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Examining the relationships between error-related brain activity (the ERN) and anxiety disorders versus externalizing disorders in young children: Focusing on cognitive control, fear, and shyness☆,☆☆

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ABSTRACT

Objective: We examine the relationship between individual differences in temperament (cognitive control, fear, and shyness) and the error-related negativity (i.e., the ERN) in a large sample of young children. Furthermore, we explore to what extent variation in temperament may underlie the associations between the ERN and anxiety disorders versus externalizing disorders.

Method: Using the Children's Behavior Questionnaire (CBQ), we focus on scales related to cognitive control (attentional focusing, attentional shifting, and inhibitory control) and a fearful/anxious temperament (fearfulness and shyness). We use diagnostic interviews to assess anxiety (specific phobia, separation anxiety disorder, social phobia, generalized anxiety disorder, obsessive-compulsive disorder, and agoraphobia) and externalizing disorders (attention deficit hyperactivity disorder; ADHD, and oppositional defiant disorder; ODD). A go/no-go task was used to measure the ERN.

Results: Results suggest that while shyness was related to an increased ERN, fearfulness was associated with a decreased ERN. Moreover, increased cognitive control was related to an increased ERN, and an exploratory model suggested that while shyness displayed an independent relationship with the ERN, the relationship between fear and the ERN was accounted for by deficits in cognitive control. Additionally, we found that the ERN was increased in children with anxiety disorders, and that this association was explained by shyness, but not fear or cognitive control. In contrast, the ERN was blunted in children with externalizing disorders (ADHD or ODD), and this association was accounted for by lower levels of both shyness and cognitive control.

Conclusions: Overall, these results are novel insofar as they suggest that the temperamental factors of shyness and cognitive control may underlie the associations between the ERN and internalizing versus externalizing disorders.

1. Introduction

An accumulating body of research suggests that psychopathology follows developmental trajectories beginning early in life that often result in chronic impairment [1–4]. Increasingly, work has focused on identifying neural markers that underlie the development of psychopathology early in life in an effort to improve prevention and intervention strategies, as well as further our understanding of the underlying etiopathogenesis of these disorders [5].

A substantial amount of work has focused on the error-related negativity (i.e., ERN) as a neural marker of psychopathology [6–9]. The ERN is a negative deflection in the event-related potential waveform that occurs when individuals make mistakes on speeded reaction-time tasks [10,11] and is generated in the anterior cingulate cortex (ACC) – a region of the brain that is thought to integrate information about threat, punishment, and pain [12]. A wealth of evidence suggests that the ERN is *increased* in individuals with internalizing disorders and *decreased* among individuals with externalizing disorders [6,9,13]. For example, the ERN has been found to be increased in anxious individuals in over 50 studies to date [7,9,14–16]. In contrast, the ERN tends to be blunted in individuals characterized by externalizing traits – such as attention-deficit/hyperactivity disorder [17–19] or substance abuse [20–22].

While the ERN has consistently been found to be associated in *opposing* directions with internalizing and externalizing disorders, little is known about the psychological, temperamental, or cognitive factors

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that may underlie these differential associations. Some have suggested that the ERN/anxiety associations may be the result of increased sensitivity to making mistakes in anxious individuals [7] or increased sensitivity to evaluation of behavior [23,24]. Furthermore, there is some evidence that the ERN may be enhanced in disorders characterized by anxious distress (e.g., social anxiety, GAD, OCD) but not disorders characterized by anxious arousal [e.g., phobias, panic disorder; [25]], and thus some have suggested an increased ERN may index distress but not arousal (i.e., fear). A separate line of work has viewed the ERN as an index of cognitive control [14] and some have suggested that the decreased ERN observed in individuals with externalizing disorders may be related to decreased cognitive control [9,18,19]. However, despite these various assertions, little work has been done to examine what factors may underlie the differential association between the ERN and internalizing versus externalizing disorders.

In the current study, we examined the relationship between individual differences in temperament and the ERN in a large sample of young children. Using the Children's Behavior Questionnaire (CBQ), we focus on scales related to cognitive control (attentional focusing, attentional shifting, and inhibitory control) and a fearful/anxious temperament (fearfulness and shyness). We conduct exploratory analyses to examine which of these CBQ factors relate to the magnitude of the ERN across the sample. Additionally, we use diagnostic interviews to assess anxiety (specific phobia, separation anxiety disorder, social phobia, generalized anxiety disorder, and agoraphobia) and externalizing disorders (attention deficit hyperactivity disorder; ADHD, and oppositional defiant disorder; ODD). As previously reported [26], the ERN is increased in children with anxiety disorders. We examine to what extent temperamental cognitive control and fearfulness and shyness may explain the relationship between anxiety disorders and the ERN. Additionally, we examine the ERN in children with externalizing disorders. Based on previous work, we hypothesized that the ERN would be *decreased* in children with ADHD or ODD. We conclude by examining whether temperamental cognitive control, fearfulness, and shyness may account for the relationship between internalizing and externalizing disorders and the ERN.

