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A genetic variant BDNF polymorphism interacts with hostile parenting to predict error-related brain activity and thereby risk for internalizing disorders in children

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Psychopathology often begins in childhood and can result in chronic, life-long impairment (Beesdo, Knappe, & Pine, 2009; Kessler et al., 2005; Last, Perrin, Hersen, & Kazdin, 1996; Rutter, Kim-Cohen, & Maughan, 2006). Elucidating developmental trajectories may pave the way for earlier intervention strategies as well as an increased understanding of the etiopathogenesis of internalizing and externalizing disorders (Pine, 2007). While approaches that examine the biological and environmental bases of psychopathology *separately* have gained some traction in understanding developmental trajectories of psychopathology, approaches that *integrate* biological and environmental vulnerabilities across development are likely to be more effective (Beauchaine & McNulty, 2013; Beauchaine, Neuhaus, Brenner, & Gatzke-Kopp, 2008). Indeed, previous work suggests that psychopathology is rooted in complex gene x environment correlations and interactions that unfold across multiple domains of analysis and change over the course of development (Beauchaine & Gatzke-Kopp, 2012; Bergen, Gardner, & Kendler, 2007). Most of the work in this area has focused on gene x environment interactions; there is much less research on interactions of other biological variables with the environment or with specific genetic polymorphisms. Identifying early neural markers that relate to the development of psychopathology, along with environmental and genetic vulnerabilities that interact with and modify these biomarkers, is likely to lead to an increased understanding of these complex developmental trajectories.

Along these lines, we previously found that harsh parenting (i.e., an environmental vulnerability) is related to increases in error-related brain activity (i.e., the error-related negativity or ERN), and that this neural measure mediated the relationship between parenting and anxiety disorder status (Meyer, Proudfit, et al., 2014). We hypothesized that harsh parenting may, like aversive conditioning, potentiate neural sensitivity to errors and thereby increase risk for anxiety. In the current investigation, we examined whether a genetic polymorphism that has been linked to fear-learning may moderate these relationships.

The ERN is a promising biomarker that has been related to both internalizing and externalizing psychopathology (Olivet & Hajcak, 2008). The ERN is a negative deflection in the ERP waveform elicited by error commission at fronto-central electrode sites

(Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993) and is thought to be generated in the anterior cingulate cortex (Debener et al., 2005; Dehaene, Posner, & Don, 1994; Hoffmann & Falkenstein, 2010) – a region of the medial prefrontal cortex where information about threat, pain, and punishment is integrated (Shackman et al., 2011). Individual variation in ERN magnitude is thought to index differences in sensitivity to error commission and defensive reactivity following mistakes (Hajcak, 2012; Weinberg, Riesel, & Hajcak, 2012). In keeping with the view that individuals with internalizing and externalizing tendencies have increased and decreased sensitivity to potential threat, respectively, studies have consistently found an increased ERN among internalizing individuals and a decreased ERN among externalizing individuals. For example, work in adults and children suggests that the ERN magnitude is increased in individuals characterized by internalizing disorders or traits, such as obsessive-compulsive disorder (OCD; Carrasco et al., 2013; Endrass, Klawohn, Schuster, & Kathmann, 2008; Endrass et al., 2010; Gehring, Himle, & Nisenson, 2000; Hajcak, Franklin, Foa, & Simons, 2008; Riesel, Endrass, Kaufmann, & Kathmann, 2011; Ruchow, Grön, et al., 2005), depression (Chiu & Deldin, 2007; Holmes & Pizzagalli, 2008, 2010; however, see: Olvet, Klein, & Hajcak, 2010; Weinberg, Klein, & Hajcak, 2012), generalized anxiety disorder (Weinberg, Olvet, & Hajcak, 2010; Xiao et al., 2011), heterogeneous anxiety disorders (Ladouceur, Dahl, Birmaher, Axelson, & Ryan, 2006; Meyer et al., 2013), OCD traits (Gründler, Cavanagh, Figueroa, Frank, & Allen, 2009; Hajcak & Simons, 2002; Santesso, Segalowitz, & Schmidt, 2006), trait anxiety (Meyer, Weinberg, Klein, & Hajcak, 2012; Pourtois et al., 2010), negative affect (Bush, Luu, & Posner, 2000; Hajcak, McDonald, & Simons, 2004), and behavioral inhibition (Amodio, Master, Yee, & Taylor, 2008; Boksem, Tops, Wester, Meijman, & Lorist, 2006; McDermott et al., 2009). In contrast, the ERN tends to be diminished in individuals characterized by externalizing disorders or traits, such as substance abuse (Franken, van Strien, Franzek, & van de Wetering, 2007; Luijten et al., 2014; Marhe, van de Wetering, & Franken, 2013), attention deficit hyperactivity disorder (ADHD; Albrecht et al., 2008; Groen et al., 2008; Hermann, Ziegler, Birbaumer, & Flor, 2002), psychopathy (Munro et al., 2007; Von Borries et al., 2010), trait impulsivity (Potts, George, Martin, & Barratt, 2006; Ruchow, Spitzer, Grön, Grothe, & Kiefer, 2005), disinhibitory personality traits (Dikman & Allen, 2000), and externalizing traits (Hall, Bernat, & Patrick, 2007).

