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Unpredictability increases the error-related negativity in children and adolescents[☆]

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ABSTRACT

The error-related negativity (ERN) is a response-locked component in the event-related potential observed as a negative deflection 50–100 ms following the commission of an error. An unpredictable context has been shown to potentiate amygdala activity, attentional bias toward threat, and the ERN in adults. However, it is unclear whether the impact of unpredictability on the ERN is also observed in children and adolescents. In a sample of 32 9–17 year-old participants, we examined the influence of a task-irrelevant unpredictable context on neural response to errors. Participants completed a flanker task designed to elicit the ERN, while simultaneously being exposed to task-irrelevant tone sequences with either predictable or unpredictable timing. Unpredictable tones were rated as more anxiety provoking compared to the predictable tones. Fewer errors were made during unpredictable relative to predictable tones. Moreover, the ERN—but not the correct response negativity (CRN) or stimulus-locked N200—was potentiated during the unpredictable relative to predictable tones. The current study replicates and extends previous findings by demonstrating that an unpredictable context can increase task performance and selectively potentiate the ERN in children and adolescents. ERN magnitude can be modulated by environmental factors suggesting enhanced error processing in unpredictable contexts.

1. Introduction

The ability to monitor the environment for threat is critical for survival. The *predictability* of threat is an important feature that can impact threat anticipation, subsequent behavioral adaptation, and the mitigation of aversive consequences. In contrast, unpredictable threat limits the ability to prepare for and respond to threat, and as such, unpredictable threat is often perceived as more aversive (Grupe & Nitschke, 2013). Indeed, animal and human studies have demonstrated that organisms prefer predictable relative to unpredictable threat (Grillon, Baas, Cornwell, & Johnson, 2006; Grillon, Baas, Lissek, Smith, & Milstein, 2004; Lejuez, Eifert, Zvolensky, & Richards, 2000), and unpredictable threat is associated with greater self-reported anxiety and startle potentiation (Grillon et al., 2006; Nelson & Shankman, 2011; Schmitz et al., 2011).

To date, most research studies have examined the impact of (un) predictability by manipulating the temporal predictability of an unconditioned aversive stimulus (e.g. electric shock presented with either predictable or unpredictable timing; Grillon et al., 2004, 2006; Lejuez et al., 2000; Nelson & Shankman, 2011; Schmitz et al., 2011). However, this experimental approach makes it unclear whether unpredictability, *independent* of the aversive stimulus, can impact sensitivity to threat. To address this question, Herry et al. (2007) examined whether a task-irrelevant unpredictable tone sequence impacted anxious responding, relative to a predictable tone sequence. Results demonstrated that the unpredictable, relative to predictable, context increased attentional bias to exogenous threat and potentiated amygdala activation in both mice and humans.

Herry et al. (2007) examined the impact of unpredictability on threat processing as indexed by attentional bias and amygdala activation. An alternative approach toward examining threat sensitivity is to assess behavioral and neural responding to errors. Indeed, it has been theorized that errors are a type of endogenous threat (Weinberg et al., 2016) that have the potential to place an individual in danger, and thus are experienced as aversive and are associated with defensive physiological responding (Hajcak, 2012). Consistent with this notion, previous research has demonstrated that errors, compared to correct responses, prime defensive motivational reactions, including amygdala activation (Pourtois et al., 2010), a potentiated startle reflex (Hajcak & Foti, 2008; Riesel, Weinberg, Moran, & Hajcak, 2013), pupil dilation (Critchley,

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Tang, Glaser, Butterworth, & Dolan, 2005), and heart rate deceleration and skin conductance responses (Hajcak, McDonald, & Simons, 2004).

An electrophysiological index of errors is the error-related negativity (ERN), a response-locked component in the event-related potential (ERP) observed as a negative deflection that peaks approximately 50–100 ms following the commission of an error. Source localization studies have indicated that the ERN is generated in the anterior cingulate cortex (ACC), a region of the medial prefrontal cortex implicated in processing aversive stimuli that include errors, pain, and negative affect (Shackman et al., 2011). The magnitude of the ERN has been shown to be sensitive to the relative value of errors. For example, the ERN is enhanced when performance is evaluated and errors are more costly (Barker, Troller-Renfree, Pine, & Fox, 2015; Hajcak, Moser, Yeung, & Simons, 2005), as well as when errors are punished (Meyer & Gawlowska, 2017; Riesel, Weinberg, Endrass, Kathmann, & Hajcak, 2012). As a result, variation in the ERN is posited to reflect reactivity to the potential significance, or threat value, of errors (Weinberg, Riesel, & Hajcak, 2012).

