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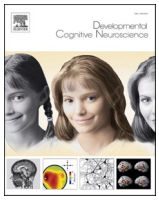

The relationship between stressful life events and the error-related negativity in children and adolescents

Lushna M. Mehra [a], Greg Hajcak [a,b], Alexandria Meyer [a,*]

[a] Department of Psychology, Florida State University, Tallahassee, FL 32306, USA
[b] Department of Biomedical Sciences, Florida State University, Tallahassee, FL 32306, USA

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ABSTRACT

The error-related negativity (ERN) has been cited as a neural marker that indexes risk for anxiety in children and across development. Environmental factors, such as punishment in the lab and parenting styles, have been shown to impact the ERN. However, little is known about how other environmental factors may shape this neural risk marker. The current study examines how the environmental factor of stressful life events may relate to the ERN in children and adolescents. In a sample of 176 females, ages 8–15 years, we examined associations between the frequency of recent stressful life events and the ERN. We also investigated whether interpersonal dependent life events or non-interpersonal life events uniquely relate to the ERN. Finally, we explored whether recent stressors differentially relate to the ERN based on age. Results suggest that youth who have experienced more frequent stressful life events have an increased (i.e., more negative) ERN. Moreover, more frequent interpersonal dependent stressors uniquely predicted the magnitude of the ERN. Lastly, results supported a moderation model wherein the relationship between the frequency of interpersonal dependent stressors and the ERN was moderated by age, such that the relationship between stressors and the ERN was significant only for younger children.

1. Introduction

Recent research has taken an increasing interest in the error-related negativity (ERN) as a neural marker of psychopathology (Cavanagh and Shackman, 2015; Hajcak, 2012; Meyer, 2016). The ERN is a response-locked event-related potential (ERP) that occurs as a sharp, negative deflection at fronto-central electrode sites approximately 50 ms following an error during a lab-based task (Falkenstein et al., 1991; Gehring et al., 1993). The ERN is thought to reflect an error monitoring signal produced in the anterior cingulate cortex (ACC), a region of the brain that is active when punishment, threat, and pain are experienced (Miltner et al., 2003; Shackman et al., 2011; van Veen and Carter, 2002). Errors are motivationally important, internal events that require immediate attention and corrective action. In line with this, errors prompt a cascade of defensive responses, including changes in skin conductance, decreased heart rate, heightened startle reflex, and pupil dilation (for review, see: Weinberg et al., 2012).

The ERN has been found to be increased (i.e., more negative) in relation to both adult and child anxiety in over 60 studies to date, including obsessive-compulsive disorder, generalized anxiety disorder, and social anxiety disorder (Endrass et al., 2010; Meyer, 2017; Riesel, 2019; Weinberg et al., 2010). Further, an increased ERN has been shown to predict onset of anxiety disorders and symptoms across development (Meyer et al., 2015b, 2017a, 2018a). For example, the ERN measured in children ages 5–7 years-old served to predict new anxiety disorder onset later in development, even when controlling for baseline anxiety symptoms (Meyer et al., 2015a). Thus, the ERN appears to be elevated amongst anxious individuals, and it may reflect increased *risk* for the development of anxiety.

Considering that an increased ERN in youth confers risk for anxiety later in life, it is important to identify what factors may shape the ERN early in development. Understanding the factors that shape this neural risk marker may lead to novel intervention and prevention approaches. Indeed, the ERN appears to be impacted by the environment – with environmental factors accounting for 40–60% of variance (Anokhin et al., 2008). In the lab, the ERN is potentiated when errors are punished and this effect has been found to persist even after punishment ends (Meyer and Gawlowska, 2017; Riesel, 2019; Riesel et al., 2012), which suggests that learning experiences related to behavior may shape the ERN. Furthermore, parenting styles have been shown to relate to the ERN in children (Brooker and Buss, 2014; Meyer et al., 2019; Meyer et al., 2015b; Meyer and Wissemann, 2020), such that harsh or

* Corresponding author.
E-mail address: meyer@psy.fsu.edu (A. Meyer).

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controlling parenting relates to an increased ERN in offspring. Controlling parents tend to punish children's mistakes more frequently and more intensely (Robinson et al., 2001), which often results in children's excessive concern about making mistakes (Kawamura et al., 2002). We have hypothesized that children's exposure to their parents' negative reactions to their mistakes (i.e., verbal and/or non-verbal reactions) may condition children to over-react to their own errors and, thus, potentiate the ERN over time and put children at risk for anxiety (Meyer et al., 2019).

In addition to the context of parenting, children and adolescents are also significantly impacted by the environmental influence of stressful life events. Indeed, stressful life events have been found to predict increases in anxiety across time (Casline et al., 2021; Faravelli, 1985; Green et al., 2010; Hankin et al., 2004; Young and Dietrich, 2015). Additionally, two studies have found that the ERN interacts with stress to predict changes in anxiety symptoms prospectively (Banica et al., 2020; Meyer et al., 2017b). Considering this, we have previously hypothesized that stressful life events may also impact the ERN early in development (Meyer et al., 2019). To our knowledge, only two studies have investigated this possibility. One study found that, among adolescents, higher numbers of adverse childhood experiences related to a larger ERN (Lackner et al., 2018). Additionally, a recent investigation by Wu et al. (2021) revealed that a greater severity of childhood adversity experiences (e.g., childhood abuse and neglect) was associated with a more negative ERN in a sample of adult males.

