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Review

A meta-analytic review of the event-related potentials (ERN and N2) in childhood and adolescence: Providing a developmental perspective on the conflict monitoring theory

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ABSTRACT

Effortful control (EC) is characterized by the ability to effectively inhibit and execute behaviors that are adaptively attuned to a specific context. Two event-related potentials (ERPs) known as the error-related negativity (ERN) and N2 are thought to measure EC, but the nature and function of these neural markers are not well understood in children. The present study provides the first comprehensive meta-analytic review of mean-level amplitude differences in the ERN and N2 from childhood to adolescence to quantify developmental changes in their magnitudes. I propose a developmental perspective on the conflict monitoring theory that facilitates evaluation of the claim that the ERN and N2 are measures of EC. As children's ability to correct their errors improves with age, increased post-response processing generated by the larger discrepancy between error and correct trials is expected to be characterized by increases in the ERN. As children's ability to ignore distracting information improves with age, decreased processing of irrelevant information is expected to be characterized by decreases in the N2. Meta-analysis of ERN studies ($k = 26$; $N = 1, 519$) and N2 studies ($k = 19$; $N = 1, 095$) indicated a 0.02 µV increase in ERN amplitude per month and 0.02 µV reduction per month in N2 amplitude across childhood and adolescence. These results are consistent with the hypotheses based on the proposed developmental account of the conflict monitoring theory. Findings suggest that there may be dissociable age effects of the ERN and N2 that are related to the development of EC.

Effortful control (EC) has historically been a construct of interest in the temperament literature and theorized to involve both attentional and inhibitory control skills, which permit the effortful inhibition or activation of adaptive behaviors in a given context (Rothbart, Sheese, & Posner, 2007). Given its importance in the development of a child's social-emotional, psychological, and academic functioning (Rueda, Checa, & Rothbart, 2010), and in predicting major life outcomes in adulthood (e.g., Caspi, Moffitt, Newman, & Silva, 1996; Moffitt et al., 2011), early EC and related skills have interested scientists in different areas of research. Two lines of research that have garnered the most evidence related to understanding EC development include the temperament and developmental cognitive neuroscience literatures. The main focus of the manuscript is to understand the functional significance of two putatively related neural measures that are thought to measure EC skills in children. I will test the claim that two neural measures commonly used in the cognitive neuroscience field known as the error-related negativity (ERN) and N2 are measures of EC. I propose the first developmental application of the conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Yeung, Botvinick, & Cohen, 2004) to best explain the nature and function of the ERN and N2, and will test hypotheses using qualitative review and a comprehensive meta-analysis of the current literatures.

Researchers have identified the ERN and N2 as two event-related potentials (ERPs) believed to index EC skills. The ERN follows

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the commission of an error whereas the N2 precedes a correct response following stimulus presentation and is enhanced on trials involving more conflict. Evidence from source localization and neuroimaging studies suggest that the ERN and N2 are generated from the anterior cingulate cortex (ACC; e.g., Gehring, Liu, Orr, & Carp, 2012; van Veen & Carter, 2002; van Veen, Cohen, Botvinick, Stenger, & Carter, 2001), providing support that both ERPs may index the activity of neural networks related to EC, which is more commonly referred to as the "executive attention network" in the developmental cognitive neuroscience literature.

The ERN was initially identified in adults appearing as a negative deflection at frontocentral electrodes within approximately 100 ms of an error, and identified as a robust marker of processes related to conflict monitoring, error detection, and error correction (Gehring et al., 2012; Yeung & Summerfield, 2012). The ERN effect is assessed by comparing its amplitude following an error to the amplitude following a correct response. The ΔERN refers to the numerical difference between the ERN and correct-related negativity (CRN) and is calculated by subtracting the CRN from the ERN (ERN − CRN = ΔERN). Unlike the ERN, the N2 is a negativity elicited prior to a response and approximately 300 ms following stimulus presentation. The N2 is maximal at frontocentral sites and its amplitude is determined by the processing of irrelevant or distracting information (Yeung & Cohen, 2006). The N2 is typically larger or more negative on correct trials involving greater conflict such as successfully inhibiting a pre-potent response (Carter & Van Veen, 2007; van Veen & Carter, 2002) or on an incongruent versus congruent trial. The ΔN2 refers to the numerical difference between the N2 on a high conflict trial and low conflict trial and is calculated by subtracting the N2 on a high conflict trial from the N2 on a low conflict trial. A more detailed description of the ERP components and indices is included in Appendix Table A.1.

