21–26. doi: 10.1016/0005-7916(88)90006-7
- Anokhin, A., Golosheykin, S., & Heath, A. (2008). Heritability of frontal brain function related to action monitoring. *Psychophysiology*, *45*, 524–534. doi: 10.1111/j.1469-8986.2008.00664.x
- Berenbaum, H., Bredemeier, K., & Thompson, R. J. (2008). Intolerance of uncertainty: Exploring its dimensionality and associations with need for cognitive closure, psychopathology, and personality. *Journal of Anxiety Disorders*, *22*, 117–125. doi: 10.1016/j.janxdis.2007.01.004
- Boksem, M., Tops, M., Kostermans, E., & De Cremer, D. (2008). Sensitivity to punishment and reward omission: Evidence from error-related ERP components. *Biological Psychology*, *79*, 185–192. doi: 10.1016/j.biopsycho.2008.04.010
- Botvinick, M., Braver, T., Barch, D., Carter, C., & Cohen, J. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*, 624–652. doi: 10.1037//0033-295x.108.3.624
- Brázdil, M., Roman, R., Daniel, P., & Rektor, I. (2005). Intracerebral error-related negativity in a simple go/nogo task. *Journal of Psychophysiology*, *19*, 244. doi: 10.1027/0269-8803.19.4.244
- Bress, J., Meyer, A., & Hajcak, G. (2013). Differentiating anxiety and depression in children and adolescents: Evidence from event-related

- brain potentials. *Journal of Clinical Child & Adolescent Psychology*, 44, 1–12. doi: 10.1080/15374416.2013.814544
- Brooker, R. J., & Buss, K. A. (2014). Harsh parenting and fearfulness in toddlerhood interact to predict amplitudes of preschool error-related negativity. *Developmental Cognitive Neuroscience*, 9, 148–159. doi: 10.1016/j.dcn.2014.03.001
- Bush, G., Luu, P., & Posner, M. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences*, 4, 215–222. doi: 10.1016/S1364-6613(00)01483-2
- Bylsma, L., Morris, B., & Rottenberg, J. (2008). A meta-analysis of emotional reactivity in major depressive disorder. *Clinical Psychology Review*, 28, 676–691. doi: 10.1016/j.cpr.2007.10.001
- Carrasco, M., Harbin, S., Nienhuis, J., Fitzgerald, K., Gehring, W., & Hanna, G. (2013). Increased error-related brain activity in youth with obsessive-compulsive disorder and unaffected siblings. *Depression and Anxiety*, 30, 39–46. doi: 10.1002/da.22035
- Carrasco, M., Hong, C., Nieuwenhuis, J., Harbin, S., Fitzgerald, K., Gehring, W., & Hanna, G. (2013). Increased error-related brain activity in youth with obsessive-compulsive disorder and other anxiety disorders. *Neuroscience Letters*, 541, 214–218. doi: 10.1016/j.neulet.2013.02.017
- Casey, B., Duhoux, S., & Cohen, M. M. (2010). Adolescence: What do transmission, transition, and translation have to do with it? *Neuron*, 67, 749–760. doi: 10.1016/j.neuron.2010.08.033
- Casey, B., Jones, R. M., & Hare, T. A. (2008). The adolescent brain. *Annals of the New York Academy of Sciences*, 1124, 111–126. doi: 10.1196/annals.1440.010
- Casey, B., Trainor, R., Orendi, J., Schubert, A., Nystrom, L., Giedd, J., . . . Rapoport, J. (1997). A developmental functional MRI study of prefrontal activation during performance of a Go-No-Go task. *Journal of Cognitive Neuroscience*, 9, 835. doi: 10.1162/jocn.1997.9.6.835
- Cavanagh, J., & Shackman, A. (2014). Frontal midline theta reflects anxiety and cognitive control: Meta-analytic evidence. *Journal of Physiology-Paris*. doi: 10.1016/j.jphysparis.2014.04.003
- Chaplin, T. M., Gillham, J. E., & Seligman, M. E. (2009). Gender, anxiety, and depressive symptoms: A longitudinal study of early adolescents. *The Journal of Early Adolescence*, 29, 307–327. doi: 10.1177/0272431608320125
- Chiu, P., & Deldin, P. (2007). Neural evidence for enhanced error detection in major depressive disorder. *American Journal of Psychiatry*, 164, 608. doi: 10.1176/appi.ajp.164.4.608
- Clark, D. M., & Wells, A. (1995). A cognitive model of social phobia. *Social Phobia: Diagnosis, Assessment, and Treatment*, 41, 00022–00023.