Moreover, some work suggests that *interpersonal stressors*, including: failure experiences, humiliation, and peer victimization may be uniquely related to robust increases in anxiety (Casline et al., 2021; Farmer and Kashdan, 2015; Hamilton et al., 2016; Kendler et al., 2003; Siegel et al., 2009). Considering the ERN has been linked to error sensitivity — the degree to which individuals react negatively to mistakes (Chong and Meyer, 2019) —, as well as checking symptoms (Weinberg et al., 2016), social anxiety symptoms (Meyer et al., 2018b), and shyness (Meyer and Klein, 2018), it has been hypothesized that an increased ERN may reflect anxiety specifically related to one's own performance or behavior. In fact, a recent study suggests that a brief, computerized intervention targeting error sensitivity may reduce the magnitude of the ERN (Meyer et al., 2020). Taken together, these findings suggest that, in addition to the shaping that may occur in the context of parenting, children's and adolescents' ERNs may also be impacted by stressful life events – particularly those that may relate to failure, social rejection, or negative interpersonal experiences. However, to our knowledge, no previous study has investigated the differential impact of various types of stressful life events on the magnitude of the ERN in children and adolescents.

The present study examines the relationship between the ERN and recent stressful life events in children and adolescents between the ages of 8 and 15 years old. We measured stressful life events utilizing a child self-report questionnaire about the frequency of negative life events occurring within the last 3 months. We examine to what extent recent stressful life events relate to the magnitude of the ERN. Based on previous work, we hypothesized that both a greater frequency of *total* negative stressful life events and of *interpersonal dependent* stressful life events would each relate to a larger (i.e., more negative) ERN. However, we had no a priori hypothesis regarding the relation between non-interpersonal stressors and the ERN. Next, we examine whether *specific types of stressful life events* uniquely predicted the ERN using a simultaneous regression. Based on the work discussed above linking the ERN to evaluative and performance concerns, we predicted that stressful life events – particularly those that may relate to failure, social rejection, or negative interpersonal experiences (i.e., interpersonal dependent events), would uniquely relate to the ERN. Finally, we conducted exploratory analyses assessing whether recent stressors impact youth differentially based on age. To do so, we examine the interaction of stressful life events and age in predicting the magnitude of the ERN.

2. Methods

2.1. Participants

The present sample was drawn from a larger, NIMH-funded, longitudinal study (R01 MH097767) investigating neural risk markers for depression in females from a community sample. It is important to note that previous studies have been published using this dataset (Chong et al., 2020; Gorday and Meyer, 2018; Meyer et al., 2018b; Meyer et al., 2021); however, none of the previous studies focused on the relationship between the ERN and stressful life events. Previous studies using this larger dataset have investigated the relationship between anxiety and the ERN (Meyer et al., 2018b; Meyer et al., 2021), parenting styles and the ERN (Chong et al., 2020), and puberty and the ERN (Gorday and Meyer, 2018). The current study aims are novel insofar as they examine the relationship between stressful life events and the ERN. For the current study, of the 317 recruited participants, 251 had EEG data. However, 17 were excluded for having a Flanker task accuracy below 60%, 1 was excluded for committing fewer than 6 errors (Olvet and Hajcak, 2009), and 2 were excluded because their ERP activity values were more than three standard deviations from the mean. Of the remaining 231 participants with usable EEG data, 36 participated in the study before the stressful life events measure was added to the protocol. Nineteen participants with missing data for the measure were also excluded from the present analyses. Overall, 176 females, ages 8–15 ($M = 12.65$, $SD = 1.65$), who had usable EEG and self-report measure data were included in the present analyses. The sample was comprised of 3.4% 8-year-olds, 6.8% 9-year-olds, 6.8% 10-year-olds, 12.5% 11-year-olds, 21.6% 12-year-olds, 25.6% 13-year-olds, and 23.3% 14-year-olds. Participants identified as 81% White, 7% Black, 6% Hispanic, and 5% Other, with 1% of participants with missing data on race and ethnicity.

Participants were recruited via a commercial mailing list. Afterward, a phone screen was conducted to ensure the following inclusion criteria were met: the participant must live with at least one biological parent, both parent and child must speak English, and there must be no significant history of developmental disabilities or medical disabilities in the child. Participants were compensated $20 per hour for their study participation. The study protocol was approved by the Institutional Review Board at Stony Brook University, and parental consent and child assent were obtained prior to study participation.

2.2. Self-report measures

The current study examined self-report measures of recent life stressors for the child. The Adolescent Life Events Questionnaire (ALEQ; Hankin and Abramson, 2002) was given to the child to self-report based their own life events. The ALEQ consists of 57 items examining how often negative life events have occurred in the past three months. Responses are recorded on a 5-point Likert scale, with response options 0 ("never") to 4 ("always"). The present study focuses on the ALEQ total score, as well as two additional subscales identified by Auerbach et al. (2010) that categorize the ALEQ's negative events into Interpersonal Dependent Events and Non-Interpersonal Events. The interpersonal dependent events and non-interpersonal events subscales separate all the items on the ALEQ into one of the two categories, and the items in each subscale are non-overlapping. The interpersonal dependent events subscale includes items that are dependent on the action of the child and are interpersonal in nature (i.e., involve the child's relationship with others) such as, "You fought with your parents over your personal goals, desires, or choice of friends," and "You had an argument with a close friend." The non-interpersonal events subscale includes items that do not directly relate to the child's relationship with others including, "A close family member lost their job" and "You did poorly on or failed a test or class project." For total and subscale scores, values are summed, and higher values represent higher frequencies of negative life events for the child over the past three months. The ALEQ has been found to be

reliable and valid in populations of youth (Hankin and Abramson, 2002). In a sample of 130 girls aged 13–18 years, Hankin and Abramson (2002) found a mean frequency score for total stressful life events of 31.48 ($SD = 10.21$). Reliability for the child-report ALEQ in the present sample was excellent for the total score ($\alpha = 0.93$) and the interpersonal dependent events subscale ($\alpha = 0.91$), and good for the non-interpersonal events ($\alpha = 0.81$) subscale.