2. Method

2.1. Participants

The current study included a subset of participants ($N = 291$) from a larger longitudinal study, who had parent-reported measures of temperament, as well as ERP data from the second wave of assessments conducted when children were approximately 6 years old ($M = 6.12$, $SD = 0.43$, range = 5.15–7.57). Of the sample, 125 children were female and 166 were male; 92% of the children were Caucasian; and 89% of the primary caregivers were mothers. Participants were originally recruited via a commercial mailing list. Eligible families had a 3-year old child without a significant medical condition or developmental disability, and at least one English-speaking biological parent. Of families who were eligible, 66.4% entered the study. Families who agreed and declined to participate did not differ significantly on child sex, race, ethnicity, parental marital status, education, or employment status. Census data suggest the sample is reasonably representative of the surrounding community [27,28]. The larger study that participants were drawn from included 550 children. Of those, a subset of participants had EEG data ($N = 325$). Additionally, 26 children were excluded for not providing self-report data (i.e., the CBQ) and 1 child was excluded due incomplete diagnostic data (i.e., the PAPA). Five children were excluded due to a co-morbid ADHD/anxiety diagnosis and 2 children were excluded due to a depressive disorder (final $N = 291$). Children who were excluded did not differ from the rest of the sample on demographic variables or any of the main study variables, *ps* > .10. The study was approved by the Stony Brook Institutional Review Board and completed with the consent of parents and the assent of child participants.

2.2. Children's behavior questionnaire (CBQ)

The CBQ [29] is a caregiver report measure designed to assess temperament in 3–7 year-old children. The questionnaire consists of 194 items that the primary caregiver rates for the child based on the last 6 months on a seven-point scale: 1 (*extremely untrue*) to 7 (*extremely true*), indicating how closely the statement describes their child's typical behavior. Scales used in the current study include: attentional focusing, attentional shifting, inhibitory control, shyness, and fear. Internal consistency of the 5 scales used in this paper ranged from 0.61 to 0.92 (median $\alpha = 0.74$) – which are similar values to previous studies in this age-range [29].

The shyness scale was designed to assess inhibited approach in situations involving social novelty or social uncertainty. For example, an item on this scale includes: “Often prefers to watch rather than join other children playing.” The fear scale assesses negative affect (unease, worry, or nervousness) related to pain, distress, or threatening situations (e.g., “Is not afraid of large dogs and/or other animals”, reverse scored). The attention shifting scale 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”). The attention focusing scale assesses the child's ability to maintain attentional focus on a task (e.g., “When drawing or coloring in a book, he/she shows strong concentration”). The inhibitory control scale assesses the child's capacity to regulate his/her behavior and suppress inappropriate responses (e.g., “Can wait before entering into new activities if he/she is asked to”).

2.3. Diagnostic interviews

As previously reported [26], the Preschool Age Psychiatric Assessment (PAPA; [30]) was used to assess a range of disorders from the DSM-IV in children when they were 6 years-old. The PAPA is a semi-structured parent-report interview with good psychometric properties [31]. The interview focuses on the previous 3 months to maximize recall. For this report, we aggregated anxiety disorders (total $N = 29$; specific phobia, $N = 18$, separation anxiety disorder, $N = 9$, social phobia, $N = 11$, generalized anxiety disorder, $N = 2$, and agoraphobia, $N = 2$) and externalizing disorders (total $N = 25$; ADHD, $N = 11$, and ODD, $N = 21$). Children with comorbid anxiety disorders were included, as well as children with comorbid externalizing disorders. Children with comorbid anxiety *and* externalizing disorders ($N = 5$), or depression ($N = 2$), were not included in the current study. Interviews were conducted face-to-face with parents by master's-level psychologists. A 2nd diagnostician rated audiotapes of 35 interviews for reliability, oversampling for psychopathology. Kappas ranged from acceptable to excellent: any anxiety disorder (0.89), ADHD (0.64), ODD (0.87).

2.4. Error-related brain activity (ERN)

Children were administered a Go/No-Go task with Presentation software (Neurobehavioral Systems, Inc.) to measure the ERN (previously described: [26,32,33]). The stimuli were green triangles presented in one of four different orientations for 1200 ms in the middle of the screen. On 60% of trials, triangles were vertically aligned and point up, 20% were vertically aligned and pointed down, 10% were tilted slightly to the left, and 10% were titled slightly to the right. Children were instructed to respond by pressing a button when upward-pointing triangles appeared on the screen, and to withhold a response to all other triangle presentations. After the presentation of the triangle and before the start of the next trial, a small gray fixation cross appeared in the middle of the screen for a random interval of time ranging from 300 to 800 ms. Children completed four blocks of 60 trials each. Participants were told that they could earn points for correct trials that they could exchange for money, and that they could win up to $5.00 (all children won $5.00 at the completion of the task). The speed of responses was also emphasized.