- Copeland, W., Angold, A., Shanahan, L., & Costello, E. (2014). Longitudinal patterns of anxiety from childhood to adulthood: The Great Smoky Mountains Study. *Journal of the American Academy of Child & Adolescent Psychiatry*, 53, 21–33. doi: 10.1016/j.jaac.2013.09.017
- Critchley, H., Tang, J., Glaser, D., Butterworth, B., & Dolan, R. (2005). Anterior cingulate activity during error and autonomic response. *Neuroimage*, 27, 885–895. doi: S1053-8119(05)00329-0
- Crone, E. A. (2014). The role of the medial frontal cortex in the development of cognitive and social-affective performance monitoring. *Psychophysiology*, 51, 943–950. doi: 10.1111/psyp.12252
- Danielmeier, C., Eichele, T., Forstmann, B., Tittgemeyer, M., & Ullsperger, M. (2011). Posterior medial frontal cortex activity predicts post-error adaptations in task-related visual and motor areas. *Journal of Neuroscience*, 31, 1780–1789. doi: 10.1523/JNEUROSCI.4299-10.2011
- Davies, P., Segalowitz, S., & Gavin, W. (2004). Development of response-monitoring ERPs in 7- to 25-year-olds. *Developmental Neuropsychology*, 25, 355–376. doi: 10.1207/s15326942dn2503_6
- de Bruijn, E., Hulstijn, W., Verkes, R., Ruigt, G., & Sabbe, B. (2004). Drug-induced stimulation and suppression of action monitoring in healthy volunteers. *Psychopharmacology*, 177, 151–160. doi: 10.1007/s00213-004-1915-6
- Debener, S., Ullsperger, M., Siegel, M., Fiehler, K., von Cramon, D., & Engel, A. (2005). Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. *Journal of Neuroscience*, 25, 11730–11737. doi: 10.1523/JNEUROSCI.3286-05.2005
- Dehaene, S., Posner, M. I., & Tucker, D. M. (1994). Localization of a neural system for error detection and compensation. *Psychological Science*, 5, 303–305. doi: 10.1111/j.1467-9280.1994.tb00630.x
- Domschke, K., Stevens, S., Pfleiderer, B., & Gerlach, A. L. (2010). Interoceptive sensitivity in anxiety and anxiety disorders: An overview and integration of neurobiological findings. *Clinical Psychology Review*, 30, 1–11. doi: 10.1016/j.cpr.2009.08.008
- Ehlers, A., & Breuer, P. (1992). Increased cardiac awareness in panic disorder. *Journal of Abnormal Psychology*, 101, 371. doi: 10.1037/0021-843X.101.3.371
- Endrass, T., Riesel, A., Kathmann, N., & Buhlmann, U. (2014). Performance monitoring in obsessive-compulsive disorder and social anxiety disorder. *Journal of Abnormal Psychology*, 123, 705. doi: 10.1037/abn0000012
- Eriksen, B., & Eriksen, C. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, 16, 143–149. doi: 10.3758/BF03203267
- Euser, A. S., Evans, B. E., Greaves-Lord, K., Huizink, A. C., & Franken, I. H. (2013). Diminished error-related brain activity as a promising endophenotype for substance-use disorders: Evidence from high-risk offspring. *Addiction Biology*, 18, 970–984. doi: 10.1111/adb.12002
- Fallgatter, A. J., Herrmann, M. J., Roemmler, J., Ehlis, A. C., Wagnener, A., Heidrich, A., . . . & Lesch, K. P. (2004). Allelic variation of serotonin transporter function modulates the brain electrical response for error processing. *Neuropsychopharmacology*, 29, 1506–1511. doi: 10.1038/sj.npp.1300409
- Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography and Clinical Neurophysiology*, 78, 447–455. doi: 10.1016/0013-4694(91)90062-9
- Falkenstein, M., Hoormann, J., Christ, S., & Hohnsbein, J. (2000). ERP components on reaction errors and their functional significance: A tutorial. *Biological Psychology*, 51, 87–107. doi: S0301051199000319
- Fiehler, K., Ullsperger, M., & Von Cramon, D. (2005). Electrophysiological correlates of error correction. *Psychophysiology*, 42, 72–82. doi: 10.1111/j.1469-8986.2005.00265.x
- Frost, R. O., & Hartl, T. L. (1996). A cognitive-behavioral model of compulsive hoarding. *Behaviour Research and Therapy*, 34, 341–350. doi: 10.1016/0005-7967(95)00071-2
- Frost, R. O., Marten, P., Lahart, C., & Rosenblate, R. (1990). The dimensions of perfectionism. *Cognitive Therapy and Research*, 14, 449–468. doi: 10.1007/BF01172967
- Ganushchak, L. Y., & Schiller, N. O. (2008). Motivation and semantic context affect brain error-monitoring activity: An event-related brain potentials study. *Neuroimage*, 39, 395–405. doi: S1053-8119(07)00793-8
- Gehring, W., Coles, M., Meyer, D., & Donchin, E. (1995). A brain potential manifestation of error-related processing. *Electroencephalographic Clinical Neurophysiology Supplement*, 44, 261–272.