2.3. Tasks and materials

Participants completed an arrowhead version of the computer-based Flanker task (Eriksen and Eriksen, 1974) during EEG data recording. Each participant was presented with five white arrowheads that occupied approximately 1.3° of vertical visual angle and 9.2° of horizonal visual angle. Arrows were presented on the center of a screen with a black background. Participants viewed the stimuli from approximately 61 cm away on a 48.3 cm monitor with a refresh rate of 60 Hz. Participants were instructed to respond as quickly and accurately as possible with either the left or right mouse button based on the direction of the central arrowhead. There was no fixed response window — i.e., trials during which participants did not make a response were omitted from analyses (all analyses focused on response-locked neural activity). There were two conditions of arrowhead presentations: "compatible" ("<<<<<" or ">>>>>") and "incompatible" (">><>>" or "<<><<"). The stimuli presented included half from each condition, such that there were equal compatible and incompatible trials presented to each participant. Stimuli were presented in random order, each for 200 ms followed by a randomly variable interval of 2300–2800 ms between offset of the previous stimulus and onset of a new stimulus. The intertrial interval was varied randomly with a fixed interval of 100 ms – e.g., 2300, 2400, 2500, 2600, 2700, or 200 ms. During the intertrial interval, a gray fixation cross was shown on the center of a black background. First, participants completed a 30-trial practice block, followed by the full task, which consisted of 11 blocks of 30 trials, totaling 330 trials. Participants paused between each block for a self-determined duration, and they choose when to progress with the next block by clicking the mouse. After each block, the participant was provided performance-based feedback. Those scoring 75% accuracy and below were prompted with "Please try and be more accurate," those scoring above 90% accuracy saw "Please try to respond faster," and those between 75% and 90% accuracy viewed "You're doing a great job."

2.4. Psychophysiological recording

The ActiveTwo BioSemi system (BioSemi, Amsterdam, Netherlands) and an elastic cap with 34 electrode sites were used to collect continuous EEG recordings during the Flanker task. Two additional electrodes were placed on both the right and left mastoids. Four facial electrodes collected eye movement and blink data using electrooculogram (EOG) with two electrodes 1 cm away from the left and right eye outer edges to measure horizontal movements and two electrodes 1 cm away from the top and bottom of the right eye to measure vertical movements. To improve the signal-to-noise ratio, the EEG signal was preamplified at each electrode and amplified with a gain of one by a BioSemi ActiveTwo system. The data were digitized at a 24-bit resolution with a sampling rate of 1024 Hz using a low-pass fifth order sinc filter with a half-power cutoff of 204.8 Hz. Each active electrode was measured online with respect to a common mode sense (CMS) active electrode producing a monopolar (non-differential) channel. Offline, data were preprocessed and analyzed using BrainVision Analyzer (BVA) Version 2.1.2.327. Data were referenced to the average of both mastoids and band-pass filtered between 0.1 and 30 Hz. Eyeblink and ocular corrections were conducted per Gratton et al. (1983). Artifact detection and rejection were conducted using the artifact rejection function in BVA with the following specified parameters: A voltage step greater than 50.0 μV between sample points, a voltage difference of 300.0 μV within a trial, and a voltage difference of less than .50 μV within 100 ms intervals were rejected from channels in each trial.

EEG data were segmented for each trial at 500 ms before the response until 1000 ms after the response, and baseline correction was performed on the interval from 500 ms to 300 ms before the response. Correct and incorrect responses were averaged separately in order to obtain the correct-related negativity (CRN) and the error-related negativity (ERN). Based on prior research and visual inspection, the activity at the interval from 0 to 100 ms was averaged to examine the ERN. Analyses focused on Fz, where visual inspection revealed error-related brain activity to be maximal. As such, average CRN and ERN activity at Fz between 0 and 100 ms after a response was exported for each participant. A subtraction-based difference score was computed for the ΔERN by subtracting average correct-related negativity activity from average error-related negativity activity. Percent accuracy, number of error trials, and both reaction time (RT) across all trials and RT by trial type (i.e., error or correct) were calculated as behavioral measures. Due to experimenter error, reaction time data is missing for one participant. This participant was still included in the overall analyses due to the fact that RT was a not a focus of the current study The reported number of error and correct trials for each participant are the number of trials that were included in the EEG analysis (i.e., the number of usable error and correct trials after artifact rejection had been completed). The analyses did not include trials during which there were no button presses.

2.5. Data analysis

Statistical analyses were conducted using SPSS Version 26. The Pearson correlation coefficient (r) was used to examine the associations between study variables (two-tailed for analyses in which we had no directional hypothesis and one-tailed for analyses in which we had a directional hypothesis). General Linear Modeling was also used, with Greenhouse-Geisser corrections applied to p values when the assumption of sphericity was violated. Repeated-measures ANOVAs were used to compare average reaction times during error and correct trials, as well as to compare the average ERN with the CRN. Two multiple regressions were conducted. The first regression examined the main research question regarding whether there is specificity of either of the ALEQ subscales (i.e., interpersonal dependent events and non-interpersonal events) in predicting the ΔERN by entering both subscales of the ALEQ predicting the ΔERN in a regression. Then, a second regression was conducted as a follow-up to determine if the pattern of results was the same while controlling for potential confounding variables. As such, the second regression added child age, task reaction time, and task accuracy to the model to determine whether either or both of the ALEQ subscales predicts the ΔERN while controlling for child age, task reaction time, and task accuracy. Following, moderation models wherein the interaction between age and stressors predicting the ΔERN were conducted using SPSS Hayes macro PROCESS (Hayes, 2012) model 1 with 5000 bootstrap samples. Finally, a moderated mediation model was conducted using PROCESS model 11 as an exploratory investigation of a comprehensive model concerning the study variables. This model tested a 3-way interaction between interpersonal stressors, authoritarian parenting (via the Parenting Styles and Dimensions Questionnaire [PDSQ; Baumrind, 1971]), and child age predicting the ΔERN, while also examining whether the ΔERN mediated the relationship between stressors and child anxiety in the same model. All analyses were conducted controlling for child anxiety symptoms using the Parent-Report of the Screen for Child Anxiety Related Emotional Disorders-Parent (SCARED; Birmaher et al., 1997) total score. For all analyses, any values where $p < .05$ were considered significant.