Neurocognitive theories of error and conflict monitoring

One of the major challenges to understanding the functional significance of the ERN and N2 is that there is no theoretical model of these processes that takes into account basic behavioral and neural changes associated with EC development. Several theoretical and computational models have been proposed to explain the functional significance of the ERN and N2 in adults, and these models are still heavily debated among researchers.

Mismatch theory

Initial theories of the N2 emphasized novelty and mismatch as determinants of the N2 amplitude. Proponents of the N2 mismatch interpretation have proposed that the N2 represents the detection of or orientation toward novelty (Courchesne, Hillyard, & Galambos, 1975). The interpretation follows that the difference between experiencing long-term exposure to recurring visual stimuli compared to exposure to an uncommon or novel stimuli produces a deviation from the expected perceptual template, thus eliciting the N2. Falkenstein's mismatch theory was among the first proposed to explain the ERN (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991). The theory posits that the ERN reflects activity of an error detect system sensitive to the mismatch between the actual response (the error) and correct response. The theory assumes that the mismatch between error and correct elicits the ERN, which implies that correct trials should not elicit any negativity. However, the CRN has been reliably produced following correct responses (Vidal, Burle, Bonnet, Grapperon, & Hasbroucq, 2003). Some have suggested that mismatch detection may occur on correct trials, but to a lesser degree than on errors (Coles, Scheffers, & Holroyd, 2001), while others have proposed an alternative explanation based on reinforcement learning theory (Holroyd & Coles, 2002).

Reinforcement learning theory

Reinforcement learning theory assumes that actions followed by positive feelings or outcomes are likely to reoccur in the future, whereas actions followed by negative outcomes are less likely to be generated again. Holroyd and Coles (2002) proposed that the ERN is generated by a negative reinforcement learning signal sent to the frontal cortex, and that this error detection information is used to execute more adaptive behaviors to improve performance. The ERN is proposed to act as a signal that trains the ACC to more efficiently control motor activity, and reinforcement learning theory posits that this process is mediated by the mesencephalic dopamine system. Longstanding evidence from the neuroscience literature has suggested that the mesencephalic dopamine system is important to the communication between the frontal cortex and basal ganglia that allows for motor control and expression of learned or reinforced responses. Specifically, animal studies in which spike activity of mesencephalic dopamine cells were recorded suggest that increases in phasic dopamine occurs in anticipation of a reward (Schultz, Tremblay, & Hollerman, 1998). Mesencephalic dopamine neurons are sensitive to changes in a predicted event such that increases in phasic dopamine occur when an event is better than expected and decreases when an event is worse than predicted, as with an error. Assuming that learning is dependent on an unpredicted event and subsequently adjusting behavior, researchers have suggested that the phasic mesencephalic dopamine activity functions as an error signal. Reinforcement learning theory proposes that the ERN is the primary link between error processing associated with the ACC and reinforcement learning associated with the mesencephalic dopamine system.

Holroyd and Coles (2002) tested this theory by comparing predictions of the ERN and behavior from computational simulations and results from human experiments. Overall, simulated and actual experimental data demonstrated high correspondence, supporting the authors' proposal that the ERN occurs when the mesencephalic dopamine system propagates a negative reinforcement learning signal to the ACC. The ACC uses this signal to adjust behavior and performance to meet task demands.

Conflict monitoring theory

Conflict monitoring refers to detecting information discrepancies (e.g., between error and correct responses) and subsequent processes to recruit EC skills to minimize future conflict. The notion that there exists a system responsible for monitoring conflicts has roots in information-processing theories (Berlyne, 1960). Researchers hypothesized that conflict could be used as a means to help regulate perceptual selection (also referred to as cognitive control in this literature base). Botvinick et al. (2001) used these theoretical considerations in proposing their conflict monitoring hypothesis as it relates to both the evaluation of information and subsequent regulation of behaviors based on such information. In contrast to reinforcement learning theory, the conflict monitoring theory posits that ACC activity arises from the detection of conflict during information processing, which signals the need for increased EC to reduce conflict in later performance. This theory assumes that the ERN and N2 are generated from a similar neural source and elicited when there are several possible response options that compete for control over the executed action (Botvinick et al., 2001; Yeung et al., 2004).