In a recent study, Jackson, Nelson, and Proudfit (2015) examined the impact of an unpredictable context on error processing by examining the ERN during a flanker task. Utilizing the same predictable and unpredictable tone sequences used by Herry et al. (2007), Jackson et al. found that the unpredictable compared to predictable tone sequence potentiated the ERN in adults. Further, Jackson et al. (2015) found that the impact of the unpredictable context was specific to the ERN: unpredictable tones did not impact the correct-response negativity (CRN), indicating that a task-irrelevant unpredictable context may render errors (i.e., potential danger) more salient.

In addition to error-salience, the ERN has been theorized to index conflict monitoring (Yeung, Botvinick, & Cohen, 2004), specifically the co-activation of error and error-correcting responses that occur on error trials. From this perspective, potentiation of the ERN in an unpredictable context might reflect increased response conflict in the post-response period. According to the conflict monitoring hypothesis, increased response conflict is also reflected in an increased stimulus-locked N200 on incongruent (i.e. < < > < <) compared to congruent (i.e. < < < < <) correct trials in the pre-response period (Nieuwenhuis, Yeung, Van Den Wildenberg, & Ridderinkhof, 2003; Yeung & Cohen, 2006; Yeung et al., 2004). It has been suggested that the N200 is associated with identifying conflict and facilitating continued performance via increased cognitive control (Clayson & Larson, 2011a, 2011b; Freitas, Banai, & Clark, 2009; Larson, Clayson, & Baldwin, 2012). Consistent with this idea, studies that have manipulated the probability of high (incompatible) versus low (compatible) conflict trials have found that when high conflict trials occur more frequently, and are therefore expected or predictable, performance is improved (fewer errors and faster response times) and the N200 is larger (Bartholow et al., 2005; Grutzmann, Riesel, Klawohn, Kathmann, & Endrass, 2014). Although Jackson and colleagues demonstrated that the ERN alone was potentiated by task-irrelevant unpredictability, they did not examine stimulus-locked ERPs, and thus it remains unclear if an unpredictable context impacts pre-response conflict monitoring and therefore increases the N200.

The ERN is an ideal tool for investigating threat-related processes across development, as it has been observed in children as young as 3 years old (Grammer, Carrasco, Gehring, & Morrison, 2014; Lo, Schroder, Moran, Durbin, & Moser, 2015), and the differentiation between errors and correct responses becomes more robust across childhood and adolescence (Davies, Segalowitz, & Gavin, 2004; Meyer et al., 2013; Tamnes, Walhovd, Torstveit, Sells, & Fjell, 2013). Moreover, a larger ERN in childhood has been linked to clinical anxiety (Ladouceur, Dahl, Birmaher, Axelson, & Ryan, 2006; Meyer et al., 2013), the development of anxiety disorders (Lahat et al., 2014; McDermott et al., 2009; Meyer, Hajcak, Torpey-Newman, Kujawa, & Klein, 2015) and to environmental factors that make errors more salient, specifically harsh parenting (Meyer et al., 2014). However, it remains unclear how contextual changes may influence error processing in children and adolescents.

For these reasons, the current study conducted a systematic replication of Jackson et al. (2015), and examined the influence of a task-irrelevant unpredictable context on the ERN during childhood and adolescence. Although uncommon in the published literature, reproducibility is a critical and basic component of empirical science that warrants prioritization in psychological science (Giner-Sorolla, 2012; Schmidt, 2009), particularly given the current replication 'crisis' suggested by recent replication efforts (Open Science Collaboration, 2015; Pashler & Harris, 2012; Pashler & Wagenmakers, 2012). Specifically, using a within-subjects design, 46 9–17 year-old participants completed a flanker task designed to elicit the N200 and ERN while predictable and unpredictable tone sequences were played in the background. We hypothesized that, similar to Jackson et al., the unpredictable compared to predictable tones would enhance the ERN. Furthermore, to clarify the interpretation of ERN findings reported by Jackson et al., the current study examined the impact of an unpredictable context on the stimulus-locked N200. If unpredictability increased conflict monitoring more broadly, then we would expect an enhanced N200 in the unpredictable, relative to predictable, tones condition on correct trials. However, we posit that unpredictability enhances threat responding more specifically, and therefore hypothesized that unpredictable tones would only potentiate the ERN, but not the CRN or N200.