- Gehring, W., Goss, B., Coles, M., Meyer, D., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science*, 4, 385–390. doi: 10.1111/j.1467-9280.1993.tb00586.x
- Gehring, W., Himle, J., & Knight, R. (2000). Prefrontal-cingulate interactions in action monitoring. *Nature Neuroscience*, 3, 516–520. doi: 10.1038/74899
- Gratton, G., Coles, M. G., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, 55, 468–484. doi: 10.1016/0013-4694(83)90135-9
- Hajcak, G., & Foti, D. (2008). Errors are aversive: Defensive motivation and the error-related negativity. *Psychological Science*, 19, 103. doi: PSCI2053
- Hajcak, G., Franklin, M., Foa, E., & Simons, R. (2008). Increased error-related brain activity in pediatric obsessive-compulsive disorder before and after treatment. *American Journal of Psychiatry*, 165, 116–123. doi: 10.1176/appi.ajp.2007.07010143
- Hajcak, G., McDonald, N., & Simons, R. (2003a). Anxiety and error-related brain activity. *Biological Psychology*, 64, 77–90. doi: 10.1016/S0301-0511(03)00103-0
- Hajcak, G., McDonald, N., & Simons, R. (2003b). To err is autonomic: Error-related brain potentials, ANS activity, and post-error compensatory behavior. *Psychophysiology*, 40, 895–903.
- Hajcak, G., McDonald, N., & Simons, R. (2004). Error-related psychophysiology and negative affect. *Brain and Cognition*, 56, 189–197. doi: 10.1016/j.bandc.2003.11.001
- Hajcak, G., Moser, J., Yeung, N., & Simons, R. (2005). On the ERN and the significance of errors. *Psychophysiology*, 42, 151–160. doi: 10.1111/j.1469-8986.2005.00270.x
- Hajcak, G., & Simons, R. F. (2002). Error-related brain activity in obsessive-compulsive undergraduates. *Psychiatry Research*, 110, 63–72.

- Hamm, A. O., Richter, J., & Pané-Farré, C. A. (2014). When the threat comes from inside the body: A neuroscience based learning perspective of the etiology of panic disorder. *Restorative Neurology and Neuroscience*, *32*, 79–93.
- Hoffmann, S., & Falkenstein, M. (2010). Independent component analysis of erroneous and correct responses suggests online response control. *Human Brain Mapping*, *31*, 1305–1315. doi: 10.1002/hbm.20937
- Holmes, A., & Pizzagalli, D. (2008). Spatio-temporal dynamics of error processing dysfunctions in major depressive disorder. *Archives of General Psychiatry*, *65*, 179.
- Holmes, A., & Pizzagalli, D. (2010). Effects of task-relevant incentives on the electrophysiological correlates of error processing in major depressive disorder. *Cognitive Affective Behavioral Neuroscience*, *10*, 119–128. doi: 10.3758/CABN.10.1.119
- Holroyd, C., & Coles, M. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, *109*, 679–709. doi: 10.1037//0033-295X.109.4.679
- Holroyd, C., & Yeung, N. (2012). Motivation of extended behaviors by anterior cingulate cortex. *Trends in Cognitive Sciences*, *16*(2), 122–128. doi: 10.1016/j.tics.2011.12.008
- Kawamura, K. Y., Hunt, S. L., Frost, R. O., & DiBartolo, P. M. (2001). Perfectionism, anxiety, and depression: Are the relationships independent? *Cognitive Therapy and Research*, *25*, 291–301.
- Kaczurkin, A. N. (2013). The effect of manipulating task difficulty on error-related negativity in individuals with obsessive-compulsive symptoms. *Biological Psychology*, *93*, 122–131.