The Active Two system (Biosemi, Amsterdam, the Netherlands) was used to acquire EEG data and 32 Ag/AGCl-tipped electrodes were used with a small amount of electrolyte gel (Signa Gel; Bio-Medical Instruments Inc., Warren, MI) at each electrode. Electrooculogram (EOG) generated from eye movements and eyeblinks was recorded with four facial electrodes; horizontal eye movements were measured by two electrodes located approximately 1 cm outside the outer edge of the eyes. Vertical eye movements and blinks were measured by two electrodes placed 1 cm above and below the right eye. The EEG signal was pre-amplified with a gain of one by a BioSemi Active Two System (BioSemi). All data were sampled at 512 Hz and the ground electrode during acquisition was formed by the common mode sense (CMS) active electrode and the driven right leg passive (DRL) electrode.

Data were processed offline with Brain Vision Analyzer (Brain Products, Gilching, Germany). EEG data were re-referenced to the nose at the age 6 assessment and high and low pass filtered at 0.1 and 30 Hz, respectively. EEG segments of 1300 ms were extracted from the continuous EEG, beginning 500 ms prior to responses. Data were then corrected for eye movements and blinks [34] and artifacts were rejected if any of the following criteria were met: a voltage step of >50 microvolts between data points, a voltage difference of 300 microvolts within a single trial, or a voltage difference of <0.5 microvolts within 100 ms intervals. After this, data were visually inspected for remaining artifacts. ERP averages were created for error and correct trials and a baseline of the average activity from −500 to −300 ms prior to the response was subtracted from each data point.

ERP and behavioral results in this sample have been reported previously [26,32,33]. The error-related negativity (ERN) and correct-related negativity (CRN) were scored as the average voltage in the window between 0 and 100 ms after response commission on error and correct trials, respectively. The delta ERN (ΔERN), thought to reflect error-specific activity, was calculated by subtracting the CRN from the ERN. All analyses focused on midline electrode Cz. Internal reliability for the ERN, CRN, and ΔERN was moderate, i.e., split-half reliability was as follows: ERN = 0.64, CRN = 0.80 and ΔERN = 0.53. Reliability values were calculated by only including children with adequate EEG data (e.g., children with 5 or less errors were excluded from these analyses).

2.5. Statistical analyses

All statistical analyses were conducted using SPSS (Version 17.0) General Linear Model Software, with Greenhouse-Geisser correction applied to p values with multiple-df. Pearson correlation coefficients (r) were used to examine the relationships between all study variables. Simultaneous multiple regressions were used to follow-up correlational results. One-way ANOVAs were conducted with group (anxiety, ADHD, or no diagnosis) as the factor to determine if there were overall differences in all main study variables. Follow-up t-tests were then conducted. We used a nonparametric bootstrapping method [35] to examine the extent to which the cross-sectional associations between clinical diagnoses and the ERN could be accounted for by indirect effects via temperament variables [36]. These analyses are intended to describe patterns of associations, rather than to infer causality. We used an SPSS macro (PROCESS: [37]), which provides a bootstrap estimate of the indirect effect between the independent and dependent variable, an estimated standard error, and 95% confidence intervals for the population value of the indirect effect. When confidence intervals for the indirect effect do not include zero, this indicates a significant indirect effect at the $p < .05$ level. Direct and indirect effects were tested using 5000 bootstrap samples.

Table 1
Correlations, means, and standard deviations for the ΔERN (error-related negativity) and the CBQ (Children's Behavior Questionnaire) scales.

	1	2	3	4	5	Mean	SD
1. ΔERN	–					−8.83	9.07
2. CBQ. Attentional focusing	−0.13*	–				4.78	0.77
3. CBQ. Attentional shifting	−0.16**	0.33**	–			4.34	1.03
4. CBQ. Inhibitory control	−0.14*	0.55**	0.70**	–		5.07	0.82
5. CBQ. Shyness	−0.11t	0.01	−0.08	0.02	–	3.12	1.27
6. CBQ. Fear	0.11t	−0.15*	−0.23**	−0.15*	0.25**	3.67	0.94

t $p < .07$.
* $p < .05$.
** $p < .01$.

3. Results

3.1. Descriptive statistics and bivariate correlations

As previously reported [26,32,33], the ERP response was more negative following errors than correct responses, $F(1, 290) = 275.99$, $p < .001$. Means and standard deviations, as well as Pearson correlations are presented for all main study variables in Table 1. As can be seen in the Table, an increased ΔERN was related to increased attentional focusing, attentional shifting, and inhibitory control. Additionally, bivariate correlations suggested that while there was a non-significant trend for increased shyness to be correlated with a larger ΔERN, increased fear showed a non-significant trend for a *smaller* ΔERN.[1,2,3]

3.2. Relationships between the ERN and fear, shyness, and cognitive control

To examine whether temperamental variables related to anxiety (i.e., fear and shyness) were independently related to the ERN, we conducted a multivariate regression predicting the ΔERN wherein the CBQ fear and shyness scale were entered simultaneously. As can be seen in Table 2, when both shyness and fear were entered simultaneously, increased fear related to a *blunted* ΔERN and increased shyness related to an *increased* ΔERN. These findings are consistent with previous work suggesting that temperamental fear relates to a decreased ΔERN in young children [33]. Moreover, these results support the notion that an increased ΔERN may index fear related to social evaluation or shyness, and rather than fear related to specific objects and situations.