Given evidence suggesting that ERN magnitude is relatively stable within children and adults across time (Meyer, Bress, & Proudfoot, 2014; Weinberg & Hajcak, 2011) and moderately heritable (Anokhin, Golosheykin, & Heath, 2008), this neurobehavioral trait may be useful in understanding developmental risk trajectories (Hajcak, 2012). In fact, we recently found that the ERN predicts the onset of anxiety disorders in young children, even when controlling for baseline anxiety symptoms and maternal history of anxiety (Meyer, Hajcak, Torpey-Newman, Kujawa, & Klein, In Press). Although there is evidence that the ERN is stable and heritable, a large portion of the variance is unaccounted for by genetic influences (between 40 – 60%; Anokhin et al., 2008), suggesting that environmental factors may play an important role in the development of the ERN. Consistent with this view, we found that punishing errors results in an increase in the ERN (Meyer, Gawlowska, & Hajcak, Under Review; Riesel, Weinberg, Endrass, Kathmann, & Hajcak, 2012); moreover, this

effect persists following punishment, suggesting that learning experiences surrounding error commission can have a lasting impact on the ERN. During child development, one of the most important aspects of the learning environment is parenting style. In fact, harsh parents punish their children's mistakes more intensely and frequently (Robinson, Mandleco, Olsen, & Hart, 2001), often resulting in children's excessive concern over making mistakes (Kawamura, Frost, & Harmatz, 2002). This led us to hypothesize that one mechanism that may contribute to an altered ERN in childhood is chronic exposure to a punitive learning environment via harsh parenting.

We recently explored this possibility in a sample of young children, finding that both observational and self-report measures of hostile parenting at age 3 prospectively predicted an enhanced ERN in children 3 years later (Meyer, Proudfit, et al., 2014). The same pattern of results was found in a group of preschool-aged children (Brooker & Buss, 2014) – greater fearfulness and harsher parenting at 2 years of age predicted larger ERN amplitudes at age 4, suggesting that early learning-related experiences that impact sensitivity to errors may lead to an increased ERN. Furthermore, in our study, a mediation analysis indicated that the ERN mediated the relationship between harsh parenting and child anxiety disorders, suggesting that an increased ERN may be one mechanism through which parenting influences child psychopathology (Meyer, Proudfit, et al., 2014).

In light of evidence that early learning impacts ERN magnitude, we were interested in exploring whether the effects of these early experiences are modulated by genetic factors in the current study. We focused on a polymorphism involved in regulating brain-derived neurotrophic factor (BDNF), a growth factor that plays an important role in learning through its influence on neuronal survival, growth, and synaptic plasticity in the central nervous system. The human genome contains a common single nucleotide polymorphism (SNP) that codes for a valine-to-methionine substitution at codon 66 (*val66met*) which leads to reduced levels of BDNF (Egan et al., 2003). Expression of the *BDNF* met allele has been associated with impairments in certain forms of learning and memory (Casey et al., 2009; Egan et al., 2003), as well as susceptibility to psychopathology (Neves-Pereira et al., 2002; Sen et al., 2003; Sklar et al., 2002). Using fear-learning paradigms, researchers have demonstrated in both mouse models and humans that carriers of the met allele are characterized by a deficit in extinction learning (Johnson & Casey, 2014; Peters, Dieppa-Perea, Melendez, & Quirk, 2010; Soliman et al., 2010), which they hypothesized may relate to an increased risk for psychopathology. Moreover, these deficits can be reversed through infusion of BDNF, further supporting the notion that this growth hormone plays an important role in extinction learning (Peters et al., 2010). If we conceptualize harsh parenting as a form of fear-learning wherein children learn to associate making mistakes with punishment, we might expect children with the met allele to be less able to extinguish this association, despite experiencing other situations wherein their mistakes are not punished. Furthermore, previous studies have found that parenting behaviors have a greater impact on children's psychological outcomes among youth carrying a met allele (Ibarra et al., 2014; Park et al., 2014; Suzuki et al., 2012; Willoughby, Mills-Koonce, Propper, & Waschbusch, 2013). Given these findings, we hypothesized that young children with the *BDNF* met allele may be differentially impacted by harsh parenting (i.e., a more punishing learning environment) compared to children without the met allele.