- Kerns, J., Cohen, J., MacDonald, A. III, Cho, R., Stenger, V., & Carter, C. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science*, *303*, 1023. doi: 10.1126/science.1089910
- Kiehl, K., Liddle, P., & Hopfinger, J. (2000). Error processing and the rostral anterior cingulate: An event-related fMRI study. *Psychophysiology*, *37*, 216–223. doi: 10.1111/1469-8986.3720216
- King, J., Korb, F., von Cramon, D., & Ullsperger, M. (2010). Post-error behavioral adjustments are facilitated by activation and suppression of task-relevant and task-irrelevant information processing. *Journal of Neuroscience*, *30*, 12759–12769. doi: 10.1523/Jneurosci.3274-10.2010
- Kozak, M. J., & Cuthbert, B. N. (2016). The NIMH Research Domain initiative: Background, issues, and pragmatics. *Psychophysiology*, *53*, 286–297.
- Krueger, R., & Markon, K. (2006). Reinterpreting comorbidity: A model-based approach to understanding and classifying psychopathology. *Annual Review of Clinical Psychology*, *2*, 111. doi: 10.1146/annurev.clinpsy.2.022305.095213
- Ladouceur, C., Dahl, R., Birmaher, B., Axelson, D., & Ryan, N. (2006). Increased error-related negativity (ERN) in childhood anxiety disorders: ERP and source localization. *Journal of Child Psychology & Psychiatry*, *47*, 1073–1082. doi: 10.1111/j.1469-7610.2006.01654.x
- Ladouceur, C., Slifka, J., Dahl, R., Birmaher, B., Axelson, D., & Ryan, N. (2012). Altered error-related brain activity in youth with major depression. *Developmental Cognitive Neuroscience*, *2*, 351–362. doi: 10.1016/j.dcn.2012.01.005
- Lang, P. J., & McTeague, L. M. (2009). The anxiety disorder spectrum: Fear imagery, physiological reactivity, and differential diagnosis. *Anxiety, Stress, & Coping*, *22*, 5–25. doi: 10.1080/10615800802478247
- Larson, M., Baldwin, S., Good, D., & Fair, J. (2010). Temporal stability of the error-related negativity (ERN) and post-error positivity (Pe): The role of number of trials. *Psychophysiology*, *47*, 1167–1171. doi: 10.1111/j.1469-8986.2010.01022.x
- Larson, M., Clayton, P., & Clawson, A. (2014). Making sense of all the conflict: A theoretical review and critique of conflict-related ERPs. *International Journal of Psychophysiology*, *93*, 283–297. doi: 10.1016/j.ijpsycho.2014.06.007
- Larson, M., South, M., & Clayton, P. (2011). Sex differences in error-related performance monitoring. *Neuroreport*, *22*, 44–48. doi: 10.1097/WNR.0b013e32832427403
- Lewinsohn, P. M., Gotlib, I. H., Lewinsohn, M., Seeley, J. R., & Allen, N. B. (1998). Gender differences in anxiety disorders and anxiety symptoms in adolescents. *Journal of Abnormal Psychology*, *107*, 109. doi: 10.1037/0021-843X.107.1.109
- Lindström, B. R., Mattsson-Mårn, I. B., Golkar, A., & Olsson, A. (2013). In your face: Risk of punishment enhances cognitive control and error-related activity in the corrugator supercilii muscle. *Plos One*, *8*, e65692. doi: 10.1371/journal.pone.0065692
- Manoach, D. S., & Agam, Y. (2013). Neural markers of errors as endophenotypes in neuropsychiatric disorders. *Frontiers of Human Neuroscience*, *7*, 350. doi: 10.3389/fnhum.2013.00350
- Markon, K., Chmielewski, M., & Miller, C. (2011). The reliability and validity of discrete and continuous measures of psychopathology: A quantitative review. *Psychological Bulletin*, *137*, 856. doi: 10.1037/a0023678
- McDermott, J. M., Perez-Edgar, K., Henderson, H. A., Chronis-Tuscano, A., Pine, D. S., & Fox, N. A. (2009). A history of childhood behavioral inhibition and enhanced response monitoring in adolescence are linked to clinical anxiety. *Biological Psychiatry*, *65*, 445–448. doi: 10.1016/j.biopsych.2008.10.043
- McLoughlin, G., Albrecht, B., Banaschewski, T., Rothenberger, A., Brandeis, D., Asherson, P., & Kuntsi, J. (2009). Performance monitoring is altered in adult ADHD: A familial event-related potential investigation. *Neuropsychologia*, *47*, 3134–3142. doi: 10.1016/j.neuropsychologia.2009.07.013
- McTeague, L. M., & Lang, P. J. (2012). The anxiety spectrum and the reflex physiology of defense: From circumscribed fear to broad distress. *Depression and Anxiety*, *29*, 264–281. doi: 10.1002/da.21891
- Meyer, A., Bress, J., & Proudfit, G. (2014). Psychometric properties of the error-related negativity in children and adolescents. *Psychophysiology*, *51*, 602–610. doi: 10.1111/psyp.12208
- Meyer, A., Hajcak, G., Torpey, D., Kujawa, A., Kim, J., Bufferd, S., ... Klein, D. (2013). Increased error-related brain activity in six-year-old children with clinical anxiety. *Journal of Abnormal Child Psychology*, *41*, 1257–1266. doi: 10.1007/s10802-013-9762-8
- Meyer, A., Jackson, F., Kujawa, A., Klein, D., & Hajcak, G. (in prep). Increased startle potentiation is related to increased error-related brain activity in children and adolescents.