2. Method

2.1. Participants

The sample included 46 children and adolescents (20 female) between the ages of 9–17 (*M* = 12.96, *SD* = 2.10) and a biological parent. The ethnic distribution was 84.8% Caucasian, 6.5% African American, 6.5% Latino, and 6.5% 'Other'. Inclusion criteria were English fluency, ability to read and comprehend questionnaires, and a biological parent who agreed to participate in the study. The sample was recruited using online classified advertisements, postings in the community, and a commercial mailing list targeting homes with children or adolescents. A biological parent provided informed consent, and participants provided assent; families received financial compensation ($20/h) for their participation. Before commencement, this study was approved by Stony Brook University's Institutional Review Board.

2.2. Stimuli

The predictable and unpredictable tone sequences were identical to those used in previous reports (Herry et al., 2007; Jackson et al., 2015). In sum, the carrier frequency was 1 kHz, with pulse duration of 40 ms and mean pulse spacing of 200 ms (5 Hz pulse repetition rate). The unpredictable tones were produced from the predictable sequence using a random temporal shift of each tone. Specifically, the randomly selected temporal shift was confined to an interval of 120 ms, with uniform probability within 120 ms. Therefore, predictable and unpredictable sequences contained the same number of tones and equal mean tone spacing (i.e. 200 ms). Tone sequences were presented at 85 dB through external computer speakers positioned approximately 50 cm in front of the participant.

2.3. Procedure

2.3.1. Flanker task

An arrow version of the flanker task was used to elicit the ERN (Hajcak & Foti, 2008; Jackson et al., 2015). On each trial five horizontally aligned white arrowheads were presented for 200 ms. Participants were required to indicate the direction of the central arrowhead using the left or right mouse button; half the trials were congruent (< < < < < or > > > > >) and half were incongruent

Table 1
Self-report ratings, behavior, and ERPs for predictable and unpredictable tone sequence trials.

	Tone sequence		t or χ^2	*Cohen's d*	p
	Predictable	Unpredictable			
Self-report ratings					
Anxiety (au)	2.91 (1.44)	3.75 (1.65)	$t = -2.83$	0.55	< 0.01
Behavior					
Number of errors	39.81 (17.70)	32.47 (13.98)	$t = 3.66$	0.46	0.001
Error RT (ms)	356.81 (53.97)	365.81 (63.87)	$t = -1.37$	0.15	0.18
Correct RT (ms)	453.36 (82.37)	470.69 (86.57)	$t = -3.64$	0.21	0.001
ERPs (μV)					
ERN	0.96 (5.81)	−0.97 (5.03)	$t = 2.80$	0.36	< 0.01
CRN	3.40 (3.45)	3.35 (4.08)	$t = 0.12$	0.01	0.91
N200 congruent	0.13 (4.25)	−0.15 (3.98)	$t = 0.70$	0.07	0.49
N200 incongruent	−0.42 (4.46)	−0.79 (3.74)	$t = 0.78$	0.09	0.44

Note. Standard deviations are presented in parentheses. au = arbitrary units; ERPs = event-related potentials; ms = milliseconds; RT = reaction time.

(< < > < < or > > < > >). The order of trial type was random. The intertrial interval varied between 600 and 1000 ms following the participant's response. The viewing distance was approximately 65 cm, and arrows filled 2° of visual angle vertically and 10° horizontally.

The task was presented using Presentation software (Neurobehavioral Systems Inc., Albany, CA). Before task commencement participants were told that they would be hearing tones during the task, but were not given further information regarding the nature or purpose of the tones, and were instructed to focus on the flanker task. Participants first completed a practice block of 20 trials, and were required to get at least 60% correct responses before moving on. The task consisted of 8 alternating blocks of 64 trials (512 total trials), during which either predictable (P) or unpredictable (U) tones were played. Block order was either UPUPUPUP or PUPUPUPU, counterbalanced across participants.

Upon completion of the task, participants rated their anxiety during the predictable and unpredictable blocks, using a 7-point Likert scale ranging from 1 (*not anxious*) to 7 (*extremely anxious*). Tones were presented again at the end of the session to confirm that participants correctly labeled the tones during the subjective ratings.

2.3.2. Physiological recording and data processing

Continuous electroencephalography (EEG) was recorded while participants completed the flanker task. ERP activity was recorded from 34 electrodes positioned according to the 10/20 system, including FCz and Iz, using the ActiveTwo BioSemi system (BioSemi, Amsterdam, Netherlands). Electrodes were placed above and below the left eye to monitor vertical electrooculographic (VEOG) activity, adjacent to the outer canthi of the left and right eyes to monitor horizontal electrooculographic (HEOG) activity, and from the left and right mastoids. The EEG signal was preamplified at the electrode to improve signal-to-noise ratio, and 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 102.4 Hz. Active electrodes were measured online with reference to a common mode sense active electrode constructing a monopolar channel. The raw EEG data were re-referenced offline to the average of the left and right mastoids and band-pass filtered from 0.1 to 30 Hz. Eyeblink and ocular-movement corrections were performed using established standards described by Gratton, Coles, and Donchin (1983).