The bivariate correlations suggested that the ΔERN was related to CBQ attentional focusing, attentional shifting, and inhibitory control (see Table 1). When all three of these indicators were entered into a simultaneous multiple regression predicting the ΔERN, none were significant, all $ps > .20$, suggesting that they are overlapping predictors. Therefore, we combined these three factors into a single cognitive control variable and all subsequent analyses focus on the summed z-scores of attentional focusing, attentional shifting, and inhibitory control.

Next, we examined whether the composite cognitive control variable and shyness independently related to the ΔERN. When shyness and cognitive control were simultaneously entered in a multivariate regression predicting the ΔERN, both predictors were significant (see Table 3), such that children characterized by increased shyness displayed an increased ΔERN and children with increased cognitive control displayed an increased ΔERN. Moreover, these effects appeared to be independent.

Next, we examined whether cognitive control and fear independently predicted the ΔERN. When fear and cognitive control were

[1] When partial correlations were conducted, controlling for reaction time and accuracy during the Go-No/Go task, the pattern of results was similar – attentional focusing and shifting, inhibitory control, and shyness were related to an increased ΔERN.

[2] Socioeconomic status (as indicated by yearly income) did not relate to any of the CBQ scales or the error-related negativity (ΔERN) in this sample, all $ps > .20$.

[3] When correlations were conducted using a residual-based score for the ERN (i.e., using the unstandardized residuals from a regression wherein the CRN was entered predicting the ERN), the pattern of results was similar. The residual-based ERN related to increased shyness at trend level, decreased fear, as well as increased attentional focusing, attentional shifting, and inhibitory control.

Table 2
Results from a simultaneous multiple regression wherein the CBQ (Children's Behavior Questionnaire) scales fear and shyness were entered predicting the ΔERN (error-related negativity).

Variables entered	ΔERN		
	B	Std. error	t
	N = 291		
Fear	0.14	0.59	2.33*
Shyness	−0.15	0.43	−2.37*
Overall model: total R-squared	0.03*		

* $p < .05$.

simultaneously entered in a multivariate regression predicting the ΔERN, only cognitive control remained significant, $F(2, 274) = 4.67$, $\beta = -0.15$, $t = -2.51$, $p < .05$. In this model, fear did not significantly predict the ΔERN, $\beta = 0.07$, $t = 1.16$, $p = .25$. This finding was novel and surprising, given that we had no a priori reason to expect fear and cognitive control to share overlapping variance with the ΔERN.

Given that shyness and fear displayed unique relationships with the ΔERN, but *fear and cognitive control did not*, we wished to examine an exploratory a model wherein shyness was uniquely related to the ΔERN and fear was related to the ΔERN via cognitive control. We wished to examine this exploratory mediation model based on the results suggesting that fear and cognitive control do not have unique associations with the ΔERN. In Fig. 1, we depict this model that combines the findings from these analyses – wherein both shyness and fear exert opposing influences on the ΔERN. In this model, the association between fear and the magnitude of the ΔERN is explained by its association with decreased cognitive control. Indeed, when we tested this full model using a nonparametric bootstrapping method [37,38], results suggested that the overall model was significant, $F(3, 271) = 4.91$, $p < .01$. The direct path between shyness and the ΔERN remained significant, $\beta = -0.99$, $SE = 0.43$, $t = -2.30$, $p < .01$, 95% CI = −1.84 to −0.14. Moreover, while the direct effect of fear on the ΔERN was not significant, $\beta = 1.04$, $SE = 0.60$, $t = 1.72$, $p = .09$, 95% CI = −0.15 to 2.22, the indirect path from fear to the ΔERN via cognitive control was significant, $\beta = 0.32$, $SE = 0.17$, 95% CI = 0.05 to 0.69. These findings suggest that the core dimensions of temperament that uniquely relate to the ΔERN in young children are shyness and cognitive control. In addition, these results help to elucidate previous work that found a blunted ΔERN in fearful young children – suggesting that alterations in cognitive control underlie this association.

3.3. Summary of temperament-ERN findings

Results suggested that when included in the same regression model, both fear and shyness related to the ΔERN independently and in opposing directions. Consistent with previous findings in adults [39–41], in young children, shyness or concern about one's own behavior was related to the ΔERN, such that shy children were characterized by an increased ΔERN. Furthermore, consistent with some previous work in adults [42,43], the magnitude of the ΔERN was increased in children

Table 3
Results from a simultaneous multiple regression wherein cognitive control and shyness were entered predicting the ΔERN (error-related negativity).