In the current study we examined the potential gene x environment interaction between the *BDNF* genotype and parenting in relation to the ERN in a longitudinal study including 201 parent and child dyads. Because we were interested in the impact of *BDNF* on early learning experiences, we assessed parenting when the children were young (approximately 3 years old) using both observational and self-report measures. During a second assessment, when children were approximately 6 years old, ERPs were recorded while children completed a Go-No/Go task to measure the ERN, and diagnostic interviews were completed with the parent to assess child psychopathology. We previously reported that both observational and self-reported harsh parenting was related to an increased ERN magnitude in these children (Meyer, Proudfit, et al., 2014); here, we examined the novel question of whether this relationship is moderated by children's *BDNF* genotype, such that children with the met allele would be more impacted by harsh parenting. Furthermore, we extend previous findings by characterizing developmental trajectories that lead to *both* internalizing and externalizing outcomes in children. To do this, we explored two separate moderated mediation models wherein we tested whether the interaction between parenting and the *BDNF* genotype predicting ERN magnitude would mediate the relationship of harsh parenting to internalizing (model 1) and externalizing disorders (model 2) in children.

Method

Participants

The sample for the current study consisted of 201 (118 male) children identified through a commercial mailing list (see Olino, Klein, Dyson, Rose, & Durbin, 2010 for details). An initial assessment was completed when children were approximately 3 years of age, wherein a primary caretaker brought their child into the laboratory to complete a series of tasks. At this assessment, the primary parent completed self-reports regarding parenting style and both the child and parent participated in a series of parent-child interaction tasks that provided an observational measure of hostile and supportive parenting behavior. Buccal cells were also collected from the inside of each child's cheek for genetic analysis. Three years later, when children were approximately 6 years of age, they returned to the laboratory for an EEG assessment and clinical interview with the parent (among a series of other tasks). As previously reported (Torpey, Hajcak, Kim, Kujawa, & Klein, 2011), EEG data from 87 out of 413 children were not included in the analyses (69 due to committing 5 or fewer errors, 16 due to having 5 or fewer artifact-free error trials, 1 due to technical error, and 1 due to having an ERP value more than 3 standard deviations from the overall mean).¹ Of the 326 children with adequate EEG data from the Age 6 assessment, 280 mothers completed questionnaires regarding their parenting style and the Teaching Tasks battery. Of these 280 mothers and children, 201 children had adequate DNA for genetic analysis. In the final sample of 201 children, the mean age at the first assessment was 3.56, *SD* = .27, and 6.04, *SD* = .38 at the second assessment. 87 % of the children were Caucasian, 1% Asian, 5% Hispanic, 1% African American, and 6 % identified as "other." The study was approved by the Stony Brook Institutional Review Board and completed with consent of the participants.

¹These 87 children did not differ from the rest of the sample in age, race, or any of the study variables, all *ps* > .20.

Observed parental hostility

At the first assessment, the parent who accompanied the child to the laboratory (93% mothers) and child participated in a session that included a modified version of the Teaching Tasks battery (Egeland et al., 1995). This battery included six standardized tasks (e.g., block-building, book-reading) that were designed to elicit various parent and child behaviors. Parental hostility was defined as a parent's expression of anger, frustration, and/or criticism towards her child. Coders rated parents' hostile behavior on a five-point scale for each task and these ratings were averaged across tasks ($M = 1.18$, $SD = .31$, Range: 1.0 – 3.00). Coders were unaware of self-reported parenting style. Interrater reliability (based on 55 assessments) and internal consistency ($ICC = .83$, $\alpha = .76$) was acceptable.