Artifact rejection involved a semiautomatic procedure. Individual channels were marked for rejection if a voltage step of more than 50.0 μV between sample points was present, if a deflection of more than 300.0 μV occurred within a trial, or if a voltage difference of less than 50.0 μV was detected within 100 consecutive ms. A visual inspection of the remaining trials was then conducted to identify and reject any other artifacts. For the ERN and CRN the baseline was identified as the interval between 500 and 300 ms before the response (Weinberg, Olvet, & Hajcak, 2010), and trials with response times below 200 ms or above 1400 ms were excluded from averaging. A negative deflection at frontocentral sites is observed after both error (i.e., the error-related negativity, ERN) and correct trials (i.e., the correct response negativity, CRN). The ERN and CRN were maximal at FCz, and scored as the average activity between 0 and 100 ms following the response. The stimulus-locked N200 was segmented for correct trials beginning 200 ms before flanker presentation and continuing for 1200 ms; the baseline was the 200 ms preceding the flanker stimulus onset. The N200 was computed separately for congruent and incongruent correct trials, and was scored as the average activity between 275 and 375 ms after flanker onset at FCz, where it was maximal.

2.4. Data analysis

Nine participants were excluded from analyses for committing errors on more than 25% of trials during the flanker task in either of the two conditions (Meyer, Weinberg, Klein, & Hajcak, 2012), three participants were excluded due to poor quality EEG recordings, and two participants did not complete the flanker task. The final sample included 32 participants (n = 14 female; age $M = 13.13$, $SD = 2.11$). To evaluate the effect of tone (un)predictability on accuracy (i.e. number of errors committed) we conducted a paired-samples *t*-test. To examine the effects of tone (un)predictability on reaction time (RT), and the ERN/CRN, we conducted separate repeated-measures ANOVA models with condition (predictable vs. unpredictable) and response (correct vs. error) as the within-subjects factors for RT and the ERPs, respectively. To examine the effects of tone (un)predictability on the stimulus-locked N200, we conducted a repeated-measures analysis of variance (ANOVA) with condition (predictable vs. unpredictable) and trial type (congruent vs. incongruent) as the within-subjects factors. Analyses were conducted using IBM SPSS Statistics, Version 22.0 (Armonk, NY).

3. Results

3.1. Self-report ratings and behavior

Table 1 displays descriptive and inferential statistics for self-report ratings and behavior during predictable and unpredictable tone blocks. Unpredictable tones were rated as more anxiety-provoking compared to predictable tones, $t(31) = -2.83$, $p < 0.01$, $d = 0.55$, and participants made fewer errors in the unpredictable compared to predictable tone condition, $t(31) = 3.66$, $p < 0.001$, $d = 0.46$. Overall, participants responded faster when making errors, compared to correct responses, $F(1,31) = 175.62$, $p < 0.001$, $\eta_p^2 = 0.85$. In addition, participants were significantly slower during the unpredictable compared to