Variables entered	ΔERN		
	B	Std. error	t
	N = 291		
Cognitive control	−0.17	0.22	−2.88**
Shyness	−0.12	0.42	−1.93*
Overall model: total R-squared	0.04**		

* $p < .05$.
** $p < .01$.

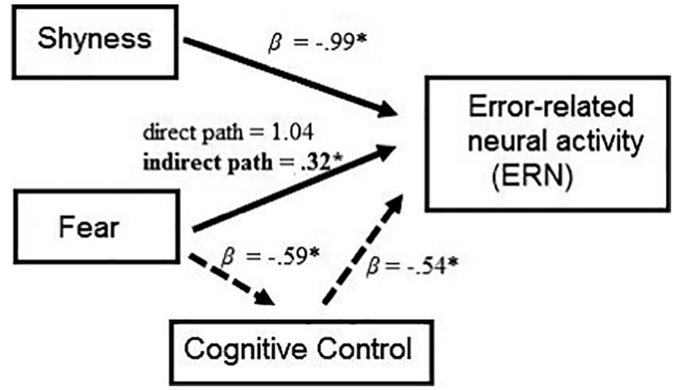

Fig. 1. A conceptual depiction of a model wherein both shyness and fear exert opposing influences on the ΔERN. In this model, the association between fear and the magnitude of the ΔERN is explained by its association with decreased cognitive control.

characterized by increased cognitive control. The nature of the relationships between shyness and cognitive control in relation to the ΔERN appeared to be independent – such that increased shyness and increased cognitive control *both* uniquely related to a potentiated ΔERN.

In contrast to this, children characterized by increased temperamental fear displayed a *blunted* ΔERN when shyness was included in the model. We had previously reported that temperamental fear, measured via observation in the lab when the children were 3-years-old, related to a blunted ΔERN when these children were 6-years-old. Results from the current study replicate this finding insofar as parent-reported fearfulness on the CBQ at age 6 also related to a decreased ΔERN in children. Moreover, we tested an exploratory, novel model wherein deficits in cognitive control may explain the relationship between temperamental fear and the ΔERN in young children. Results supported this hypothesis, suggesting that children high in temperamental fear may be characterized by decreased cognitive control and thus display a blunted ΔERN.

3.4. Clinical diagnoses: relationships with the ERN, shyness, and cognitive control

Building on these findings, we wished to examine to what extent these core dimensions of temperament (shyness, fear, and cognitive control) may help explain the associations between the ΔERN and *clinical* levels of anxiety (i.e., anxiety disorders) and externalizing (i.e., ADHD or ODD) symptoms. In Table 4, all main study variables are depicted for three groups: children with anxiety disorders only ($N = 27$); children with ADHD or ODD only ($N = 23$); or children with no diagnosis ($N = 225$). In the column on the right, F-values are presented for one-way ANOVAs with group entered as the factor (anxiety, ADHD or ODD, or no diagnosis) and subscript letters depict statistical differences between groups based on follow-up *t*-tests. Different subscripts indicate the means differ significantly. Consistent with our previous report [26], children with an anxiety disorder were characterized by an increased ΔERN relative to controls. In the current study, we extend these findings to examine the ΔERN in children with *externalizing* disorders. Results suggested that children with ADHD or ODD were characterized by a *blunted* ΔERN relative to controls. Topographical headmaps and waveforms during error and correct trials, as well as the difference (error minus correct) are depicted by clinical group in Fig. 2.

As can be seen in Table 4, cognitive control, fear, and shyness differed between the groups as well. Children with ADHD or ODD were characterized by decreased cognitive control relative to children with an anxiety disorder and children without a diagnosis. Moreover, shyness differed between all three groups: children with an anxiety disorder scored the highest on shyness, then children with no diagnosis, and then children with ADHD or ODD. Additionally, fear was increased in

Table 4
In Table 4, the ΔERN (error-related negativity), cognitive control, shyness, and fear are depicted (means and standard deviations) for three groups: children with anxiety disorders only ($N = 27$); children with ADHD or ODD only ($N = 23$); or children with no diagnosis ($N = 225$). F-values are presented on the right for one-way ANOVAs with group (Anxiety Disorder, ADHD or ODD, and No Diagnosis) as the factor. Additionally, subscript letters depict statistical differences between groups based on follow-up *t*-tests. Different subscripts indicate the means differ significantly. * $p < .05$, ** $p < .01$.

	Anxiety disorder ($N = 27$)	ADHD or ODD ($N = 23$)	No diagnosis ($N = 225$)	F
ΔERN	$-11.71\ (7.73)_a$	$-5.40\ (12.86)_b$	$-8.83\ (8.65)_c$	3.31*
Cognitive control	$0.44\ (1.75)_a$	$-2.30\ (3.04)_b$	$0.18\ (2.39)_a$	11.76**
Shyness	$4.13\ (1.38)_a$	$2.47\ (0.96)_b$	$3.07\ (1.22)_c$	12.50**
Fear	$4.44\ (0.98)_a$	$3.49\ (1.29)_b$	$3.60\ (0.85)_b$	10.76**

children with anxiety disorders relative both to children with ADHD or ODD and children with no diagnosis.