Self-reported parenting style

The primary parent also completed the Parenting Styles and Dimensions Questionnaire (PSDQ; Robinson, Mandleco, Olsen, & Hart, 2001) at the first assessment. The PSDQ contains 37 items. Parents rate each item on a scale from 1 (*never*) to 5 (*always*), measuring three parenting styles: authoritative (high control, high warmth), authoritarian (high control, low warmth), and permissive (low control, high warmth). The factors' internal consistencies (authoritative: $\alpha = .82$, authoritarian: $\alpha = .75$, permissive: $\alpha = .74$) were acceptable. Observed parental hostility and the PSDQ Authoritarian factor ($M = 20.26$, $SD = 4.87$) were significantly, albeit modestly, correlated, $r = .19$, $p < .001$. As aggregate measures of parenting from multiple sources have been shown to be more consistent and generalizable than single measures (Bögels & Melick, 2004), we z-scored and combined the PSDQ Authoritarian factor and observed hostile parenting score to derive an index reflecting both self-reported and observed parenting (i.e., harsh parenting; $M = .05$, $SD = 1.52$, Range: $-2.22 - 5.95$).

Diagnostic interviews

As previously reported (Meyer et al., 2013a), the Preschool Age Psychiatric Assessment (PAPA; Egger, Ascher, & Angold, 1999) was used to assess a range of disorders from the *Diagnostic Statistical Manual of Mental Disorders* (DSM-IV-TR; American Psychiatric Association, 2000) in children at the second assessment when they were 6 years old. The PAPA is a semi-structured parent-report interview with good psychometric properties (see Egger et al., 2006). The interview focuses on the previous 3 months to maximize recall. For this report we aggregated internalizing disorders ($N = 73$; specific phobia, separation anxiety disorder, social phobia, generalized anxiety disorder, obsessive-compulsive disorder, agoraphobia, major depressive disorder, and dysthymia) and externalizing disorders ($N = 25$; ADHD and oppositional defiant disorder [ODD]). Interviews were conducted face-to-face with parents by M.A.-level psychologists. A second diagnostician rated audiotapes of 35 interviews for reliability, oversampling for psychopathology. Kappas ranged from acceptable to excellent: any anxiety disorder (.89), separation anxiety (1.00), specific phobia (.79), agoraphobia (1.00), any depressive disorder (.64), ADHD (.64), ODD (.87). In the statistical models, children were dichotomously coded as either meeting or not meeting criteria for having an internalizing disorder (Model 1) or an externalizing disorder (Model 2).

Genotyping

Buccal cells were collected from the inside of each child's cheek for genetic analysis during the first laboratory visit. The Qiagen DNA Micro-Kit (Qiagen Valencia, CA, USA) was used to isolate genomic DNA (gDNA) from individual buccal cells according to manufacturer instructions (see Hayden et al., 2010 for details). Individual gDNA isolates were used to genotype the *val66met* polymorphism in the *BDNF* gene using the amplified refractory polymerase chain reaction-restriction fragment length polymorphism method described by Sheikh and colleagues (2010). In the current sample, 94 children (47%) were homozygous for the val/val genotype, 97 (48%) were heterozygous, and 10 (5%) were homozygous for the met/met genotype. Because of the relative infrequency of the met/met genotype in Caucasian samples (and associated lower power), analyses compared children with the val/val genotype with those with at least one met allele (Hayden et al., 2010).

EEG task and materials

As previously described (Meyer et al., 2013a; Torpey et al., 2011), a Go/No-Go task was administered using Presentation software (Neurobehavioral Systems, Inc.). The stimuli were green equilateral triangles presented in one of four different orientations for 1,200 ms in the middle of the monitor. On 60% of the trials, triangles were vertically aligned and pointed up, 20% were vertically aligned and pointed down, 10% were tilted slightly to the left, and 10% were tilted slightly to the right. Children were told to respond to upward-pointing triangles by pressing a button, and to withhold a response to all other triangles. Following the presentation of the triangle, a small gray fixation cross was displayed in the middle of the monitor for between 300 – 800 ms before the next trial began. Children completed four blocks of 60 trials each.

Psychophysiological recording

The Active Two system (Biosemi, Amsterdam, 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, Michigan) at each electrode position. All data were sampled at 512 Hz. The ground electrode during acquisition was formed by the common mode sense active electrode and the driven right leg passive electrode.