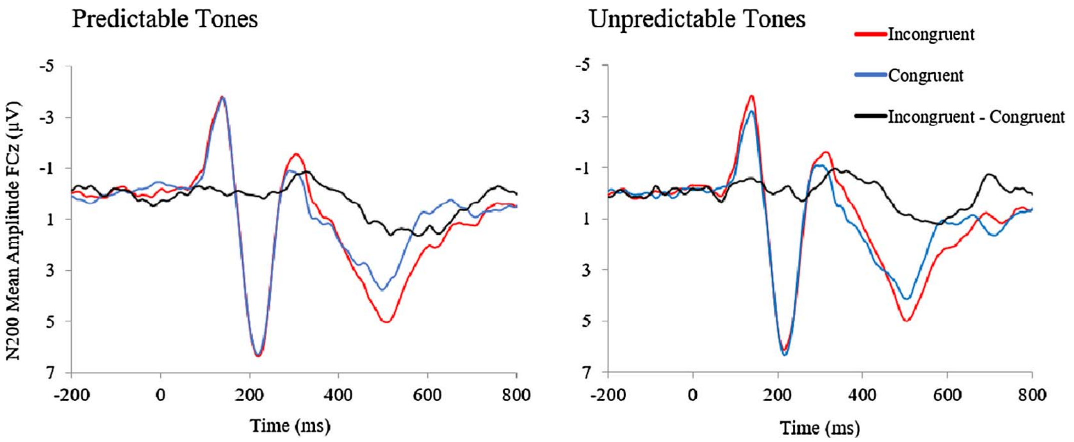

Fig. 1. ERP waveforms (top) display the average electrocortical response to incongruent (red) and congruent (blue) correct trials, and their difference (black) while participants were exposed to predictable (left) versus unpredictable (right) tone sequences. The N200 was scored between 275 and 375 ms post stimulus at FCz. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

predictable tone condition, $F(1,31) = 6.96, p < 0.05, \eta_p^2 = 0.18$.

3.2. ERN

Grand average ERPs are shown in Fig. 2. Descriptive and inferential statistics for the ERN and CRNare provided in Table 1. Results revealed that the ERN was more negative than the CRN overall, $F(1,31) = 16.53, p < 0.001, \eta_p^2 = 0.35$, and that ERPs were more negative in the unpredictable compared to predictable condition overall, $F(1,31) = 5.78$, $p < 0.05$, $\eta_p^2 = 0.16$.[1] These findings were qualified by a Response × Condition interaction, $F(1,31) = 5.98$, $p < 0.05$, $\eta_p^2 = 0.16$. Follow-up analyses indicated that the ERN was enhanced during the unpredictable relative to predictable condition, $F(1,31) = 7.85, p < 0.01, \eta_p^2 = 0.20$, but there was no effect of condition on the magnitude of the CRN, $F(1,31) = 0.01$, *ns*.

A follow-up analysis of covariance (ANCOVA) was conducted controlling for the number of errors in the predictable and unpredictable tones conditions, and the Response × Condition interaction remained significant, $F(1,29) = 5.74, p < 0.05, \eta_p^2 = 0.17$. The interaction also remained significant after simultaneously controlling for the difference in subjective anxiety ratings during predictable and unpredictable tones, $F(1,28) = 6.09$, $p < 0.05$, $\eta_p^2 = 0.18$. Furthermore, the interaction remained significant after simultaneously controlling for average reaction times on error and correct responses during predictable and unpredictable tones, $F(1,24) = 5.78$, $p < 0.05$, $\eta_p^2 = 0.19$. Based on these analyses, the frequency of errors, condition differences in subjective anxiety ratings, and response times did not account for the observed effect of unpredictable tones on the ERN.[2]

Visual inspection of ERPs (see Fig. 2) suggested that condition differences may emerge before the response. Therefore to determine when significant differences between conditions developed we segmented ERP averages into 50 ms bins, beginning at −300 ms (i.e. −300 to −250 ms) and continuing until 100 ms (i.e. 50–100 ms), resulting in a total of 8 bins for each condition. Next, we conducted a repeated measures ANOVA with time (50 ms bins) × predictability (predictable vs. unpredictable) × response (error vs. correct) as within-subjects factors. Results revealed that the predictability × response interaction remained significant, $F(1,31) = 13.76$, $p < 0.001$, $\eta_p^2 = 0.31$, indicating that unpredictable errors were significantly more negative than predictable errors. In addition, there was a significant bin × response interaction, $F(7,217) = 12.58$, $p < 0.01$, $\eta_p^2 = 0.29$. Follow-up *t*-tests comparing error and correct responses for each bin collapsed across predictable and unpredictable conditions revealed that the ERN was significantly more negative than the CRN beginning 50 ms *before* the response, $t(31) = -2.67$, $p < 0.05$. Evaluating predictable and unpredictable conditions separately revealed that in the predictable condition the ERN becomes significantly more negative than the CRN 0–50 ms *after* the response, $t(31) = -2.47$, $p < 0.05$. In contrast, in the unpredictable condition the ERN is significantly more negative than the CRN beginning 100–50 ms *before* the response, $t(31) = -2.67$, $p < 0.05$. These findings suggest that unpredictable tones make the differentiation between error and correct trials evident earlier.

