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Review

A review examining the relationship between individual differences in the error-related negativity and cognitive control

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1. The ERN and cognitive control: from within- to between-subjects effects

Almost 30 years ago, two independent groups discovered the error-related negativity (ERN, or Ne; Falkenstein et al., 1991; Gehring et al., 1993), an event-related brain potential (ERP) evident as a large negative deflection that peaks approximately 50 ms after error commission in speeded reaction time tasks. Although it is clear that the ERN is elicited by performance failures, the specific functional significance of the ERN continues to be debated. The ERN is often discussed within the broader context of performance monitoring: how the detection of errors and subsequent adjustments in performance are critical for successful goal-directed actions (Ridderinkhof et al., 2004). From this perspective, the ERN reflects the evaluation of actions that require corrective action. Indeed, early computational models proposed that the ERN reflected neural activity in the anterior cingulate cortex (ACC) that improved the subsequent selection of appropriate information and actions (Holroyd and Coles, 2002; Yeung et al., 2004). Many researchers argued that there was a direct link between error-monitoring activity of the ACC and subsequent adjustments in performance (Carter et al., 1998; Van Veen and Carter, 2006)—the ERN was viewed as a signal that engaged cognitive control processes.

Gehring's original paper on the ERN provided the first empirical support linking ERN amplitude and cognitive control: within-subjects, the ERN was larger when performance instructions emphasized accuracy over speed, when post-error slowing was also increased; thus, the ERN was potentiated under conditions characterized by greater cognitive control (Gehring et al., 1993). Since then, additional research has linked the ERN to within-subject post-error slowing (for a review of these studies, see: Cavanagh and Shackman, 2015).

It is important to note that the work and theories described above focus on the functional significance of the ERN from a *within-participants* perspective—e.g., how does variability in the ERN across *types* of trials relate to behavioral measures following those trial *types*? The vast majority of cognitive neuroscience research takes a within-subjects perspective to understanding human brain function (Hajcak et al., 2017). However, researchers frequently interpret between-subjects differences in neural activity in terms of insights derived from within-subject comparisons. For example, many researchers have interpreted variability in the ERN across individuals as reflecting *individual differences* in cognitive control (Compton et al., 2013; Grammer et al., 2018; Lo et al., 2015; McDermott et al., 2012; Pontifex et al., 2009). Indeed, the ERN is currently included in the NIMH Research Domain Criteria (RDoC) – a matrix intended to explain variability across people – as a measure of "Cognitive Control".

In terms of evidence that the ERN "indexes cognitive control", studies most often cite either within-subjects studies (for example, Cavanagh and Frank, 2014; Cavanagh and Shackman, 2015; Cavanagh et al., 2012) or theories that link the ERN to control within individuals (Botvinick et al., 2001; Falkenstein et al., 1991; Gehring et al., 1993; Holroyd and Coles, 2002). However, the logic of automatically translating within-subject associations to between-subject effects is flawed.

Consider a classic example: accuracy and typing. It is certainly true that typing speed and accuracy are inversely correlated within subjects: the faster an individual types, the more mistakes they are likely to make. However, it is not the case that typing speed is negatively correlated with accuracy across subjects—rather, individuals who are more experienced and skilled typists are likely to be *both* faster *and* more accurate. In this way, the within-subject effect (↑ speed = ↓ accuracy) would be the *opposite* of a between-subject effect (↑ speed = ↑ accuracy). Thus, a within-subject effect (i.e., ERN relates to increased cognitive control) does not *imply* the same between-subject effect (i.e., people with a larger ERN are characterized by greater cognitive control)—though this error in logic is pervasive in clinical neuroscience.