3. Results

3.1. Self-report

In the present sample, the ALEQ total scores ranged from 0 to 122 (M = 32.73, SD = 23.01), the interpersonal dependent events subscale ranged from 0 to 68 (M = 15.31, SD = 13.37), and the non-interpersonal events subscale ranged from 0 to 32 (M = 9.66, SD = 6.93). Age was significantly positively correlated with the ALEQ total score, r (174) = 0.29, p < .001, as well as both the interpersonal dependent events subscale, r (174) = 0.22, p = .004, and the non-interpersonal events subscale, r (174) = 0.34, p < .001, such that older children reported more frequent recent stressors. See Table 1 for descriptive statistics for the ALEQ and its subscales.

3.2. Behavioral data

On average, participants responded correctly to 84.18% (SD = 7.54, range = 60.06–97.88%) of the Flanker trials and had an average reaction time of 452.89 ms (SD = 88.42, range = 319.51–774.98). A repeated-measures ANOVA with a Greenhouse-Geisser correction revealed faster participant reaction time on error trials (M = 363.97, SD = 71.55 ms) compared to correct trials (M = 470.01, SD = 93.73 ms), F (1, 174) = 647.05, p < .001. Neither accuracy nor average reaction time was significantly correlated with ALEQ total or subscale scores. However, participant age was related to reaction time on both error trials, r (173) = −0.34, p < .001, and correct trials, r (173) = −0.48, p < .001), such that reaction time across trials decreased with increasing age. Additionally, participant age was negatively associated with the number of error trials, r (173) = −0.36, p < .001, such that older children committed fewer errors. Participant age was negatively associated with both the ERN, r (174) = −0.22, p = .003, as well as with the ΔERN, r (174) = −0.18, p = .019, such that older children were characterized by enhanced error-related brain activity. Finally, the number of error trials was positively associated with both the ERN, r (173) = 0.22, p = .003, and the ΔERN, r (173) = 0.21, p = .005, such that a smaller ERN was associated with more error trials. See Table 1 for descriptive statistics for age, average reaction time, and accuracy.

Table 1
Descriptive statistics for current study variables.

	N	Minimum	Maximum	Mean	Standard Deviation
ΔERN (μV)	176	-23.09	10.70	-3.98	4.70
ERN (μV)	176	-16.13	14.92	-2.19	5.53
CRN (μV)	176	-10.44	22.22	1.78	5.38
Average Reaction Time (ms)	175	319.51	774.98	452.89	88.42
Accuracy (% correct)	176	60.06	97.88	84.18	7.54
Number of Error Trials	175	7	123	50.58	23.39
Participant Age (years)	176	8.04	15.00	12.65	1.65
Adolescent Life Events Questionnaire (ALEQ)	176				
Interpersonal Dependent Events Subscale	176	0	68	15.31	13.37
Non-Interpersonal Events subscale	176	0	32	9.66	6.93
Total	176	0	122	32.73	23.01

Note. Descriptive statistics for variables examined in the current study are included for behavioral measures (average reaction time, accuracy), participant age, error-related brain activity (ΔERN, ERN, CRN), and the measure of stressful life events and its subscales – the Adolescent Life Events Questionnaire child-report (ALEQ).

3.3. Error-related brain activity and total stressful life events

The ERN (M = −2.19, SD = 5.54 μV) was significantly more negative than the CRN (M = 1.78, SD = 5.38 μV) at Fz, F (1, 175) = 125.67, p < .001. A subtraction-based difference score (ΔERN) was created by subtracting the CRN from the ERN at the Fz electrode. See Table 1 for descriptive statistics for measures of error-related brain activity. There were significant relationships between the ΔERN and the ALEQ interpersonal dependent events subscale, r (174) = −0.18, p = .010, as well as between the ΔERN and the total ALEQ score, r (174) = −0.13, p = .043, such that as the frequency of recent life stressors increased, the ΔERN also increased (i.e., became more negative). There was no significant relationship between the non-interpersonal events subscale and the ΔERN, r (174) = −0.08, p = .160. [1] Even when controlling for child anxiety symptoms, the correlation between the ALEQ interpersonal dependent events subscale and the ΔERN remained significant, r (170) = −0.18, p = .008, as did the association between the ΔERN and total ALEQ score, r (170) = −0.14, p = .037. The association between the ΔERN and the non-interpersonal events subscale remained nonsignificant, r (170) = −0.08, p = .160, when controlling for anxiety symptoms.

Fig. 1 depicts the topographical headmaps for the difference wave (ΔERN; error minus correct for 0–100 ms) and the waveforms for error, correct, and difference for high and low stressor groups based on the ALEQ child-report interpersonal dependent events subscale.

3.4. Examining the specificity of interpersonal dependent stressful life events in predicting error-related brain activity

To examine the specificity of interpersonal dependent stressors from the ALEQ in predicting the ΔERN, multiple linear regressions were conducted. The first regression examined whether experiencing more frequent interpersonal dependent stressful life events predicts the ΔERN while controlling for the frequency of non-interpersonal stressors. Although the overall model was not significant, the frequency of interpersonal dependent stressors, while controlling for non-interpersonal dependent stressors, was a significant predictor of the ΔERN, such that as a child reported more frequent recent experiences of interpersonal dependent stressors, the ΔERN was larger (i.e., more negative). The frequency of non-interpersonal stressors was not a significant predictor of the ΔERN while controlling for interpersonal dependent stressors.