Data were processed offline with Brain Vision Analyzer (Brain Products, Gilching, Germany). EEG data were re-referenced to the nose and high- and low-pass filtered at .1 Hz and 30 Hz, respectively. EEG segments of 1500 ms were extracted from the continuous EEG, beginning 500 ms prior to responses. Data were then corrected for eye-movements and blinks (Gratton, Coles, & Donchin, 1983) and artifacts were rejected if any of the following criteria were met: a voltage step of more than 50 microvolts between data points, a voltage difference of 300 microvolts within a single trial, or a voltage difference of less than .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 the full sample have been previously reported (Torpey et al., 2011). The error-related negativity (ERN) and correct-related negativity (CRN) were scored

as the average voltage in the window between 0 ms and 100 ms after response commission on error and correct trials, respectively; the CRN and ERN were quantified at Fz, where error-related brain activity was maximal. The delta ERN (Δ ERN), thought to reflect error-specific activity, was calculated by subtracting the CRN from the ERN.

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, repeated-measures comparisons when necessitated by violation of the assumption of sphericity. The Pearson correlation coefficient (r), one-way ANOVAs, and chi-squares were used to examine associations between all study variables.

We used a nonparametric bootstrapping method (MacKinnon, Lockwood, & Williams, 2004) to examine whether the *BDNF* polymorphism moderated the relationship between harsh parenting and error-related brain activity. After this, we used a bootstrapping test to explore the extent to which the *BDNF* polymorphism moderated the mediation of error-related brain activity on the relationship between parenting and child psychopathology. This approach has been shown to be more statistically powerful than other tests of moderated mediation (MacKinnon, Lockwood, Hoffman, West, & Sheets, 2002). To test for moderated mediation, we used an SPSS macro (Process: Preacher & Hayes, 2004), which provided 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. Process uses ordinary least squares methods for estimating two-way interactions in moderation models and estimates regions of significance using the Johnson-Neyman Technique. All variables were z-scored before being included in analyses.

Results

Consistent with previous reports from the larger sample (Meyer et al., 2013; Torpey, Hajcak, Kim, Kujawa, & Klein, 2011), the ERP response was more negative following errors than correct responses, $F(1, 200) = 64.61, p < .001^2$ (see Figure 1). The ERN was larger among children with internalizing disorders, $M = -6.51 \mu V, SD = 8.06$, compared to children without internalizing disorders, $M = -3.75 \mu V, SD = 8.42, F(1, 200) = 5.17, p < .05$, but did not differ between children with and without externalizing disorders, $F(1, 200) = .71, p = .40$. The ERN also did not differ between the two *BDNF* genotype groups, $F(1, 200) = .05, p = .83$. As previously reported (Meyer, Proudfit, et al., 2014), an enhanced ERN in children was related to harsh parenting, $r(199) = -.12, p = .08$, albeit at a trend level in this smaller sample.

²Behavioral data for the sample has been previously reported (Meyer et al., 2013; Torpey et al., 2011). In the current sample, children were faster on error trials, $M = 503.14$ ms, $SD = 87.73$, compared to correct trials, $M = 622.82$ ms, $SD = 72.19, F(1, 194) = 691.34, p < .001$. Children committed an average of 25.97, $SD = 14.07$, errors and 212.33, $SD = 15.14$ correct responses. Neither reaction times nor accuracy related to any of the study variables, all $ps > .05$.

Additionally, harsh parenting did not differ by *BDNF* genotype group, $F(1, 200) = .15, p = .70$. While parenting did not differ between children with and without internalizing disorders, $F(1, 200) = .04, p = .84$, parents of children with externalizing disorders were characterized by a harsher parenting style, $F(1, 200) = 5.98, p < .05$. Also, rates of both internalizing and externalizing disorders were comparable between the two *BDNF* genotype groups, $\chi^2(1, N = 201) = 2.04, p = .15$, and $\chi^2(1, N = 201) = 1.33, p = .25$, respectively.

Moderation of the *BDNF* genotype on the relationship between parenting and child error-related brain activity

We used a nonparametric bootstrapping method (MacKinnon, Lockwood, & Williams, 2004) to examine whether the *BDNF* polymorphism moderated the relationship between harsh parenting and error-related brain activity. Results suggested that while neither the main effects of the *BDNF* gene nor harsh parenting were significantly related to the ERN in this model, both $ps > .8$, the interaction between the *BDNF* genotype and harsh parenting explained a significant amount of variance in ERN magnitude in children, $R^2 = .02, F(1, 197) = 3.67, p = .05$. As depicted in Figure 2, among children with a met allele, harsh parenting was associated with an increased ERN, $t = -2.56, p < .01$, (95 % confidence interval [CI]: -0.45 to -0.06). However, among children with the val/val *BDNF* genotype, harsh parenting was not associated with the ERN magnitude in children, $t = .21, p = .84$, (95 % confidence interval [CI]: $-.18$ to $.23$). Probing regions of significance in the interaction indicated that differences in ERN magnitude between the *BDNF* groups were only apparent at high levels of harsh parenting (above 5.13, $p < .05$), with no differences evident at lower levels of harsh parenting (harsh parenting values between -2.22 and 2.26 , all $ps > .10$). Trend-level differences were observed when harsh parenting values were between 2.27 and 5.13 (ps ranged between .06 - .10).

