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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