- Meyer, A., Klein, D., Torpey, D., Kujawa, A., Hayden, E., Sheikh, H., ... Hajcak, G. (2012). Additive effects of the dopamine D2 receptor and dopamine transporter genes on the error-related negativity in young children. *Genes, Brain and Behavior*, *11*, 695–703. doi: 10.1111/j.1601-183X.2012.00812.x
- Meyer, A., Proudfit, G., Bufferd, S., Kujawa, A., Laptook, R., Torpey, D., & Klein, D. (2015). Self-reported and observed punitive parenting prospectively predicts increased error-related brain activity in six-year-old children. *Journal of Abnormal Child Psychology*, *43*, 1–9. doi: 10.1007/s10802-014-9918-1
- Meyer, A., Proudfit, G., Torpey-Newman, D., Kujawa, A., & Klein, D. (2015). Enhanced error-related brain activity in children predicts the onset of anxiety disorders between the ages of 6 and 9. *Journal of Abnormal Psychology*, *124*, 266–274. <http://dx.doi.org/10.1037/abn0000044>.
- Meyer, A., Riesel, A., & Proudfit, G. (2013). Reliability of the ERN across multiple tasks as a function of increasing errors. *Psychophysiology*, *50*, 1220–1225. doi: 10.1111/psyp.12132
- Meyer, A., Weinberg, A., Klein, D., & Hajcak, G. (2012). The development of the error-related negativity (ERN) and its relationship with anxiety: Evidence from 8 to 13 year-olds. *Developmental Cognitive Neuroscience*, *2*, 152–161. doi: 10.1016/j.dcn.2011.09.005
- Miltner, W., Lemke, U., Weiss, T., Holroyd, C., Scheffers, M., & Coles, M. (2003). Implementation of error-processing in the human anterior cingulate cortex: A source analysis of the magnetic equivalent of the error-related negativity. *Biological Psychology*, *64*, 157–166. doi: 10.1016/S0301-0511(03)00107-8
- Moran, T., Taylor, D., & Moser, J. (2012). Sex moderates the relationship between worry and performance monitoring brain activity in undergraduates. *International Journal of Psychophysiology*, *85*, 188–194. doi: 10.1016/j.ijpsycho.2012.05.005
- Moser, J., Durbin, C., Patrick, C., & Schmidt, N. (2015). Combining neural and behavioral indicators in the assessment of internalizing psychopathology in children and adolescents. *Journal of Clinical Child & Adolescent Psychology*, *44*, 329–340. doi: 10.1080/15374416.2013.865191
- Moser, J., Hajcak, G., & Simons, R. (2005). The effects of fear on performance monitoring and attentional allocation. *Psychophysiology*, *42*, 261–268. doi: 10.1111/j.1469-8986.2005.00290.x
- Moser, J., Moran, T., & Jendrusina, A. (2012). Parsing relationships between dimensions of anxiety and action monitoring brain potentials in female undergraduates. *Psychophysiology*, *49*, 3–10. doi: 10.1111/j.1469-8986.2011.01279.x
- Moser, J., Moran, T., Schroder, H., Donnellan, M. B., & Yeung, N. (2013). On the relationship between anxiety and error monitoring: A meta-

- analysis and conceptual framework. *Frontiers in Human Neuroscience*, 7. doi: 10.3389/fnhum.2013.00466
- Mueller, E., Makeig, S., Stemmler, G., Hennig, J., & Wacker, J. (2011). Dopamine effects on human error processing depend on catechol-O-methyltransferase VAL158MET genotype. *The Journal of Neuroscience*, 31, 15818–15825. doi: 10.1523/JNEUROSCI.2103-11.2011
- Müller, S. V., Möller, J., Rodriguez-Fornells, A., & Münte, T. F. (2005). Brain potentials related to self-generated and external information used for performance monitoring. *Clinical Neurophysiology*, 116, 63–74.