3.3. N200

Grand average ERPs are shown in Fig. 1. Results indicated that the N200 was larger (i.e. more negative) on incongruent, relative to congruent, correct trials, $F(1,31) = 6.00, p < 0.05, \eta_p^2 = 0.16$. There was no effect of (un)predictability on the N200, $F(1,31) = 0.91$, *ns*. In addition, the Condition × Trial interaction was not significant, $F(1,31) = 0.03$, *ns*.[3]

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[1] To determine if the observed differences in ERPs during the predictable and unpredictable conditions was due to differences in the preceding stimulus-locked ERPs, we also examined the stimulus-locked P3. The EEG was segmented beginning 200 ms before flanker presentation and continuing for 1200 ms; the baseline was the 200 ms preceding flanker onset. The stimulus-locked P3 was scored for correct trials only where it was maximal, at Pz as the average activity between 300 and 600 ms after flanker onset. To examine potential differences in the P3 across predictable/unpredictable conditions, we conducted a Condition (Predictable vs. Unpredictable) repeated-measures ANOVA. Results indicated no main effect involving condition ($ps > 0.17$). These results suggest that the enhanced ERN in the unpredictable, relative to predictable, condition was not due to condition-related differences in the stimulus-locked P3.

[2] Follow-up analyses were conducted to determine the potential impact of age as a moderator of tone (un)predictability on RT and the ERN; we conducted separate repeated-measures analysis of covariance (ANCOVA) models with condition (predictable vs. unpredictable) and response (correct vs. error) as the within-subjects factors and mean-centered age as a continuous covariate for RT and ERPs, respectively. Behavioral results indicated that older participants responded significantly faster than younger participants, $F(1, 30) = 16.79$, $p < 0.001$, $\eta_p^2 = 0.36$, and this finding was qualified by a Response × Age interaction, $F(1, 30) = 9.14$, $p < 0.01$, $\eta_p^2 = 0.23$, which indicated that older participants were faster than their younger counterparts on errors trials, $F(1, 30) = 12.24$, $p < 0.01$, $\eta_p^2 = 0.29$, Pearson's $r = -0.54$, $p < 0.01$, but this discrepancy was even greater during correct trials, $F(1, 30) = 17.88$, $p < 0.001$, $\eta_p^2 = 0.37$, Pearson's $r = -0.61$, $p < 0.001$. ERP results revealed that age was significantly related to the CRN and ERN overall, $F(1, 30) = 8.63$, $p < 0.01$, $\eta_p^2 = 0.22$, such that older participants had smaller ERPs. However, there were no significant interactions of condition or response with age ($ps > 0.11$). For RT and ERP analyses, including age as a covariate did not change the pattern of results; all reported findings remained significant. Age was not significantly associated with self-reported anxiety ratings during the task ($ps > 0.10$).

[3] To determine if the effect of unpredictability on error processing was specific to the ERN, we also examined the temporally later error positivity (Pe), a slow positive wave that occurs following the commission of an error (Falkenstein, Hohnsbein,