2. Does the ERN index individual differences in cognitive control?

Many studies have found that participants who commit fewer errors are characterized by a larger ERN (Cavanagh and Shackman, 2015). This is a between-subjects association that could imply a relationship between ERN and cognitive control. However, it is unclear whether error rates in speeded response time tasks in which accuracy and speed are often equally emphasized reflect cognitive control. Cavanagh and Shackman (2015) found both between and within-subject associations

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between the ERN and post-error slowing, although it remains unclear whether post-error slowing is itself a measure of cognitive control (Danielmeier and Ullsperger, 2011; Notebaert et al., 2009). In a recent retrospective on the ERN, Gehring et al., 2018 wrote, "Less well supported are our initial findings that corrective behaviors were associated with greater ERN activity … to date, there is still no clear causal link between the ERN … and performance adjustments" (Gehring et al., 2018).

Indeed, it is unclear whether performance measures derived from tasks used to measure the ERN (e.g., reaction time or accuracy differences on a flankers task) relate to valid between-subject measures of cognitive control. Hedge and colleagues recently demonstrated that robust within-subject effects on behavior (i.e., RT and accuracy differences on a range of tasks) are characterized statistically by low between-subject variability, thus limiting their ability to relate to other individual difference measures (Hedge et al., 2018). Rather than relating ERN to performance measures derived from the task in which the ERN was elicited, a superior strategy for assessing construct validity would be to examine the ERN in relation to more typical and well-validated individual difference measures of cognitive control.[1]

From a neuropsychological perspective, cognitive control refers to the ability to regulate or coordinate thoughts and actions to achieve goals—and is often used interchangeably with the term executive functions (EF). Cognitive control and EF are thought to reflect three core processes: 1.) inhibition (i.e., inhibitory control, selective attention, cognitive inhibition,please undo this changec.), 2.) working memory, and 3.) cognitive flexibility (i.e., set shifting, mental flexibility, etc.; Diamond, 2013; Lehto et al., 2003; Miyake et al., 2000). Inhibition is the ability to control one's attention, behavior, thoughts or emotions to override an automatic or prepotent response, or to selectively attend to a stimulus while ignoring another (Diamond, 2013). Working memory is the ability to hold information in one's mind and to do mental work on that representation (Baddeley and Hitch, 1994). Finally, cognitive flexibility refers to the ability to change perspectives spatially or interpersonally, or to change how we are thinking about something (Davidson et al., 2006).

Indeed, a handful of studies have examined standard individual difference measures of cognitive control or EF in relation to the ERN (see Table 1). For example, Miller et al. (2012) measured working memory in undergraduate students by administering a computerized task (Unsworth et al., 2005) and in a subsequent session, the ERN was measured in the top ($N = 12$) and bottom ($N = 12$) quartile of students on working memory. Miller and colleagues found that individuals characterized by increased working memory capacity were also characterized by a larger ERN. This pattern of results was later replicated by Coleman et al. (2018) in a slightly larger sample ($N = 25$ in top working memory quartile and $N = 25$ in bottom working memory quartile). Again, individuals in the high working memory group displayed a larger ERN than individuals in the low working memory group. Moreover, there is even preliminary evidence that training working memory over an extended period of time (24 sessions) may increase the amplitude of the ERN within individuals (Horowitz-Kraus and Breznitz, 2009).

In line with these findings, Weaver et al. (2017) used concurrent eye-tracking and EEG to measure the ERN during a task wherein participants made eye-movements to targets embedded in a search display which included distractors. During this task, the salience of the

[1] Behavioral measures derived from some tasks used to measure the ERN (e.g., Stroop task) may provide indicators of cognitive control (Friedman and Miyake, 2017). However, research relating ERN to task performance typically examine measures such as RT or accuracy—not more validated measures of cognitive control (e.g., Stroop interference). In light of this, the current review focuses on studies using validated measure of cognitive control in relation to the ERN.

Table 1
Presents main findings from studies examining the link between individual differences in cognitive control and the error-related negativity (i.e., ERN).