Next, we examined whether the temperamental variables (i.e., shyness, fear, and cognitive control) may help to explain the association between clinical anxiety disorders and the ΔERN (see Fig. 3). In this model, the indirect pathway from anxiety disorders via shyness to the ΔERN was significant, $\beta = 0.07$, $SE = 0.04$, 95% CI = 0.01 to 0.19. However, the indirect pathway from anxiety disorders via cognitive control to the ΔERN did not reach significance, $\beta = -0.02$, $SE = 0.04$, 95% CI = −0.01 to 0.31. Additionally, the indirect pathway from anxiety disorders via fear to the ΔERN was not significant, $\beta = 0.03$, $SE = 0.04$, 95% CI = −0.16 to 0.02. These results suggest that increased temperamental shyness may underlie the increased ΔERN observed in clinically anxious children. However, neither alterations in cognitive control nor

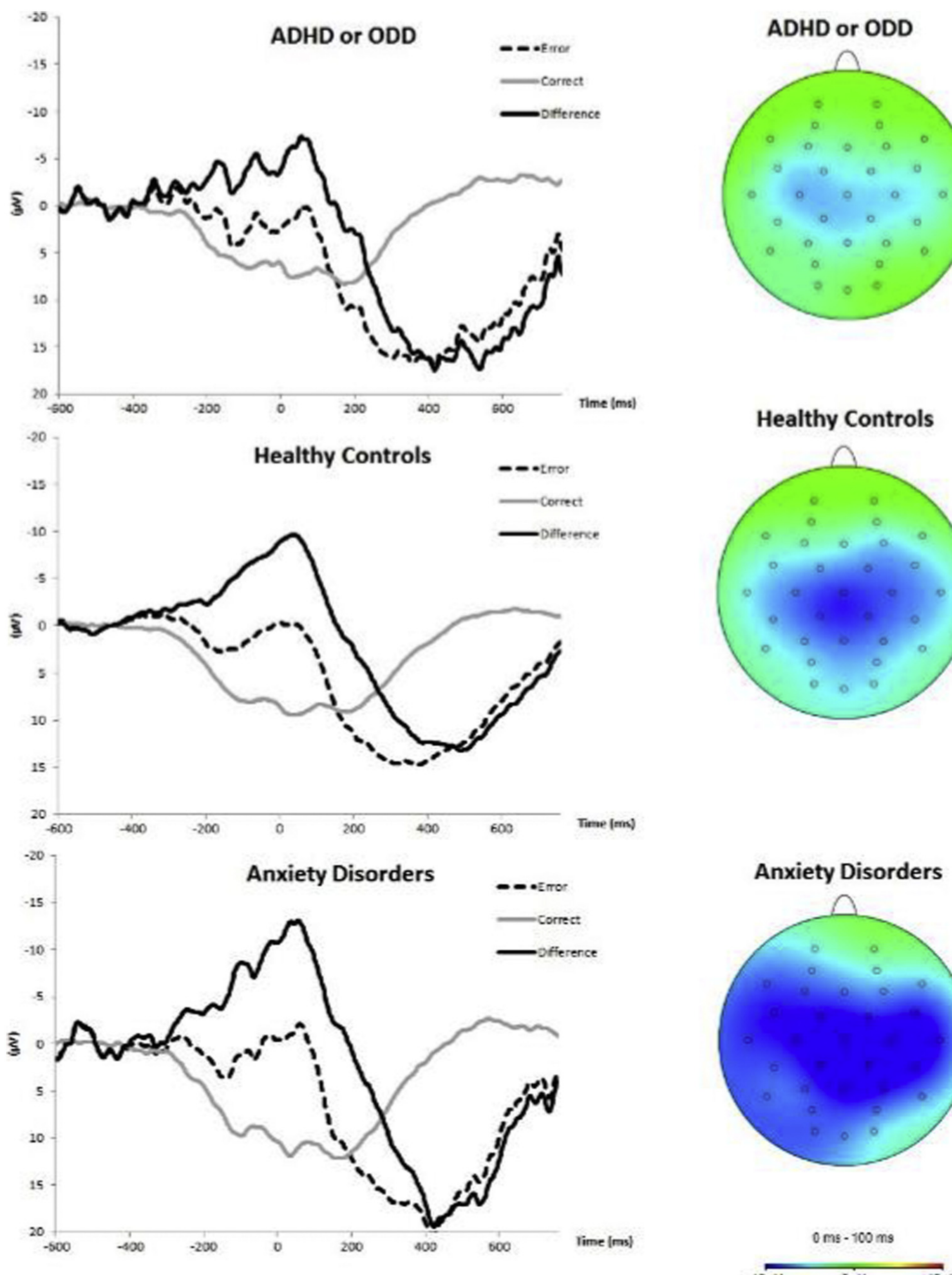

Fig. 2. On the left, waveforms at Cz are depicted for the 3 groups (ADHD/ODD, healthy controls, and anxiety disorders). The response to correct is depicted with a grey solid line, the response to errors is depicted with a black dotted line, and the difference (error minus correct) is depicted with a black solid line. On the right, topographical headmaps (error minus correct) are depicted for the 3 groups – blue indicates more negativity (i.e., a larger ERN).