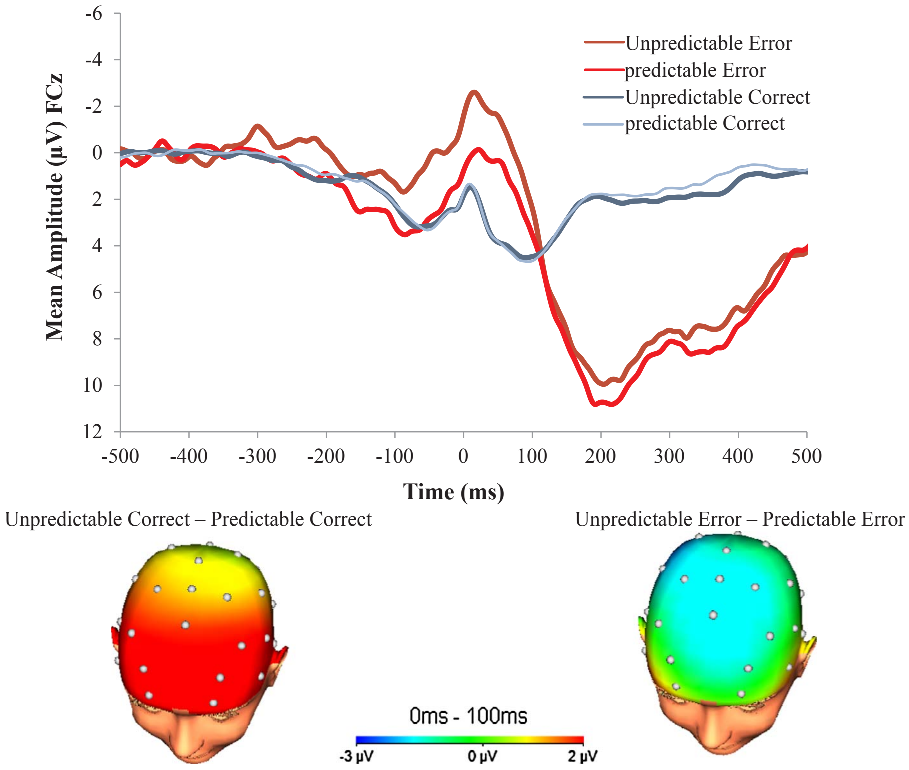

Fig. 2. ERP waveforms (top) display the average electrocortical response to error (ERN) and correct (CRN) trials while participants were exposed to predictable versus unpredictable tone sequences. The ERN was scored between 0 and 100 ms post response at FCz. Head maps (bottom) show the scalp topography of the difference between unpredictable and predictable (unpredictable minus predictable) tone sequences on the CRN (left) and ERN (right).

4. Discussion

The current study examined the impact of an unpredictable relative to predictable task-irrelevant context on the ERN in a sample of children and adolescents. Consistent with previous research (Jackson et al., 2015), participants rated the unpredictable context as more anxiety provoking. Moreover, participants were slower and made fewer errors in the unpredictable context. In this way, the unpredictable context led to both increases in anxiety and a more cautious response strategy. As hypothesized, the unpredictable context was also associated with an enhanced ERN, but this potentiation was not evident on correct trials in either the response-locked (i.e., CRN) or stimulus-locked (i.e., N200) data. These results remained significant even after controlling for behavioral differences and differences in self-reported anxiety ratings across conditions. Notably, the difference between unpredictable and predictable tones on the ERN was comparable to effects observed in young adults (Jackson et al., 2015).

The present study replicates and extends the findings of Jackson et al. (2015) by demonstrating an enhanced ERN during a task-irrelevant unpredictable context in a sample of children and adolescents. Herry et al. (2007) found that unpredictable auditory tones elicited increased amygdala activation, attentional bias toward threat, and avoidant behaviors—the current study found that unpredictable tones similarly increased the electrocortical response to errors in children and adolescents. In addition, the self-report findings replicate previous studies utilizing unpredictable and predictable auditory tone sequences (Herry et al., 2007; Jackson et al., 2015; Nelson, Kessel, Jackson, & Hajcak, 2016). Together, the electrocortical and behavioral data suggest that a task-irrelevant unpredictable tone sequence both induce anxiety, as indicated by increased self-reported anxiety ratings to unpredictable tones (compared to predictable tones), and potentiate the ERN. These data are consistent with the possibility that unpredictability elicits a state of hypervigilance to potential threat, and that hypervigilance for potential threat may be characterized by hypersensitivity to errors. This possibility is consistent with the fact that unpredictable context led both to an increased ERN and a more cautious response strategy. The unpredictable context may have made errors more aversive—a possibility that could be further tested in future studies using additional self-report and psychophysiological measures.

Cumulative evidence suggests that an unpredictable environment alone can increase defensive reactivity, as demonstrated by increased amygdala activation, behavioral bias, attention to threat, and the processing of endogenous threat (i.e., the ERN). Furthermore, when paired with the results from Jackson et al. (2015), the current study supports the notion that variation in the ERN reflects the degree to which errors are evaluated as salient or threatening (Hajcak, 2012; Hajcak & Foti, 2008; Proudfit, Inzlicht, & Mennin, 2013; Weinberg et al., 2012, 2016). Indeed, an unpredictable context is associated with decreased ability to anticipate future consequences, thereby rendering errors more dangerous. Previous research has shown that the ERN can be modulated by contextual manipulations that alter the threat value of errors, such as when errors are punished (Meyer & Gawlowska, 2017; Riesel et al., 2012), performance is evaluated (Barker et al., 2015), or errors are more ‘costly’ (Hajcak et al., 2005).

Late childhood and adolescence is a time of increased risk for the development of anxiety disorders (Beesdo, Knappe, & Pine, 2009), and previous research has suggested that environmental factors, such as a punitive parenting style, may increase anxiety and the ERN (Meyer et al., 2014). The current study demonstrated that an unpredictable context *alone* is sufficient to potentiate the neural response to errors, indicating an additional environmental factor that may impact

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(*footnote continued*)
Hoormann, & Blanke, 1991). The baseline was identified as the interval between 500 and 300 ms before the response, and the Pe was scored where it was maximal, as the average activity between 200 and 400 ms following the response at Cz. To examine the effects of tone (un)predictability on the Pe, we conducted separate repeated-measures analysis of variance (ANOVA) models with condition (predictable vs. unpredictable) and response (correct vs. error) as the within-subjects factors. Results revealed that the Pe was potentiated following errors compared to correct responses, $F(1, 31) = 77.54$, $p < 0.001$, $\eta_p^2 = 0.71$. However, there were no differences in the Pe during unpredictable compared to predictable blocks, and the Response × Condition interaction was not significant ($ps > 0.40$). These results suggest that the enhanced ERP following errors in the unpredictable, relative to predictable, condition was specific to the ERN.