First author	EF measure	EF construct	Population	Results
Miller et al., 2012	OSPAN	Working memory	Undergraduate students; $N = 24$	↑Working memory = ↑ERN
Coleman et al., 2018	OSPAN	Working memory	Undergraduate students; $N = 50$	↑Working memory = ↑ERN
Weaver et al., 2017	Color change detection task	Visual working memory	Undergraduate students; $N = 20$	↑Visual working memory = ↑ERN (when distractor was salient)
Larson and Clayson, 2011	Digit Span, Trail Making, Word Association, Rey Test	Memory, Verbal Fluency, Attention/EF	Undergraduate students; $N = 89$	↑Attention/EF = ↑ERN
Seer et al., 2017	Edinburgh Cognitive and Behavioral ALS Screen, Frontal Assessment Battery, Wisconsin Card Soring Test	ALS specific executive functions, frontal lobe functions, cognitive flexibility	Patients with ALS; $N = 18$; healthy controls; $N = 19$	↑EF = ↑ERN, among patients with ALS EF ≠ ERN, among healthy controls
Grammer et al., 2018	Woodcock-Johnson III	Attentional Control	5 year-old children; $N = 49$	*No cross-sectional relationship between attentional control and the ERN ↑Baseline ERN = ↑attentional control at follow-up
Meyer et al., 2018	CBQ parent report	Attentional focusing, attentional shifting, inhibitory control	6 year-old children; $N = 291$	↑Attentional focusing = ↑ERN ↑Attentional shifting = ↑ERN ↑Inhibitory control = ↑ERN

distractor and the target was manipulated. Visual working memory was measured in the same participants (i.e., 20 undergraduate students), during a separate change-detection task. Results suggested that increased visual working memory was related to a larger ERN, but only when the ERN was measured when distractors were salient. While it is unknown how this measure of the ERN relates to more standard measures (e.g., the ERN measured during a flankers task), this study provides support for the link between the ERN and cognitive control (i.e., visual working memory).

Only one study, to our knowledge, has attempted to link the ERN to cognitive control using a broad neurophysiological assessment in healthy adults. Larson and Clayson (2011) administered a neurophysiological assessment to 89 undergraduate students. Measures included an assessment of attention/working memory (Digit Span from the Wechsler Adult Intelligence Scale), processing speed/executive functioning (Trail Making), verbal fluency (Controlled Oral Word Association Test), and verbal memory (Rey Auditory-Verbal Learning Test) - yielding factor scores indexing memory, verbal fluency, and attention/executive functioning. Results suggested that the ERN was increased in relation to the attention/executive functioning factor score, but not memory or verbal fluency.

Seer et al. (2017) measured the ERN in 18 patients with amyotrophic lateral sclerosis (ALS) and 19 healthy controls. They measured executive functioning with the Edinburgh Cognitive and Behavioral ALS Screen, the Frontal Assessment Battery, and a modified version of the Wisconsin Card Soring Test, and created a latent variable for EF based on these measures. Results suggested that while the ERN was not related to EF among healthy individuals, an increased ERN was related to increased EF among patients with ALS. WhileAlthough results should be interpreted with caution due to the small sample size, they suggest that the link between the ERN and EF may be robust among individuals with ALS.

One study has examined the ERN in relation to cognitive control using a neuropsychological assessment in children. Grammer et al. (2018) evaluated 49 children approximately 5 years-old at two time points approximately 6 months apart. The ERN was measured, as well as attentional control via the Woodcock-Johnson III Test of Cognitive Abilities. Results from this study suggested that attentional control was not related to the ERN at the baseline assessment. However, a larger ERN at baseline predicted greater attentional control (and, thus change in attentional control) at the follow-up assessment. These results were interpreted as indicating that error monitoring has implications for understanding changes in cognitive control early in childhood.

We recently examined the relationship between individual differences in cognitive control and the ERN in a large sample of 6 year-old children (N = 291; Meyer and Klein, 2018). Rather than using a neuropsychological assessment to measure cognitive control, we utilized a validated parent-report measure, the Children's Behavior Questionnaire (CBQ; Rothbart et al., 2001). The CBQ includes measures of cognitive control, including attentional focusing, attentional shifting, and inhibitory control. Attentional focusing assesses the child's ability to maintain attentional focus on a task (e.g., "When drawing or coloring in a book, she/he shows strong concentration"); attentional shifting assesses the child's ability to move from one activity to the next (e.g., "Can easily leave off working on a project if asked"); finally inhibitory control assesses the child's capacity to regulate her/his behavior (e.g., "Can wait before entering into new activities if asked"). Results suggested that the ERN was associated with all three of these scales, such that a larger ERN correlated with increased cognitive control. Furthermore, when all three scales were entered into a simultaneous regression predicting the ERN, none were significant—suggesting that the common variance shared between all three scales related to the ERN.