Moderated mediation model: predicting internalizing disorders

We previously reported a mediation model wherein the ERN mediated the relationship between harsh parenting and child anxiety disorder status (Meyer, Proudfit, et al., 2014). In the current study, we examined a moderated mediation model wherein the interaction between the *BDNF* genotype and harsh parenting predicting the ERN mediated the relationship between parenting and internalizing disorders in children (see Figure 3). In this model, the interaction between the *BDNF* genotype and harsh parenting predicted ERN magnitude in children, $t = 1.92, p = .05$. Additionally, as can be seen in Table 1, the ERN predicted internalizing disorders, $z = -2.21, p < .05$, (95 % confidence interval [CI]: $-.67$ to $-.04$). While the direct path between parenting and internalizing disorders was not significant, $z = -.08, p = .93$, (95 % confidence interval [CI]: $-.20$ to $.18$), results supported a moderated mediation model, estimate = .10, (95 % confidence interval [CI]: .01 to .26). The pattern of the moderated mediation was consistent with the original mediation model: among children with a met *BDNF* genotype, the relationship between harsh parenting and internalizing disorders was mediated by ERN magnitude, estimate = .09, (95 % confidence interval [CI]: .01 to .23), but this relationship was not significant among children with the val/val *BDNF* genotype, estimate = $-.01$ (95 % confidence interval [CI]: $-.10$ to $.06$). In other words, the mediation of parenting to child psychopathology via error-related brain

activity was contingent on the *BDNF* genotype, only occurring among children with at least one met allele.

Moderated mediation model: predicting externalizing disorders

To examine specificity, we ran a second model, using the same moderated mediation pattern described above, this time predicting externalizing disorders instead of internalizing disorders (see Figure 4 and Table 2). Again, in this model, the interaction between the *BDNF* genotype and harsh parenting predicted ERN magnitude, $t = 1.92$, $p = .05$. However, ERN magnitude did not predict externalizing disorders in children, $z = 1.19$, $p = .23$, (95 % confidence interval [CI]: $-.16$ to $.66$). Although the results did not support a moderated mediation model, estimate = $-.04$, (95 % confidence interval [CI]: $-.18$ to $.05$), the direct path between harsh parenting and externalizing disorders was significant, $z = 2.48$, $p < .01$, (95 % confidence interval [CI]: $.07$ to $.57$), such that harsher parenting was associated with an increased rate of externalizing disorders in children.³

Discussion

Overall, the results were consistent with our hypotheses: the *BDNF* genotype interacted with harsh parenting such that harsh parenting only related to an increased ERN among children carrying at least one met allele. Among children with the *BDNF* val/val genotype, parenting did not relate to ERN magnitude. Additionally, the mediation of parenting to internalizing disorders in children via error-related brain activity was contingent on the *BDNF* genotype – this relationship was evident only among children with at least one met allele. Furthermore, while harsh parenting was related to an increased rate of externalizing disorders in children, the mediation via *BDNF* and ERN was not significant, suggesting unique mechanisms whereby parenting is related to internalizing versus externalizing outcomes in children.

Consistent with previous work suggesting that punishing errors has a lasting impact on the ERN (Meyer et al., Under Review; Riesel et al., 2012), harsh parenting was related to an increased ERN magnitude in children (Meyer, Proudfit, et al., 2014). We extended previous findings in this sample by exploring whether the *BDNF* genotype moderated the effects of parenting in predicting the ERN, and found that parenting only impacted error-processing among children with a met allele. Previous work suggests that carriers of the *BDNF* met allele are more affected by parenting behavior (Ibarra et al., 2014; Park et al., 2014; Suzuki et al., 2012; Willoughby et al., 2013), display deficits in extinction learning (Johnson & Casey, 2014; Peters et al., 2010; Soliman et al., 2010), and are more susceptible to psychopathology (Neves-Pereira et al., 2002; Sen et al., 2003; Sklar et al., 2002). Harsh parenting may operate in a similar way as fear-learning paradigms in the lab, wherein children associate making mistakes with punishment (i.e., parental criticism). Perhaps children with a met allele are unable to extinguish this learned association, despite