trajectories of risk for anxiety. It will be important for future studies to examine the impact of individual differences in anxiety on the ERN across differing contexts and real-world indicators of environmental instability (e.g. poverty). Further, given the increased risk of developing an anxiety disorder across late childhood and adolescence (Beesdo et al., 2009), future research should examine the role of contextual manipulations of unpredictability on the ERN in individuals at increased risk for developing an anxiety disorder.

The current study conceptualized variation in the amplitude of the ERN as reflecting the threat value or salience of errors (Weinberg et al., 2012). Alternatively, the ERN has been conceptualized as an index of conflict monitoring (Yeung et al., 2004), reflecting the co-activation of error and error-correcting responses. According to the conflict monitoring hypothesis, the same processes that give rise to the ERN also produce a larger N200 on incongruent compared to congruent correct trials in the stimulus-locked ERPs. Consistent with past research, we found a larger N200 for incongruent trials (Nieuwenhuis et al., 2003; Yeung & Cohen, 2006; Yeung et al., 2004). Previous research has suggested that a potentiated N200 on high conflict trials may reflect the activation of cognitive control and subsequent response inhibition (Bartholow et al., 2005; Grutzmann et al., 2014), therefore contexts demanding the greater allocation of resources to produce a correct response should result in a larger N200. Although behavioral performance was improved in the unpredictable condition, the current study found no impact of (un)predictability on the N200. These findings suggest that the unpredictable context did not result in increased response conflict more broadly, but rather was specific to the ERN.

It is important to note that visual inspection of the ERP waveforms suggested that the ERN elicited during the unpredictable condition may have emerged before response onset. Follow-up analyses indicated that overall, the ERN was significantly more negative than the CRN beginning 50 ms before the response. Furthermore, in the predictable condition differences between the ERN and CRN emerged immediately following the response (i.e. between 0 and 50 ms). However, in the unpredictable condition the ERN was significantly more negative than the CRN beginning approximately 100–50 ms before the response. Evaluations of the stimulus-locked P300 amplitude on correct trials and the baseline correction window (-500 to -300 ms) did not reveal condition differences, suggesting that observed differences are response-locked.[1] These findings indicate that unpredictable tones made the differentiation between error and correct trials evident earlier, in addition to larger. Notably, Meyer and Gawlowska (2017) recently found that individuals with high trait anxiety demonstrate an early ERN (i.e. 50 ms before the response) when errors were punished. Therefore, in addition to magnitude, latency may be an important consideration for future investigations of contextual manipulations on the ERN.

Several limitations to the current study warrant discussion. The present study did not have sufficient power to examine potential moderation of age or other variables of interest, such as anxiety symptoms, on the relationship between (un)predictability and the ERPs. Future studies would benefit from a larger child/adolescent sample in order to examine potential developmental or psychopathological differences during this sensitive period. Subjective anxiety ratings for the predictable and unpredictable blocks were collected at the end of the task. Given that retrospective ratings of emotion may be impacted by a number of factors (e.g. experiential knowledge, episodic memory, beliefs; Robinson & Clore, 2002), future studies should consider assessing anxiety in real-time (i.e. immediately after the completion of each block). In addition, the current study did not include a condition without tones, limiting our ability to draw conclusions regarding the impact of predictability on the ERN. That is, predictable tones may have led to a *reduction* in the ERN. Future studies may consider including a condition without tones to better examine the role of predictability on the ERN across development. Given that previous research has found an association between unpredictability, amygdala activation and behavioral measures of threat bias, future studies might examine if potentiation of the ERN to unpredictability is also associated with increased amygdala activation and behavioral measures of threat bias (Herry et al., 2007).

In conclusion, the current study illustrated that an unpredictable context can increase state anxiety, improve task performance and potentiate the ERN in children and adolescents. These findings replicate and provide further support that environmental unpredictability biases individuals toward potential threat and enhances the neural processing of errors (i.e., endogenous threat). In addition, the current study adds to the literature by demonstrating that variation in ERN magnitude and latency can be modulated by environmental predictability. These findings replicate and provide additional information regarding the impact of unpredictability in threat sensitivity, and the neural processing of errors.

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