Although they did not use direct measures of cognitive control, Hirsh and Inzlicht (2010) found that the magnitude of the ERN was correlated with better academic performance in 31 undergraduate students. Because self-regulation is thought to underlie academic achievement (Covington, 2000), these results are broadly in line with the work reviewed above that indicates that variability in the magnitude of the ERN is related to individual differences in cognitive control. Although it is important to note that other constructs relevant to academic performance, such as conscientiousness or social anxiety, were not measured in this study.

Kim et al. (2016) examined the relationship of the ERN to early math and reading achievement. The ERN was measured in 113 young children (3–7 years-old), and early math and reading skills were assessed using the Woodcock Johnson Tests of Achievement. In contrast to the findings from Hirsh and Inzlicht (2010), the magnitude of the ERN was *not* related to academic achievement in this study. Thus, findings linking the ERN to academic performance are mixed and future work is needed to clarify this relationship.

If the ERN is increased in relation to normative variability in cognitive control, then it ought to be reduced in clinical conditions characterized by *reduced* cognitive control. Although ADHD encompasses a wide array of symptoms and traits (e.g., decreased motivation and social awareness; Castellanos et al., 2006; De Boo and Prins, 2007), ADHD is characterized by difficulty with attention and deficits in executive functioning (Kofler et al., 2008; Kofler et al., 2010; Rapport et al., 2008).

As can be seen in Table 2, 14 studies to date have found a reduced ERN among individuals with ADHD (Albrecht et al., 2008; Chang et al., 2009; Czobor et al., 2017; Groen et al., 2008; Herrmann et al., 2010; Liotti et al., 2005; Marquardt et al., 2018; McLoughlin et al., 2009; Meyer and Klein, 2018; Michelini et al., 2016; Rosch and Hawk Jr, 2013; Samyn et al., 2014; Senderecka et al., 2012; van Meel et al., 2007). It is important to note that nearly as many studies have failed to find this association (11 studies to date; see Table 2; Groom et al., 2010; Herrmann et al., 2009; Jonkman et al., 2007; O'connell et al., 2009; Shen et al., 2011; Van De Voorde et al., 2010; Wiersema et al., 2009; Wiersema et al., 2005; Wild-Wall et al., 2009; Zhang et al., 2009). Indeed, one study found an *increased* ERN in children with ADHD (Burgio-Murphy et al., 2007). Although the findings are mixed, the overall evidence suggests a potential link between ADHD diagnostic status and a reduced ERN—and these data from ADHD are consistent with the notion that the ERN is linked to individual differences in cognitive

Table 2
Presents main findings from studies examining the link between attention-deficit hyperactivity disorder (ADHD) and the error-related negativity (ERN).