³Our sample included 5 Asian children (out of 201). Results from chi-squared analyses suggest that *BDNF* expression did differ in Asian children: all 5 were met dominant, $X^2 = 4.12$, $p < .05$. However, *BDNF* expression did not differ by any other ethnic group, all p s $> .10$. We re-examined a moderation mediation model wherein the interaction between the *BDNF* genotype and harsh parenting predicting the ERN mediated the relationship between parenting and internalizing disorders in children, excluding those 5 children who identified as Asian. The pattern of results was the same as reported in the manuscript: among children with a met *BDNF* genotype, the relationship between harsh parenting and internalizing disorders was mediated by ERN magnitude, estimate = $.08$, (95% confidence interval [CI]: $.007$ to $.252$).

experiencing other situations in which their mistakes are not paired with punishment. The possibility that the deficit in extinction learning that characterizes *BDNF* met allele carriers underlies the association between harsh parenting and ERN magnitude in children could be explored in future studies that also measure extinction learning in the lab.

Examining the regions of significance from the harsh parenting x *BDNF* interaction suggested that the magnitude of the ERN differed by genotype group only in children who experience high levels of harsh parenting. It was not the case that children with the met allele who experienced low levels of harsh parenting had a significantly reduced ERN amplitude. These findings support a *diathesis-stress model* – suggesting that adverse developmental experiences (i.e., high levels of harsh parenting) were more likely to impact children carrying a vulnerability marker (i.e., the *BDNF* met allele). These findings do not support a *differential susceptibility model* – which assumes that sources of vulnerability (i.e., the *BDNF* met allele) are actually plasticity factors that not only amplify risk for maladaptation but also increase the probability of positive adaptation (Roisman et al., 2012).

Children with internalizing disorders were also characterized by increased error-related brain activity. As previously discussed, this is consistent with a large body of work suggesting that individuals with internalizing disorders and traits display increased ERNs, which has been hypothesized to reflect an increased sensitivity and defensive response to errors, or perhaps more broadly, increased responding to internal sources of threat (Hajcak, 2012; Weinberg et al., In Press). Inconsistent with some previous findings, we did not find a relationship between the magnitude of the ERN and externalizing disorders. One reason for this could be the relatively smaller number of children with externalizing disorders in the sample, leading to insufficient power to detect this relationship. Another reason may be the substantial co-morbidity between internalizing and externalizing disorders in this sample. Consistent with this, in a *post-hoc* analysis wherein we removed all children with internalizing disorders from the sample, children with externalizing disorders were characterized by a blunted ERN. Future work should explore the degree to which co-morbidity of internalizing and externalizing psychopathology may influence error-related brain activity in children.

Extending our previous work, by examining *both* internalizing and externalizing outcomes, we found evidence for specificity in terms of delineating trajectories from parenting to psychopathology in children. By investigating a genotype (i.e., *BDNF*), an environmental factor (i.e., *harsh parenting*), and a neural marker (i.e., the ERN), we were able to further characterize pathways leading to divergent psychopathology outcomes (Beauchaine & McNulty, 2013). We found that harsh parenting only impacted children's error processing if children carried the *BDNF* met allele, and that this pathway explained a significant amount of variance in the relationship between harsh parenting and internalizing disorders. In contrast, this mediated pathway through the ERN did not predict externalizing outcomes, which were instead directly predicted by harsh parenting.

It is important to consider limitations to the current investigation. As previously mentioned, only 25 children in the current sample had an externalizing disorder and we may have not had sufficient power to detect associations and/or interactions with the ERN. Additionally, the amount of variance in the ERN predicted by the parenting/*BDNF* interaction was small

(2%). While we would not expect a single genetic polymorphism to explain a large amount of variance in psychological outcomes, the clinical application of the current findings in isolation would be relatively limited. Future work might identify other interactions between risk factors and genes to be used in conjunction with the current findings.