The second regression added child age, average task reaction time, and task accuracy to the model to examine whether experiencing more frequent interpersonal dependent stressful life events predicts the ΔERN while controlling for non-interpersonal dependent stressors in addition to age, reaction time, and accuracy.[2] The overall model was significant and suggested that all variables together explain 12.8% of the variance in the ΔERN. Specifically, as the frequency of recent interpersonal dependent stressors increased, the ΔERN became more negative, while

[1] This overall pattern of relationships between stressful life events and the ERN was similar when using a residual-based difference score of the ERN – i.e., more negative life events on the ALEQ related to more error-related brain activity. However, none of the associations were significant when examining the pattern of relationships between the raw ERN (i.e., not a difference-score) and stressful life events, all ps > 0.05.

[2] In order to control for number of error trials, which is highly correlated with task accuracy, a separate multiple regression was conducted to determine whether the interpersonal dependent stressor subscale was a unique predictor of the ΔERN while controlling for non-interpersonal dependent stressors, age, reaction time, and number of error trials. The overall pattern of results was the same, and the relation between interpersonal dependent stressors and the ΔERN remained significant while controlling for the aforementioned variables. Like task accuracy, number of error trials was also a significant predictor of the ΔERN while controlling for interpersonal stressors, non-interpersonal stressors, age, and reaction time.

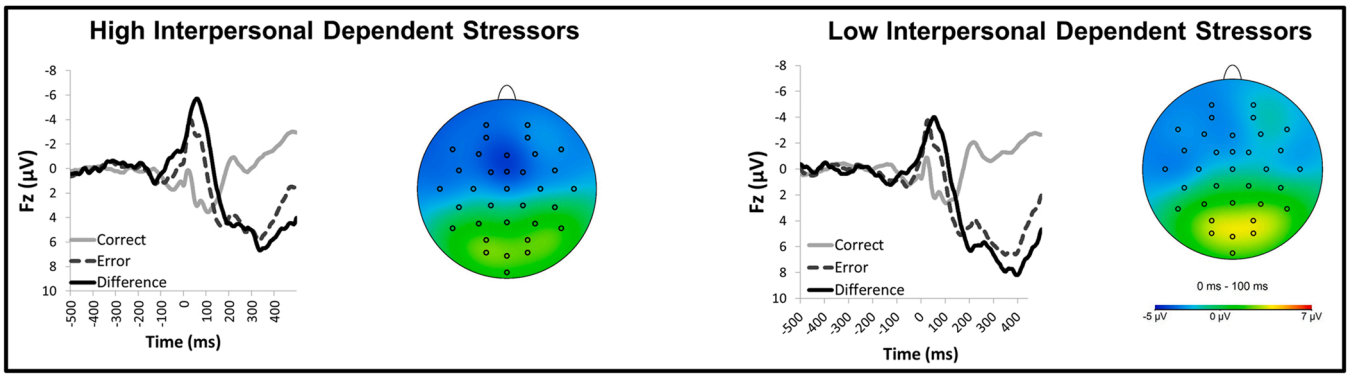

Fig. 1. *Topographical Headmaps for the ΔERN in High and Low Stressor Groups. Note.* Topographical headmaps for the difference wave (ΔERN; error minus correct for 0–100 ms) and the waveforms for error, correct, and difference for high and low stressor groups based on significant relationships between the ΔERN and Adolescent Life Events Questionnaire child-report (ALEQ). The ALEQ interpersonal dependent stressors headmaps were created using participants in the top ("high") and bottom ("low") quartiles for the subscale.

controlling for non-interpersonal events, age, accuracy, and reaction time. Additionally, as average task reaction time decreased, the ΔERN became more negative, while controlling for interpersonal stressors, non-interpersonal stressors, task accuracy, and age. Task accuracy was also a significant predictor of the ΔERN when accounting for interpersonal stressors, non-interpersonal stressors, task reaction time, and age. Finally, child age was not a significant predictor of the ΔERN while controlling for interpersonal stressors, non-interpersonal stressors, task accuracy, and average task reaction time. Tables 2 and 3 display test statistics for each regression, including measures of multicollinearity.

Lastly, we examined the same multiple regressions above while controlling for child anxiety symptoms. In the regression examining the specificity of interpersonal dependent events and non-interpersonal events in predicting the ΔERN, while also controlling for anxiety symptoms, the full model remained nonsignificant, $F(3, 171) = 2.10$, $p = .102$, and the interpersonal dependent events subscale remained a significant predictor of the ΔERN while controlling for non-interpersonal stressors and child anxiety symptoms, $\beta = -0.23$, $t = -2.30$, $p = .023$. Then, a regression was conducted to determine if the pattern of results was the same while also controlling for the original potential confounding variables (i.e., child age, reaction time, accuracy), as well as child anxiety. Patterns remained the same while also controlling for anxiety symptoms. The full model remained significant, $F(6167) = 5.06$, $p < .001$, and, specifically, as the frequency of recent interpersonal dependent stressors increased, the ΔERN became more negative, while controlling for non-interpersonal events, age, accuracy, reaction time, and anxiety, $\beta = -0.22$, $t = -2.40$, $p = .018$.

3.5. Developmental analyses – Moderation models

We also conducted exploratory analyses to examine to what extent the relationship between recent stressful life events and the error-related negativity might differ across development. To do so, we conducted moderation models wherein we tested the interaction between each of the stressful life events subscales and child age predicting the ΔERN. In the first model, we examined the interaction between the child report of non-interpersonal stressors from the ALEQ and age. Results suggested that this interaction was not significant, $\Delta R^2 < 0.001$, $F(1, 172) = 0.003$, $p = .960$. Next, we examined the interaction between child report of interpersonal dependent stressors from the ALEQ and age. Results from this model suggest that the interaction was significant, $\Delta R^2 = 0.05$, $F(1, 172) = 9.39$, $p = .003$, such that the relationship between recent interpersonal dependent stressors and the ΔERN was significant only amongst younger children, $b = -0.15$, 95% CI [−0.23, −0.07], $t = -3.60$, $p < .001$. Fig. 2 depicts this interaction.[3] Importantly, the moderation examining this same interaction (i.e., between interpersonal dependent stressors and child age predicting the ΔERN) remained significant while controlling for child anxiety symptoms, $\Delta R^2 = 0.05$, $F(1, 170) = 8.96$, $p = .003$, such that the relationship between recent interpersonal dependent stressors and the ΔERN was significant only amongst younger children, $b = -0.15$, 95% CI [−0.23, −0.07], $t = -3.62$, $p < .001$.