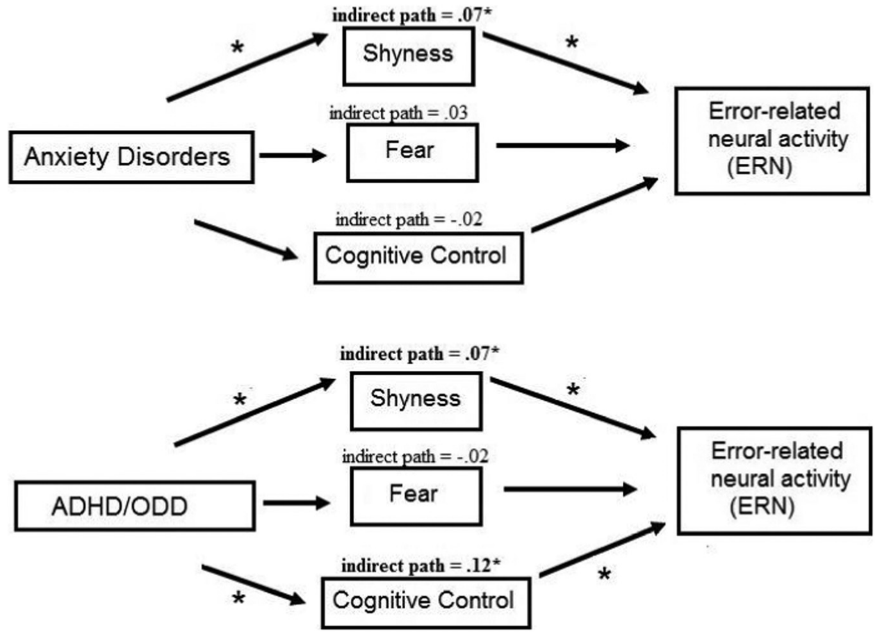

Fig. 3. A conceptual model depicting the indirect pathways between clinical disorders (anxiety disorders and ADHD/ODD) and the error-related negativity (ERN). As can be seen in the model, the indirect pathway from anxiety disorders to shyness to the ERN was significant. Additionally, the indirect pathway from ADHD/ODD to the ERN via shyness and cognitive control was significant.

fear appear to account for the relationship between the ΔERN and clinical anxiety.

We then examined whether cognitive control, fear, and shyness may underlie the association between externalizing disorders (i.e., ADHD or ODD) and the ΔERN. Results from this model indicate that the indirect pathways between ADHD/ODD and the ΔERN via *both* shyness and cognitive control were significant, $\beta = 0.07$, $SE = 0.04$, 95% CI = 0.01 to 0.17, and $\beta = 0.12$, $SE = 0.08$, 95% CI = 0.01 to 0.31, respectively. In contrast, the indirect pathway from ADHD/ODD to the ΔERN via fear did not reach significance, $\beta = -0.02$, $SE = 0.04$, 95% CI = −0.15 to 0.03. These results suggest that both *decreased* temperamental shyness and *decreased* cognitive control may underlie the blunted ΔERN observed in children with ADHD or ODD (see conceptual model in Fig. 3).

4. Discussion

In the current study, we explored the temperamental correlates of a neural risk marker (i.e., the ERN) cross-sectionally in a large sample of young children. Results suggest that while shyness was related to an increased ERN, temperamental fearfulness was associated with a *decreased* ERN. Moreover, increased cognitive control was related to an increased ERN, and an exploratory model suggested that while shyness displayed an independent relationship with the ERN, the relationship between fear and the ERN was accounted for by deficits in cognitive control. Additionally, we found that the ERN was increased in children with anxiety disorders, and that this association was explained by shyness, but not fear or cognitive control. In contrast, the ERN was blunted in children with externalizing disorders (ADHD or ODD), and this association was accounted for by lower levels of both shyness and cognitive control. Overall, these results are novel insofar as they suggest that the temperamental factors of shyness and cognitive control can be viewed as underlying the associations between the ERN and internalizing versus externalizing disorders.