- Nelson, L. D., Patrick, C. J., & Bernat, E. M. (2011). Operationalizing proneness to externalizing psychopathology as a multivariate psychophysiological phenotype. *Psychophysiology*, 48, 64–72. doi: 10.1111/j.1469-8986.2010.01047.x
- Nieuwenhuis, S., Holroyd, C. B., Mol, N., & Coles, M. G. (2004). Reinforcement-related brain potentials from medial frontal cortex: Origins and functional significance. *Neuroscience & Biobehavioral Reviews*, 28, 441–448. doi: 10.1016/j.neubiorev.2004.05.003
- Nieuwenhuis, S., Ridderinkhof, K. R., Talsma, D., Coles, M. G., Holroyd, C. B., Kok, A., & Van der Molen, M. W. (2002). A computational account of altered error processing in older age: dopamine and the error-related negativity. *Cognitive, Affective, & Behavioral Neuroscience*, 2, 19–36. doi: 10.3758/CABN.2.1.19
- Olatunji, B. O., Broman-Fulks, J. J., Bergman, S. M., Green, B. A., & Zlomke, K. R. (2010). A taxometric investigation of the latent structure of worry: Dimensionality and associations with depression, anxiety, and stress. *Behavior Therapy*, 41, 212–228. doi: 10.1016/j.beth.2009.03.001
- Olvet, D., & Hajcak, G. (2008). The error-related negativity (ERN) and psychopathology: Toward an endophenotype. *Clinical Psychology Review*, 28, 1343–1354. doi: 10.1016/j.cpr.2008.07.003
- Olvet, D., & Hajcak, G. (2009). Reliability of error-related brain activity. *Brain Research*, 1284, 89–99. doi: 10.1016/j.brainres.2009.05.079
- Olvet, D. M., Hatchwell, E., & Hajcak, G. (2010). Lack of association between the 5-HTTLPR and the error-related negativity (ERN). *Biological Psychology*, 85, 504–508. doi: 10.1016/j.biopsycho.2010.09.012
- Olvet, D., Klein, D., & Hajcak, G. (2010). Depression symptom severity and error-related brain activity. *Psychiatry Research*, 179, 30–37. doi: 10.1016/j.psychres.2010.06.008
- Parrish, C. L., & Radomsky, A. S. (2010). Why do people seek reassurance and check repeatedly? An investigation of factors involved in compulsive behavior in OCD and depression. *Journal of Anxiety Disorders*, 24, 211–222. doi: 10.1016/j.janxdis.2009.10.010
- Patrick, C., Venables, N., Yancey, J., Hicks, B., Nelson, L., & Kramer, M. (2013). A construct-network approach to bridging diagnostic and physiological domains: Application to assessment of externalizing psychopathology. *Journal of Abnormal Psychology*, 122, 902. doi: 10.1037/a0032807
- Pourtois, G., Vocat, R., N'Diaye, K., Spinelli, L., Seeck, M., & Vuilleumier, P. (2010). Errors recruit both cognitive and emotional monitoring systems: Simultaneous intracranial recordings in the dorsal anterior cingulate gyrus and amygdala combined with fMRI. *Neuropsychologia*, 48, 1144–1159. doi: 10.1016/j.neuropsychologia.2009.12.020
- Preacher, K. J., & Hayes, A. F. (2004). SPSS and SAS procedures for estimating indirect effects in simple mediation models. *Behavior Research Methods, Instruments, & Computers*, 36, 717–731. doi: 10.3758/BF03206553
- Rabbitt, P. M. (1966). Error correction time without external error signals. *Nature*, 212, 438. doi: 10.1038/212438a0
- Rabinak, C., Holman, A., Angstadt, M., Kennedy, A., Hajcak, G., & Phan, K. (2013). Neural response to errors in combat-exposed returning veterans with and without post-traumatic stress disorder: A preliminary event-related potential study. *Psychiatry Research: Neuroimaging*, 213, 71–78. doi: 10.1016/j.pscychres.2013.01.002
- Rawal, A., Collishaw, S., Thapar, A., & Rice, F. (2013). “The risks of playing it safe”: A prospective longitudinal study of response to reward in the adolescent offspring of depressed parents. *Psychological Medicine*, 43, 27–38. doi: 10.1017/S0033291712001158