First author	Population	Results
Herrmann et al., 2010	Adult ADHD	ADHD = ↓ERN
Chang et al., 2009	Adult ADHD	ADHD = ↓ERN
Marquardt et al., 2018	Adult ADHD	ADHD = ↓ERN
Czobor et al., 2017	Adult ADHD	ADHD = ↓ERN
Albrecht et al., 2008	Pediatric ADHD	ADHD = ↓ERN
Samyn et al., 2014	Pediatric ADHD	ADHD = ↓ERN
McLoughlin et al., 2009	Pediatric ADHD	ADHD = ↓ERN
Rosch and Hawk Jr, 2013	Pediatric ADHD	ADHD = ↓ERN
van Meel et al., 2007	Pediatric ADHD	ADHD = ↓ERN
Meyer et al., 2018	Pediatric ADHD	ADHD = ↓ERN
Senderecka et al., 2012	Pediatric ADHD	ADHD = ↓ERN
Liotti et al., 2005	Pediatric ADHD	ADHD = ↓ERN
Groen et al., 2008	Pediatric ADHD	ADHD = ↓ERN
Michelini et al., 2016	Adult and pediatric ADHD	ADHD = ↓ERN
Herrmann et al., 2009	Adult ADHD	Null effect
Wiersema et al., 2009	Adult ADHD	Null effect
O'connell et al., 2009	Adult ADHD	Null effect
Wild-Wall et al., 2009	Pediatric ADHD	Null effect
Jonkman et al., 2007	Pediatric ADHD	Null effect
Wiersema et al., 2005	Pediatric ADHD	Null effect
Groom et al., 2010	Pediatric ADHD	Null effect
Zhang et al., 2009	Pediatric ADHD	Null effect
Van De Voorde et al., 2010	Pediatric ADHD	Null effect
Shen et al., 2011	Pediatric ADHD	Null effect
Burgio-Murphy et al., 2007	Pediatric ADHD	ADHD = ↑ERN

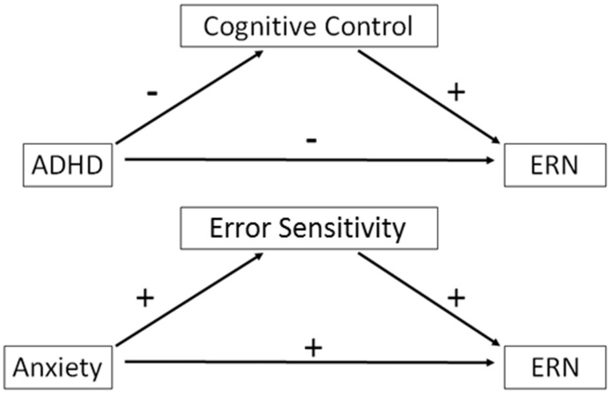

Fig. 1. Models linking individual differences to variability in the ERN. ADHD is depicted as relating to ERN through cognitive control (top), whereas Anxiety is depicted relating to the ERN via increased error sensitivity (bottom).

control.

3. Interim summary and conclusions

Studies that interpret the ERN "as an index of cognitive control" tend to cite within-subjects effects rather than between-subject studies (i.e., those in Table 1 would be more appropriate citations). It is important to note that only seven studies to date have investigated the relationship between individual differences in cognitive control and the magnitude of the ERN. Additional studies have related the ERN to academic performance and clinical ADHD. Although ADHD is not solely defined by poor cognitive control, studies in ADHD are broadly consistent with the view that a larger ERN relates to increased cognitive control capacities. This relationship is depicted in Fig. 1 (top), where the negative relationship between ADHD and ERN is mediated through poor cognitive control. This is an intuitively appealing model insofar as all the measures and constructs hang together: ADHD is characterized by poor cognitive control, cognitive control relates to the ERN, and the ERN is reduced in ADHD.

4. The ERN and individual differences in anxiety

About a decade after the discovery of the ERN, several key studies on individual differences in the ERN were published. Gehring et al. (2000) first found that patients with obsessive-compulsive disorder (OCD) were characterized by an exaggerated ERN. In the last 20 years, more than 50 studies have found that the ERN is increased among anxious individuals (Cavanagh and Shackman, 2015; Meyer, 2017b; Moser et al., 2013). The relationship between the ERN and OCD has been replicated multiple times, and an increased ERN has also been found among individuals with generalized anxiety disorder (GAD) and social anxiety disorder – effects that are evident in both children and adults (Endrass et al., 2014; Meyer, 2017a; Meyer, 2017b; Riesel et al., 2015; Riesel et al., 2014; Weinberg et al., 2012a; Weinberg et al., 2015b; Weinberg et al., 2010).