Table 2
Multiple regression of interpersonal dependent stressful life events and non-interpersonal stressful life events predicting the ΔERN.

	b	SE *b*	*β*	*t*	*p*	Tolerance	VIF
Interpersonal Dependent Events	-0.07	0.03	-0.21	-2.20	0.029	0.61	1.65
Non-Interpersonal Events	0.04	0.07	0.06	0.59	0.553	0.61	1.65

Note. Multiple regression examining the Adolescent Life Events Questionnaire child-report (ALEQ) measure subscales predicting the ΔERN.

3.6. Comprehensive model approach – Moderated mediation model

Finally, we attempted to integrate the current findings with prior work concerning the role of parenting experiences and child anxiety. An investigation of parenting and anxiety by Chong et al. (2020) found that child age moderated the relation between parenting style and the ERN, such that harsher parenting was associated with a more negative ERN only for younger children. Chong et al. (2020) also found that the association between parenting style and anxiety disorder diagnosis was mediated by the ERN, but only for younger children. We sought to integrate these findings into a model with interpersonal dependent

[3] We also conducted separate moderation models wherein child anxiety symptoms and child pubertal stage were entered as moderators of the relationship between interpersonal dependent stressful life events and the ERN. The model examining the Parent-Report of the Screen for Child Anxiety Related Emotional Disorders-Parent (SCARED; Birmaher et al., 1997) total score as a moderator of the association between interpersonal stressors and the ΔERN suggested that the interaction was not significant, $\Delta R^2 = 0.01$, $F(1, 171) = 1.29$, $p = .258$. However, the model examining the Parent-Report on the Pubertal Development Scale (PDS; Petersen et al., 1988) mean score as the moderator for the interpersonal stressor and ΔERN relation was significant, $\Delta R^2 = 0.05$, $F(1, 171) = 8.57$, $p = .004$, such that the association was significant only amongst children in a less developed pubertal stage, $b = -0.15$, 95% CI [−0.24, −0.07], $t = -3.65$, $p < .001$. It is important to note that although age and pubertal stage are highly correlated, $r(173) = 0.72$, $p < .001$, age remained a significant moderator when controlling for pubertal stage, and pubertal stage also remained a significant moderator when controlling for child age.

Table 3
Multiple regression of interpersonal dependent stressful life events and non-interpersonal stressful life events predicting the ΔERN, while controlling for age, accuracy, and reaction time.

	b	SE *b*	*β*	*t*	*p*	Tolerance	VIF
Interpersonal Dependent Events	-0.07	0.03	-0.21	-2.33	0.021	0.61	1.65
Non-Interpersonal Events	0.04	0.06	0.06	0.67	0.504	0.55	1.81
Child Age	0.23	0.27	0.08	0.84	0.400	0.56	1.80
Average Reaction Time	0.02	< 0.01	0.32	3.81	< 0.001	0.71	1.40
Accuracy	-0.16	0.05	-0.26	-3.26	0.001	0.78	1.29

Note. Multiple regression examining the Adolescent Life Events Questionnaire child-report (ALEQ) measure subscales predicting the ΔERN, while controlling for age, task reaction time, and task accuracy.

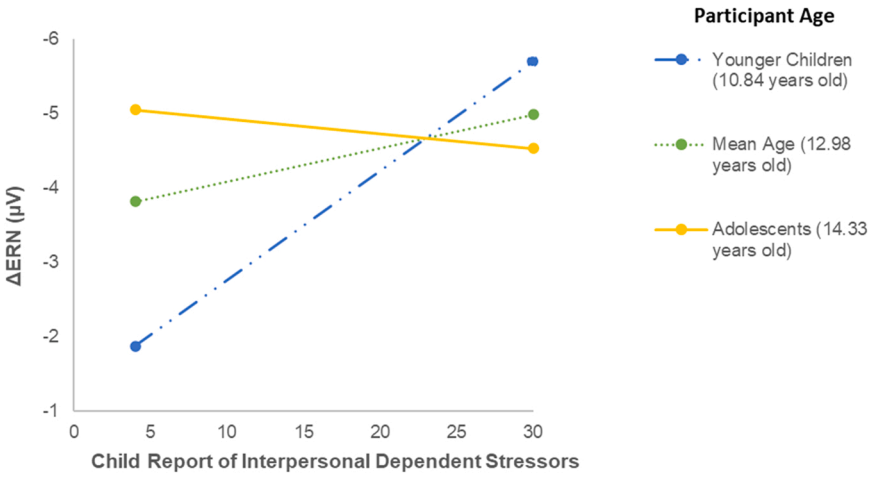

Fig. 2. *Graph Depicting the Interaction between Child Age and Interpersonal Dependent Stressors. Note.* Depiction of the child age by life stressor interaction predicting error-related brain activity (ΔERN; error-related negativity minus correct-related negativity) at electrode Fz. Life stressors were self-reported items assessing frequency of stressful life events from the Adolescent Life Events Questionnaire (ALEQ). The mean age of participants in the sample was 12.98 years old. Younger children are defined as one standard deviation below the mean (i.e., 10.84 years old) and adolescents as one standard deviation above the mean (i.e., 14.33 years old). Among *younger* children, a larger (i.e., more negative) ΔERN was associated with greater child-reported frequency of interpersonal dependent stressors. The categorical distinction in age in this figure is for visualization purposes only.