Our results suggested that increased temperamental shyness was associated with an increased ERN. This finding is consistent with previous work suggesting that the ERN is increased in socially anxious individuals [23,24,44], as well as behaviorally inhibited children [24,41,45,46]. On the CBQ, the shyness scale was designed to measure discomfort in social situations (e.g., "often prefers to watch rather than join other children playing"; [29]) and thus may relate to increased monitoring of one's own behavior and/or increased distress related to social evaluation. Results from the current study support the assertion that the ERN may, in part, index increased behavioral monitoring which may lead to excessive sensitivity to social scrutiny. Furthermore, results suggested that greater shyness explained the relationship between the ERN and anxiety disorders, and that lower shyness partially accounted for the relationship between the ERN and externalizing disorders (ADHD/ODD). Thus, it seems that one reason why clinically anxious children may display an increased ERN is due to increases in shyness. However, children with externalizing disorders may be characterized by a decreased ERN due to *lower* levels of shyness. This is a novel finding, highlighting the fact that at least one facet of temperament (i.e., shyness) may explain the opposing associations of the ERN with internalizing versus externalizing disorders.

Results from the current study suggested that temperamental fear was associated with a *decreased* ERN in children. We had previously reported in this sample that temperamental fear, measured via observation in the lab when the children were 3 years old, related to a blunted ΔERN when these children were 6 years old. Results from the current study replicate this finding insofar as parent-reported fearfulness on the CBQ at age 6 also related to a decreased ΔERN in children.

Moreover, we found that children characterized by increased cognitive control also displayed an increased ERN. This is consistent with some previous work linking working memory to the ERN [42,43]. Although the ERN has previously been proposed to index cognitive control [14], there is surprisingly little work linking individual differences in cognitive control with the ERN. To our knowledge, this is the first study to do so in children. Importantly, although the ERN reflected variation in cognitive control, results suggested that it was the shyness dimension (and not cognitive control) that links the ERN with anxiety disorders.

Consistent with some previous work [17–19], the ERN was blunted in children with externalizing disorders (ADHD and ODD). No previous work had investigated what psychological factors may underlie this association. Results from the current study suggest that decreases in both shyness and cognitive control may explain the association between a blunted ERN and ADHD/ODD. This suggests that the ERN may index at least *two separable psychological phenomena* in relation to risk for psychopathology. Future work should explore to what extent this pattern of results is found at different stages of development.

The current study was limited insofar as we examined associations between the ERN, temperament, and psychopathology at one developmental time-point. Results were based on cross-sectional data, and were collected in a relatively narrow age-range (5–7 years of age). Future work should extend these findings by examining these relationships longitudinally and at different developmental stages. Furthermore, the current study was primarily exploratory – i.e., the findings were not hypothesized a priori. Therefore, we should interpret these results with caution and findings should be replicated in other samples to confirm this pattern of results. Finally, we should reemphasize that although we examined indirect effects between variables, the cross-sectional design precludes knowledge of temporal relationships between these variables. Hence, our interpretations are limited to describing the structural relationships between the study variables.

In the current study, we utilize parent report on child temperament and cognitive control. While the CBQ is a well validated and widely used measure, it is limited insofar as parent report of cognitive control may index broad behavioral tendencies, such as persistence and self-control. Future studies should use validated lab-based measures of cognitive control to examine the relationships between the ERN and diagnoses. Furthermore, a lab-based behavioral measurement of cognitive control may allow for the disentanglement of various control dimensions (e.g., attention shifting, working memory, inhibitory control, etc.). Work could then be done to examine whether it is one of these dimensions in particular that mediates the relationship between the ERN and anxiety versus externalizing disorders.

Additionally, another limitation of the current study was the moderate reliability of the ERN and CRN measured during the Go/No-Go task. However, this level of reliability (ERN = 0.64, CRN = 0.80, and ΔERN = 0.53) is comparable to other published studies. For example, in Meyer et al., (2014), split-half reliabilities were calculated for the ERN in a sample of children between the ages of 8 and 13 years-old, finding that the internal reliability of the ERN ranged from 0.38–0.88 [47]. Notably, that study was conducted among children older than the current study, which focuses on 5–7 year-olds. To our knowledge, this is the first study to report on the psychometric properties of the ERN in a sample of children in *early* childhood (i.e., below 7 years old). Future work should explore to what extent various tasks and data processing methods could increase the internal reliability of the ERN in young children. This is especially important in light of the fact that the ERN appears to be a risk marker for anxiety that emerges *early in development* [48].

Despite the wealth of evidence suggesting that an increased ERN may be an important developmental risk marker and correlate for internalizing and externalizing disorders, no study to date had investigated what *psychological construct(s)* may underlie these associations. This is important for prevention and intervention efforts. If we target neural markers of risk early in development, we may be able to prevent or alter developmental cascades resulting in psychopathology. A necessary first step in the development of these novel intervention strategies is identifying what psychosocial constructs to target. The current study suggests that both shyness and cognitive control may be useful targets in modulating the ERN. Indeed, some anxiety prevention approaches do target behavioral inhibition [49–51], and thus may be useful in modifying the ERN. Future work should aim to identify with even greater precision what psychological phenomena (e.g., sensitivity to making mistakes or performance anxiety) mediate the relationship between the ERN and various forms of psychopathology.

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