An increased ERN has also been linked to dimensional symptoms of anxiety (Meyer et al., 2018; Weinberg et al., 2016). Work examining differential facets of anxiety have suggested that the ERN may index transdiagnostic variation in checking symptoms (Weinberg et al., 2016), social anxiety symptoms (Meyer et al., 2018), and shyness (Meyer and Klein, 2018). Indeed, there are now multiple reviews and meta-analyses on this topic (see: Cavanagh and Shackman, 2015; Hajcak, 2012; Meyer, 2017a; Meyer, 2017b; Moser et al., 2013; Saunders and Inzlicht, 2018; Weinberg et al., 2015a; Weinberg et al., 2016; Weinberg et al., 2012b).

Despite replicable effects linking an increased ERN to individual differences in anxiety, there is considerable debate regarding *why* anxious individuals are characterized by a larger ERN (Moser et al., 2014; Moser et al., 2013; Proudfit et al., 2013; Weinberg et al., 2015a; Weinberg et al., 2016). If the ERN doesn't index anxiety, per se, why might anxious individuals have a larger neural response to errors? One possible explanation of this between-subject effect comes from within-subjects studies on the ERN. Specifically, a number of within-subjects comparisons have demonstrated that the ERN is increased when errors are made more aversive or valuable. For instance, the ERN is increased when performance is evaluated (Hajcak et al., 2005), when errors are more valuable (Hajcak et al., 2005) or punished (Meyer and Gawlowska, 2017; Riesel et al., 2012). Moreover, the ERN in increased in children when a critical parent is observing them complete a go/no-go task (Meyer et al., 2019). Thus, the ERN may index individual differences in the degree to which errors are processed as aversive or important (Chong and Meyer, 2018; Hajcak, 2012; Weinberg, Riesel et al., 2012). In fact, recent work has linked the magnitude of the ERN specifically to the construct of error sensitivity (i.e., distress experienced in the context of mistakes; Chong and Meyer, 2018). Fig. 1 (bottom) depicts the possibility that error sensitivity explains the relationship between individual differences in anxiety and the ERN: the relationship between individual differences in anxiety and the ERN is mediated by how sensitive individuals are to making mistakes.

Fig. 1 sets up important questions and juxtapositions. Does the ERN index sensitivity to errors or cognitive control? Could the ERN relate to both constructs? If the ERN reflects individual differences in cognitive control, could the increased ERN evident among anxious individuals reflect individual differences in cognitive control (Moser et al., 2013)? Might the relationship between ADHD and ERN be better explained by individual differences in error sensitivity, assuming that errors are less salient among those with ADHD?

NIMH includes the ERN in RDoC as a measure of "Sustained Threat" as well as "Cognitive Control"; however, few studies have investigated these constructs simultaneously in relation to the ERN. We have recently examined the relationship between cognitive control (attentional focusing, attentional shifting, and inhibitory control) and shyness in relation to the magnitude of the ERN in a large sample of young children (Meyer and Klein, 2018). Results suggested that when shyness and cognitive control were simultaneously entered predicting the magnitude of the ERN, they were both significant and independent predictors. On the CBQ, the shyness scale measures discomfort in social and performance situations (e.g., "often prefers to watch rather than join other children playing"). Thus, while shyness is not the same as "error sensitivity" (i.e., aversion to making mistakes), it may be a close approximation insofar as it indexes performance anxiety. If we view shyness as proxy for error sensitivity, then results from this study suggest that the ERN displays unique associations with these two domains – i.e., a large ERN may indicate that an individual is high in cognitive control or high in error sensitivity, or both.

Fig. 1 makes different predictions about the ERN-ADHD and ERN-anxiety association explicit in mediational terms – the association between individual differences in the ERN and anxiety ought to be accounted for by the intervening construct of error sensitivity (bottom), and the association between individual differences in the ERN and ADHD ought to be accounted for by individual differences in cognitive control (top). Indeed, one could further test the specificity of these modes (i.e., demonstrating that ADHD-ERN associations are *not* accounted for by individual differences in error sensitivity). That is, models that examine what mediates the association between ERN and other individual difference phenotypes can help shed light on the question: what accounts for individual differences in the ERN? Indeed, a handful of studies have begun to use mediation models to interrogate the nature of ERN associations with other individual difference variables.