stressful life events, considering that interpersonal dependent stressful life events may impact the ERN in a similar way as harsh parenting styles. Thus, we examined whether a 3-way interaction between authoritarian parenting experiences (via the Parenting Styles and Dimensions Questionnaire [PDSQ]; Baumrind, 1971), child age, and frequency of recent interpersonal stressors predicted the ERN, and whether the ERN mediated the relation between interpersonal stressors and total child anxiety. The 3-way interaction between parenting, age, and interpersonal stressors did not significantly predict the ΔERN, *coeff* = −0.005, *SE* = 0.004, *t* = −1.28, *p* = .202, 95% CI [−0.013,.003]. In this model, only the 2-way interpersonal stressor by age interaction predicted the ΔERN, *coeff* = 0.05, *SE* = 0.02, *t* = 3.42, *p* < .001, 95% CI [.022,.083]. Further, the indirect pathway wherein interpersonal stressors predicted child anxiety via the ΔERN was not significant and results did not support a moderated mediation, *index of moderated mediation* = −0.0001, *SE* = 0.0009, 95% CI [−0.003,.001].

4. Discussion

Results from the current study suggest that recent stressful life events, as reported by children, using a measure of frequency of stressful life events occurring in the past three months (i.e., the ALEQ), relate to increased error-related brain activity (a neural risk marker for anxiety) in children and adolescents between the ages of 8 and 15 years old. Consistent with our hypothesis, increased (i.e., more negative) error-related brain activity was specifically associated with recent interpersonal dependent stressors (i.e., events dependent on actions of the child and involve their relationship with others). However, recent non-interpersonal events (e.g., a child moving to a new town) were not related to error-related brain activity. Finally, results suggested that the relationship between stressors and the ERN was moderated by age, such that interpersonal dependent stressors predicted error-related brain activity only in younger children, but not in older children or adolescents. The current study replicates prior work suggesting that stressful or traumatic life events relate to increased error-related brain activity (Lackner et al., 2018) and extends those findings by examining how interpersonal dependent and non-interpersonal stressful life events differentially relate to the magnitude of the ERN, as well as how these relationships may differ across development.

Results from the current study were consistent with our hypothesis that a greater frequency of total negative stressful life events would relate to a larger ERN. This finding is similar in nature to that of Lackner et al. (2018), who found that adolescents in a high trauma group (i.e., those who had more than four adverse childhood experiences) had greater error-related activity when compared to medium and low trauma groups. In a parallel manner, Wu et al. (2021) found that a greater self-reported severity of childhood adversity experiences, including severe domains of abuse and neglect, related to a larger ERN in adult males. It is interesting to note that Lackner et al. (2018) assessed and did not find a relationship between the frequency of traumas and error-related activity. However, our results suggest that there is an association between the frequency of recent stressful life events and the ERN, even when controlling for anxiety. As our measure included a range of severity of stressful life events, from doing poorly on a project to experiencing a death, rather than solely traumas of high severity, perhaps the frequency of these more common, lower severity stressors, has a more continuous impact on the ERN.

It should be noted that the relationship between stressors and error-related brain activity was significant when using differences scores (i.e., subtraction and regression-based difference scores), but not when using the ERN on its own (for a further discussion of these methods of scoring within-subjection conditions, see: Meyer et al., 2017a). This pattern of results suggests that neural activity specific to errors, and not general response monitoring, may be related to stressors.

Further, in a novel examination of the specificity of interpersonal dependent and non-interpersonal stressful life events predicting the ERN, we found that the child report of recent *interpersonal dependent stressors* on the ALEQ uniquely predicted the ERN while controlling for

the frequency of non-interpersonal stressors. The relationship between interpersonal dependent stressors and error-related brain activity remained significant when controlling for age, reaction time, and accuracy, as well as when controlling for number of error trials and child anxiety, which suggests that neither performance on the task, child anxiety, nor development account for the relationship between interpersonal dependent stressful life events and the ERN.

In our exploratory aim to examine how age might moderate the relationship between recent stressful life events and the ERN, we found a significant relationship between frequency of interpersonal dependent stressors and the ERN that was moderated by age, even when controlling for task accuracy and average task reaction time, number of error trials, anxiety, depression, and pubertal stage; however, the non-interpersonal stressors by age interaction did not significantly predict the ERN. Results suggested that for younger children, more frequent interpersonal dependent stressors predicted a larger ERN, but this effect was not significant in older children or adolescents. Additionally, as prior studies using this dataset have examined the associations between the ERN and anxiety (Meyer et al., 2018b; Meyer et al., 2021) and puberty (Gorday and Meyer, 2018), we assessed whether anxiety or pubertal stage moderated the association between interpersonal dependent stressors and the ERN. While anxiety was not found to significantly moderate the relationship between the ERN and stressors, child pubertal stage was a significant moderator, such that for less pubertally developed children, more frequent interpersonal stressors predicted a larger ERN, even when controlling for child age. Thus, it appears that child age and pubertal stage may have independent moderating roles on the interpersonal stressor and ERN association. It may be that there are separate qualities associated with age and pubertal status, such as social factors specific to younger ages or having lower levels of developmental hormones at lesser pubertal stages that promote the development of the ERN in the face of frequent interpersonal stressors. Various aspects of the specific social, biological, and psychological contexts associated with development may be important to examine in future work.