- Riesel, A., Endrass, T., Kaufmann, C., & Kathmann, N. (2011). Overactive error-related brain activity as a candidate endophenotype for obsessive-compulsive disorder: Evidence from unaffected first-degree relatives. *American Journal of Psychiatry*, 168, 317–324. doi: 10.1176/appi.ajp.2010.10030416
- Riesel, A., Weinberg, A., Endrass, T., Kathmann, N., & Hajcak, G. (2012). Punishment has a lasting impact on error-related brain activity. *Psychophysiology*, 49, 239–247. doi: 10.1111/j.1469-8986.2011.01298.x
- Rottenberg, J., Gross, J. J., & Gotlib, I. H. (2005). Emotion context insensitivity in major depressive disorder. *Journal of Abnormal Psychology*, 114, 627. doi: 10.1037/0021-843X.114.4.627
- Ruchow, M., Herrnberger, B., Wiesend, C., Gron, G., Spitzer, M., & Kiefer, M. (2004). The effect of erroneous responses on response monitoring in patients with major depressive disorder: A study with event-related potentials. *Psychophysiology*, 41, 833–840. doi: 10.1111/j.1469-8986.2004.00237.x
- Schoenberger, P. L. (2014). The error processing system in major depressive disorder: Cortical phenotypal marker hypothesis. *Biological Psychology*, 99, 100–114. doi: 10.1016/j.biopsycho.2014.03.005
- Schrijvers, D., de Bruijn, E., Maas, Y., De Grave, C., Sabbe, B., & Hulstijn, W. (2008). Action monitoring in major depressive disorder with psychomotor retardation. *Cortex*, 44, 569–579. doi: 10.1016/j.cortex.2007.08.014
- Schrijvers, D., de Bruijn, E., Maas, Y., Vancollie, P., Hulstijn, W., & Sabbe, B. (2009). Action monitoring and depressive symptom reduction in major depressive disorder. *International Journal of Psychophysiology*, 71, 218–224. doi: 10.1016/j.ijpsycho.2008.09.005
- Schut, A. J., Castonguay, L. G., & Borkovec, T. D. (2001). Compulsive checking behaviors in generalized anxiety disorder. *Journal of Clinical Psychology*, 57, 705–715. doi: 10.1002/jclp.1043
- Segalowitz, S. J., Santesso, D. L., Murphy, T. I., Homan, D., Chantziantoniou, D. K., & Khan, S. (2010). Retest reliability of medial frontal negativities during performance monitoring. *Psychophysiology*, 47, 260–270. doi: 10.1111/j.1469-8986.2009.00942.x
- Shackman, A. J., Salomons, T. V., Slagter, H. A., Fox, A. S., Winter, J. J., & Davidson, R. J. (2011). The integration of negative affect, pain and cognitive control in the cingulate cortex. *Nature Reviews Neuroscience*, 12, 154–167. doi: 10.1038/nrn2994
- Shea, M. T., Stout, R., Gunderson, J., Morey, L. C., Grilo, C. M., McGlashan, T., . . . Znarani, M. C. (2002). Short-term diagnostic stability of schizotypal, borderline, avoidant, and obsessive-compulsive personality disorders. *American Journal of Psychiatry*, 159, 2036–2041. doi: 10.1176/appi.ajp.159.12.2036
- Simmonite, M., Bates, A. T., Groom, M. J., Jackson, G. M., Hollis, C., & Liddle, P. F. (2012). Error processing-associated event-related potentials in schizophrenia and unaffected siblings. *International Journal of Psychophysiology*, 84, 74–79. doi: 10.1016/j.ijpsycho.2012.01.012
- Simons, R. F. (2010). The way of our errors: Theme and variations. *Psychophysiology*, 47, 1–14. doi: 10.1111/j.1469-8986.2009.00929.x
- Spence, S., Rapee, R., McDonald, C., & Ingram, M. (2001). The structure of anxiety symptoms among preschoolers. *Behaviour Research and Therapy*, 39, 1293–1316. doi: 10.1016/S0005-7967(00)00098-X
- Starcevic, V. (1995). Pathological worry in major depression: A preliminary report. *Behaviour Research and Therapy*, 33, 55–56. doi: 10.1016/0005-7967(93)E0028-4
- Sutton, R. S., & Barto, A. G. (1998). *Introduction to reinforcement learning*. Cambridge, MA: MIT Press.