For instance, we recently examined the psychological and cognitive factors that may underlie the association between the ERN and anxiety versus ADHD in young children (Meyer and Klein, 2018). Consistent

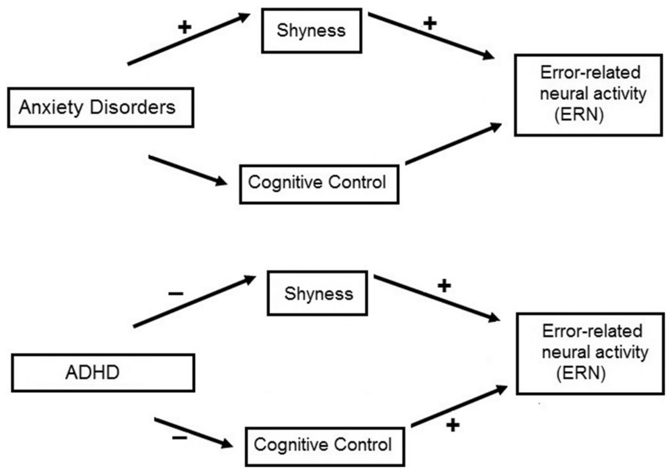

Fig. 2. Conceptual depiction of the indirect pathways between clinical disorders (i.e., Anxiety Disorders versus ADHD) and the error-related negativity (ERN). As can be seen, the pathway from Anxiety Disorders to the ERN via shyness was significant and in the positive direction (i.e., the extent to which anxious children were shy accounted for the observed increased ERN). Moreover, the pathway from ADHD to the ERN via shyness *and* cognitive control was significant, and both were in the negative direction (i.e., the extent to which children with ADHD were low in shyness and low in cognitive control accounted for the observed decreased ERN).

with previous work, the ERN was increased in anxious children and decreased in children with ADHD. However, the association between the ERN and anxiety disorder status was mediated by individual differences in shyness, but not cognitive control (Fig. 2). In other words, the extent to which children with anxiety disorders were characterized by increased shyness explained their increased ERN. Critically, *both* shyness and cognitive control explained the association between the ADHD and the ERN (Fig. 2). That is, there were independent pathways linking ADHD to a reduced ERN through both decreased shyness and decreased cognitive control. In other words, the extent to which children were characterized by decreased shyness and/or decreased cognitive control was related to the decreased ERN magnitude observed in children with ADHD. These data provide relatively specific support for the notion that a decreased ERN an ADHD can reflect reduced cognitive control; however, these data also suggest that ADHD can relate to a decreased ERN through decreased shyness.

We recently conducted a similar study in young children in which we directly assessed the construct of error sensitivity via self-report (Chong and Meyer, 2018). Children completed the Child Error Sensitivity Index, a 9-item self-report measure that included items such as "When I make a mistake, I feel anxious", "When I notice a mistake I made, I feel upset", "I like to do things perfectly, and "I am afraid of making mistakes in front of other people." This measure demonstrated good internal reliability and convergent validity with other relevant measures. Children who reported being higher in error sensitivity were also characterized by an increased ERN. Importantly, the relationship between the ERN and child anxiety symptoms was mediated by child error sensitivity. This is an example of how we may begin to empirically determine what psychological factors underlie associations between ERN and clinically meaningful constructs such as anxiety and/or ADHD using mediation models. It will be important for future work to extend these findings on error sensitivity and the ERN to adults, and to simultaneously assess cognitive control – to determine whether both constructs might mediate the ERN-anxiety association.

5. Summary and future directions

Between-subjects claims about the ERN and cognitive control have historically been based on either within-subject effects or individual differences in behavioral measures that were obtained within the tasks used to elicit the ERN. In the current paper, we first reviewed studies that more directly assessed the relationship between ERN and individual differences in validated measures of cognitive control. Although the evidence is limited, the available research suggests that a larger ERN relates to increased cognitive control. Although the evidence is somewhat mixed, findings also indicate that the ERN is generally reduced among individuals with clinical ADHD – a disorder characterized by deficits in executive functioning. These findings suggest important avenues for future research. For instance, the ERN may be useful as a novel target of intervention for individuals with ADHD (i.e., training that increases cognitive control may help to increase the ERN and thereby reduce symptoms or risk).