These preliminary findings suggest that the ERN may be more sensitive to the impact of the environment (i.e., stressful life events) early in development. Consistent with our results, a recent study by Chong et al. (2020) also found a relationship between environmental factors and age in an examination of the ERN across female participants aged 10–17. They reported a significant association between authoritarian/harsh parenting styles and the ERN specifically in younger children, but not in older children and adolescents. Taken together, it is possible that there is a sensitive period in development during which the neural systems underlying error-processing are more vulnerable to the impact of specific types of environmental stressors, and then becomes less malleable after this period ends. While the results from this study suggest that interpersonal stressors are related to the ERN in younger, but not older children, future work is needed to determine the extent to which the ERN may be differentially impacted by the environment during different developmental periods. Previous work has found sensitive or critical periods across species for the development of perceptual systems (e.g., the visual system; Hensch, 2005), as well as affective processes (e.g., fear learning and attachment; Hartley and Lee, 2015). Abnormal experiences during sensitive periods have been shown to result in long-term impairment that cannot easily be reversed due to the increasing stability of the organization of neural circuits after the sensitive period ends. Results from the current study, although exploratory, suggest that early and middle childhood may be an important developmental period for the formation of the ERN and may be ideal for targeted, intervention approaches. However, it should be noted that much of the work on sensitive periods (e.g., the visual system) has been conducted in animal models and as such, a high level of specificity regarding sensitive periods (e.g., when they open and when they close) was able to be elucidated. Results from the current study are broad and should be viewed as a rudimentary first step towards delineating potential sensitive periods in the development of error-related processing.

Results from the current study suggest a developmental shift in the relationship between interpersonal stressors and error-related brain activity, since this relationship was only significant amongst relatively younger children. Another way of framing these developmental changes is that at low frequencies of recent interpersonal dependent stressors, age related to the ERN in the expected direction, in that older children had a larger ERN; however, at higher levels of interpersonal dependent stressors, age was no longer related to the ERN (i.e., all children in this group were characterized by a larger ERN). Thus, an alternative interpretation of the current results is that younger children who experience above-average interpersonal dependent stressors are characterized by advanced maturation of the ERN. However, it should be noted that the current study is entirely between-subject and cross-sectional. Future work, including repeated assessments within individuals across childhood and adolescence, is needed to further understand these developmental processes. Additionally, it should be noted that changes in brain structure (i.e., the development of the anterior cingulate cortex) may underlie the developmental patterns observed in the current study (Velanova et al., 2008). And, it is also possible that differences in the processing of stressful life events, including factors such as recall of events or coping skills, in children compared to adolescents may underlie the associations observed (Compas, 1987; Hatch and Dohrenwend, 2007; Silvers et al., 2012). Future work is needed to clarify these issues. However, as age was positively associated with the frequency of stressful life events, such that older children and adolescents reported more frequent stressors in the past three months, it is important to consider whether the measure of stressful life events (i.e., the ALEQ) adequately captured the types of stressors encountered by younger children, and thus the frequency of recent stressors experienced. It may be that younger children experienced alternate types of stressors not assessed by the present measure. It is also possible that the occurrence of the types of stressful life events represented in the measure, geared toward adolescents, are more salient during earlier periods of development (e.g., encountering stressors related to romantic relationships as a child may be less common and more salient). As such, these results are preliminary and should be replicated in future studies, using alternate methods of measuring stressful life events.

Finally, we aimed to integrate the current study findings with prior work examining associations between parenting style experiences and child anxiety. However, we did not find a significant relationship between interpersonal stressors and the ERN moderated by child age and an authoritarian parenting style. In the same model, we also did not find that the ERN mediates the association between interpersonal stressors and child anxiety. These results suggest that child age and experiences of an authoritarian parenting style, in combination, do not significantly impact the association between interpersonal stressors and the ERN. It could be that experiencing an authoritarian parenting style is adequately represented within the conceptualization of interpersonal stressors (i.e., experiencing harsh parenting is considered an interpersonal stressor that was adequately taken into account with that measure), such that its addition to a model does not provide further explanatory information regarding the interpersonal stressor and ERN relationship. As we also found that the ERN does not mediate the association between interpersonal stressors and child anxiety in this model, it appears that alterations in a child's ERN might not be the mechanism under which interpersonal stressors are associated with child anxiety. However, as these analyses were conducted in a cross-sectional sample, it is important to consider that longitudinal investigations would be needed to clarify the direction of any potential associations. While this study presents a novel exploration of how stressful life events may contribute to shaping the ERN, it has several limitations. The current study sample only included females, which restricts our knowledge about the generalizability of these relationships between stressful life events and the ERN in males. Additionally, considering the paucity of previous work examining the potential impact of stressors on the ERN, we viewed this study as a first step towards elucidating the relationship between error-

related brain activity and environmental stressors. However, it should be noted that there are many factors that are not included in the current study that may relate to the development of the ERN, such as parental ERN, family risk for anxiety, parenting styles, pubertal hormones, socio-economic status, cortisol, attention biases, cognitive control, etc. Future work should be done to further understand what environmental and genetic influences may impact the development of the ERN. Moreover, our measure of stressful life events examined the occurrence of these events in the past 3 months, but it may be more helpful to examine an exact timeline of when particular types of stressful life events occurred in order to draw more specific conclusions about their relationships with the ERN and whether there are effects of recency. Finally, the cross-sectional nature of the study limits our ability to discern whether stressful life events impact the ERN, or whether having a larger ERN predisposes one to experience stressful life events (or increases the perception of experiencing negative events). Thus, in the current study, we are unable to determine the direction of these effects and, moreover, we are unable to determine if there is a bidirectional relationship between life stressors and error-related brain activity. Future studies utilizing a longitudinal design should investigate this topic.

Overall, the current study presents a novel investigation of factors that relate to the ERN by examining its relationship with stressful life events in youth. Few studies have looked at such environmental factors in relation to this neural marker of anxiety. Exploring the direction of the relationship between stressful life events and the ERN as well as further understanding specific types of events and how their timing relates to the ERN would benefit the development of early prevention and treatment approaches. Further, determining whether there is a sensitive period during which the ERN is more malleable would be a critical step toward effectively preventing and managing anxiety prior to its chronic course.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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