- Taylor, S. (2012). Endophenotypes of obsessive-compulsive disorder: Current status and future directions. *Journal of Obsessive-Compulsive and Related Disorders*, 1, 258–262. doi: 10.1016/j.jocrd.2012.06.004
- Thorndike, E. L. (1927). The law of effect. *The American Journal of Psychology*, 39, 212–222.
- Torpey, D., Hajcak, G., Kim, J., Kujawa, A., Dyson, M., Olino, T., & Klein, D. (2013). Error-related brain activity in young children: Associations with parental anxiety and child temperamental negative emotionality. *Journal of Child Psychology and Psychiatry*, 54, 854–862. doi: 10.1111/jcpp.12041
- Ullsperger, M., King, J., & Von Cramon, D. (2008). Post-error performance optimization by modulation of goal-relevant sensory processing. *International Journal of Psychophysiology*, 69, 212–212. doi: 10.1016/j.ijpsycho.2008.05.028
- Ullsperger, M., & von Cramon, D. (2006). How does error correction differ from error signaling? An event-related potential study. *Brain Research*, 1105, 102–109. doi: 10.1016/j.brainres.2006.01.007
- van Veen, V. (2006). *A neuroimaging approach to the relationship between attention and speed-accuracy tradeoff*. Pittsburgh, PA: University of Pittsburgh.
- Watson, D. (2005). Rethinking the mood and anxiety disorders: A quantitative hierarchical model for DSM-V. *Journal of Abnormal Psychology*, 114, 522. doi: 10.1037/0021-843X.114.4.522
- Watson, D. (2009). Differentiating the mood and anxiety disorders: A quadripartite model. *Annual Review of Clinical Psychology*, 5, 221–247. doi: 10.1146/annurev.clinpsy.032408.153510
- Watson, D., O'Hara, M., Naragon-Gainey, K., Koffel, E., Chmielewski, M., Kotov, R., . . . Ruggero, C. (2012). Development and validation of

- new anxiety and bipolar symptom scales for an expanded version of the IDAS (the IDAS-II). *Assessment*, *19*, 399–420. doi: 10.1177/1073191112449857
- Watson, D., O'Hara, M., & Stuart, S. (2008). Hierarchical structures of affect and psychopathology and their implications for the classification of emotional disorders. *Depression and Anxiety*, *25*, 282–288. doi: 10.1002/da.20496
- Weinberg, A., Dieterich, R., & Riesel, A. (2015). Error-related brain activity in the age of RDoC: A review of the literature. *International Journal of Psychophysiology*. doi: 10.1016/j.ijpsycho.2015.02.029
- Weinberg, A., & Hajcak, G. (2011). Longer term test-retest reliability of error-related brain activity. *Psychophysiology*, *48*, 1420–1425. doi: 10.1111/j.1469-8986.2011.01206.x
- Weinberg, A., Klein, D., & Hajcak, G. (2012). Increased error-related brain activity distinguishes generalized anxiety disorder with and without comorbid major depressive disorder. *Journal of Abnormal Psychology*, *121*, 885. doi: 10.1037/a0028270
- Weinberg, A., Kotov, R., & Proudfit, G. (2015). Neural indicators of error processing in generalized anxiety disorder, obsessive-compulsive disorder, and major depressive disorder. *Journal of Abnormal Psychology*, *124*, 172–185. doi: 10.1037/abn0000019
- Weinberg, A., Olvet, D., & Hajcak, G. (2010). Increased error-related brain activity in generalized anxiety disorder. *Biological Psychology*, *85*, 472–480. doi: 10.1016/j.biopsycho.2010.09.011
- Weinberg, A., Riesel, A., & Hajcak, G. (2012). Integrating multiple perspectives on error-related brain activity: ERN as a neurobehavioral trait. *Motivation and Emotion*, *36*, 84–100. doi: 10.1007/s11031-011-9269-y
- Xiao, Z., Wang, J., Zhang, M., Li, H., Tang, Y., Wang, Y., . . . Fromson, J. A. (2011). Error-related negativity abnormalities in generalized anxiety disorder and obsessive-compulsive disorder. *Progress in Neuropsychopharmacological Biological Psychiatry*, *35*, 265–272. doi: 10.1016/j.pnpbp.2010.11.022
- Zambrano-Vazquez, L., & Allen, J. J. (2014). Differential contributions of worry, anxiety, and obsessive compulsive symptoms to ERN amplitudes in response monitoring and reinforcement learning tasks. *Neuropsychologia*, *61*, 197–209. doi: 10.1016/j.neuropsychologia.2014.06.023

(RECEIVED January 11, 2015; ACCEPTED July 30, 2015)