Previous work in humans and other animals supports the notion that parenting behavior has a substantial impact on brain development and stress reactivity in offspring (Caldji et al., 1998; Francis, Diorio, Liu, & Meaney, 1999; Kertes et al., 2009; Kryski et al., 2013; Teicher et al., 2003). Some work has suggested that parenting may program biological responses to threatening stimuli through epigenetic mechanisms, allowing offspring to thrive under the unique demands of their environment (Francis et al., 1999). The findings from the current study support this notion insofar as harsh parenting may increase the threatening nature of errors and thereby potentiate children's neural response to their own mistakes, especially in children with relatively less available BDNF. It is possible that other measures of threat sensitivity may also be differentially impacted by parenting as a function of *BDNF* genotype (e.g., startle response, amygdala reactivity, cortisol reactivity), and these processes may then also characterize developmental trajectories leading to psychopathology. Future work should explore these possibilities.

Previous work has suggested that magnitude of the ERN increases across development (Tamnes, Walhovd, Torstveit, Sells, & Fjell, 2013), reaching adult-like levels around age 18. Although we were unable to test this in the current study, it is possible that children with the met allele who experienced harsh parenting early in life experienced a greater developmental increase in the ERN than other children. Future work could explore whether the normative increase in the ERN magnitude across development is greater in some subgroups of children (e.g., with the BDNF met allele, with harsh parents, with increases in anxiety) than others.

It is also important to consider the fact that genetic and environmental influences most likely shift in importance across the lifespan (Bergen et al., 2007). For example, the region of the brain wherein the ERN is generated, the anterior cingulate cortex, demonstrates more environmental plasticity later in development relative to early childhood (Lenroot et al., 2009). In addition, previous work has suggested that BDNF levels substantially increase across development so that the deficit in BDNF levels found in met allele carriers may have a specific impact on learning *earlier* in development (Casey et al., 2009). Parenting may also become less important across development as peer groups increase their influence on behavior (Larson & Richards, 1991). Thus, it will be important for future work to consider both environmental and genetic factors as having a dynamic impact on outcomes across development in order to accurately characterize pathological trajectories and perhaps identify critical risk periods wherein certain factors are particularly related to subsequent outcomes.

Finally, identifying critical periods wherein specific genotypes and/or environmental influences are important may aid us in early intervention strategies (Beauchaine et al., 2008). Previous work has suggested that early parenting interventions may alter the trajectory of psychopathology in at-risk children (e.g., Rapee, Kennedy, Ingram, Edwards, & Sweeney, 2010). In the future, it may be possible to target children, for example, in a certain age range,

with specific genotypes (e.g., *BDNF*), neural risk markers (e.g., an increased ERN), and other risk factors, for early parenting interventions. By taking a targeted, or personalized, approach, we may be better able to allocate resources towards preventing life-long pathological trajectories (Shoham & Insel, 2011).

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Figure 1. Response-locked ERP waveforms for correct (light) and error (dashed) trials, as well as the difference waveform (i.e., error minus correct, dark) for the entire sample at Fz. Negative is plotted up, and response onset occurred at 0 ms.

Figure 2.
Depiction of the interaction between harsh parenting and the BDNF genotype in predicting the error-related negativity in children.

Figure 3.

A moderation mediation model with harsh parenting predicting internalizing disorders, wherein this relationship is mediated by the interaction between the *BDNF* genotype and harsh parenting predicting children's ERN magnitude. * $p < .05$

Figure 4.

A moderation mediation model with harsh parenting predicting externalizing disorders, wherein this relationship is mediated by the interaction between the *BDNF* genotype and harsh parenting predicting children's ERN magnitude. * $p < .05$

Table 1

Moderated mediation model: predicting internalizing disorders.

	coefficient	se	z	p	LLCI	ULCI
Direct effect: ERN on internalizing	-.04	.02	-2.21	< .05	-.67*	-.04*
Direct effect: Hostile parenting on Internalizing	-.02	.15	-.08	.93	-.20	.18
Conditional indirect effects of hostile parenting on internalizing by <i>BDNF</i> group:						
val/val	-.01	.04	-.	-.	-.10	.06
met	.09	.05	-.	-.	.01*	.23*
Full model: Index of moderated mediation	.10	.07	-.	-.	.01*	.26*

Table 2

Moderated mediation model: predicting externalizing disorders.

	coefficient	se	z	p	LLCI	ULCI
Direct effect: ERN on externalizing	.03	.03	1.19	.23	-.16	.66
Direct effect: Hostile parenting on externalizing	.49	.20	2.48	<.01	.07*	.57*
Conditional indirect effects of hostile parenting on externalizing by <i>BDNF</i> group:						
val/val	.01	.04	-	-	-.04	.12
met	-.06	.08	-	-	-.20	.11
Full model: Index of moderated mediation	-.04	.09	-	-	-.18	.05