The current review focused on the general construct of cognitive control and its relationship to the ERN; it will be important for future studies to examine whether ERN better relates to specific facets of cognitive control (e.g., inhibition vs. working memory vs. cognitive flexibility). Based on the work reviewed in the current manuscript, there is initial evidence supporting a link between the ERN and working memory (verbal and visual), as well as inhibition (inhibitory control and attention). Nonetheless, future work is needed to examine whether the ERN differentially or more robustly relates to specific domains of cognitive control.

Although the relationship between the ERN and individual differences in anxiety has been well-replicated, there is ongoing debate regarding why anxious individuals are characterized by an increased ERN. Based in part on within-subjects effects of error value, we have previously suggested that errors are more aversive or salient for anxious individuals, such that the increased ERN in anxiety reflects a disposition to process mistakes as more salient or aversive. In the current paper, we review recent work linking the ERN to self-reported error sensitivity (Chong and Meyer, 2018)—and initial evidence that error sensitivity mediates the association between ERN and anxiety. These data are broadly consistent with the proposal that increased ERN in anxiety reflects affective and motivational differences related to error processing.

Finally, we presented additional results from mediation models capable of shedding light on potential mechanisms that link ERN to other individual differences. Specifically, the association between ERN and ADHD was explained by both low levels of shyness and decreased cognitive control; on the other hand, the relationship between ERN and anxiety disorders was accounted for by shyness but not cognitive control. In this way, the current review raises the possibility that anxiety and cognitive control have unique and non-overlapping relationships with the ERN. It is also possible that anxiety and cognitive control *interact* to predict the magnitude of the ERN, or that by including both measures in the same model, we might improve the clinical utility of the ERN (i.e., we may improve the ability of the ERN in predicting anxiety if we control for baseline cognitive control, or vice versa).

The current review suggests that individual differences in the amplitude of the ERN are at once determined by both affective (e.g., increased concern about mistakes and shyness) and cognitive (i.e., increased cognitive control) traits. In this way, the ERN may reflect a neurobehavioral trait that integrates individual differences in affect and cognitive control. We have previously suggested that the ERN is likely impacted simultaneously by multiple correlated phenotypes (Hajcak et al., 2019). The current paper suggests a further way in which this is true: anxiety and ADHD are positively correlated but related to the ERN in opposite directions. Although both anxiety and ADHD may be characterized by similar affective (e.g., negative emotionality) and cognitive (i.e., lower EF) abnormalities, they likely differ in terms of their relationship with shyness and error sensitivity.

As was highlighted throughout the current review, the issue of measurement – particularly the measurement of cognitive control – is an important consideration when examining potential links with the ERN. We have reviewed work that has utilized a wide variety of measurement approaches (e.g., self-report and task-derived measures). For example, the Meyer and Klein (2018) study relied solely on parent-report of child cognitive control. Ideally, future work will utilize a psychoneurometric approach (Patrick et al., 2013; Yancey et al., 2016) wherein cognitive control is measured via self-report, as well as via multiple task-based measures and perhaps even physiological or neurological measures, to create a latent variable indicator of individual differences in cognitive control.

Removing shared variance between anxiety and ADHD might be useful in further clarifying phenotypes that drive variability in the ERN. Future work might utilize various measures of anxiety (e.g., clinical interviews, self-report, observation), measures of error sensitivity, and different facets of cognitive control (i.e., working memory, inhibition, and flexibility) in large samples, at different developmental time points, to determine how each relates to the ERN. It will be particularly important for such studies to simultaneously assess the impact of multiple phenotypes, to parse unique variance in correlated constructs, and to test competing views of the ERN through sensible statistical models. Overall then, there is still much work to be done to precisely characterize the meaning of individual differences in the ERN.

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