According to the conflict monitoring theory, the ERN does not represent explicit error detection as posited by the mismatch theory, but rather the ERN reflects post-response conflict on error trials while the N2 represents pre-response conflict on correct trials. The post-response conflict on errors occurs with continuing to process the stimulus that triggers activation of the correct response following the error, and thus conflict with the error just committed. Similarly, the pre-response conflict occurs in the period of time prior to making a correct response. The conflict monitoring theory thus supports a unified account of the ERN and N2, suggesting that they may share similar responsibilities in supporting EC. This hypothesis is further supported by fMRI findings (Kiehl, Liddle, & Hopfinger, 2000; Menon, Adleman, White, Glover, & Reiss, 2001) indicating a common region of activation in the caudal ACC on error and correct conflict trials. The conflict monitoring theory also posits that the ERN and N2 may be dissociable. Yeung and Cohen (2006) have used a computational model to address dissociable effects of cognitive deficits on the ERN and N2 that could apply to developmental changes in the ERN and N2 related to EC skills. This model proposes that while the ERN and N2 may share a similar neural generator (the ACC), each component is sensitive to different aspects of monitoring conflict and task processing. Researchers acknowledge that conflict occurs at numerous levels of information processing, including perceptual representation, stimulus classification, and response selection (Botvinick, Cohen, & Carter, 2004). Studies suggest that ACC activity relevant to the ERN and N2 is strongest at the level of response selection (e.g., Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Milham, Banich, & Barad, 2003) which is consistent with research outlining the robust connectivity between motor areas and the ACC (Paus, 2001; Picard & Strick, 1996).

More specifically, the theory posits that the ERN amplitude is determined by the processing of relevant stimulus information whereas the N2 amplitude is determined by processing of distracting information (Botvinick et al., 2004; Yeung & Cohen, 2006). As a result, dissociation observed between the ERN and N2 (i.e., Ridderinkhof et al., 2002; Swick & Turken, 2002) may be explained by the complementary effects that EC deficits have on processing of target/relevant versus distracting/irrelevant stimuli. The hypotheses follow that impairments in target stimuli processing tend to lead to a decrease in the ERN amplitude because the strength of post-response processing is reduced and error-correction activity is therefore reduced as well. If impairments in target stimuli processing co-occur with increases in processing irrelevant stimuli, then increases in the N2 amplitude are observed because interference from distracting information on high conflict trials is also increased. Indeed, Yeung and Cohen (2006) simulate these predictions using a computational model, which yields results consistent with the posited theory.

Developmental perspective on the conflict monitoring theory

Given that the developmental literature on the functional significance of conflict monitoring ERPs is sparse, there are no theoretical accounts of the ERN and N2 that make specific predictions in the context of basic development and maturation of EC skills. However, the conflict monitoring theory provides a thorough account of the ERN and N2 that may be more easily adapted to account for behavioral and neural maturation related to EC development. Specifically, the proposal that the ERN and N2 may be dissociable based on the notion that the ERN reflects processing of target/relevant stimuli and the N2 reflects processing of distracting/irrelevant stimuli (Yeung & Cohen, 2006) provides a suitable framework for developmental predictions.

The model accounts for findings in studies reporting dissociations between the ERN and N2 in adults; one that reported a reduced ERN and unchanged N2 upon consumption of alcohol (Ridderinkhof et al., 2002), and another that reported a reduced ERN and increased N2 in a patient with left-ACC lesion (Swick & Turken, 2002). Yeung and Cohen (2006) describe a computerized model of performance on the flanker task to simulate the role of the ACC in conflict monitoring (for full computational and implementation details see Yeung et al., 2004). The flanker paradigm (Eriksen & Eriksen, 1974) is a commonly used computer task to elicit the ERN. Five arrows (or developmentally appropriate stimuli such as fish) are presented with congruent (e.g., > > > >) and incongruent (e.g., > > < > >) conditions. Participants are instructed to press one of two buttons that corresponds to the direction of the central target stimulus while ignoring the flanking arrows, and to respond as quickly and accurately as possible. Responding to incongruent trials is more difficult than congruent trials, and therefore, incongruent trials are also referred to as “high conflict” trials. Results from a computerized simulation (Yeung et al., 2004) supported hypotheses that the ERN amplitude is determined by processing of the target stimuli whereas the N2 amplitude is dependent on processing of distracting or irrelevant information. This is consistent with the notion that the ERN is produced when there is post-response conflict between the erroneous response and the correcting response. Error corrections reflect continued processing of the target stimulus after the error, and the greater the discrepancy between early processing of the stimuli and the correcting response, then the larger the ERN amplitude.

The flanker task has been used to elicit the N2, but a more commonly used paradigm is the go/no-go task. In the go/no-go task, participants are asked to produce speeded and accurate responses to one kind of stimuli ("go" or "low conflict" trial), but to inhibit their responses to another kind of stimuli ("no-go" or "high conflict" trial). The N2 amplitude represents the discrepancy between high conflict and low conflict trials with correct responses only. Therefore, any continued stimulus processing post-response only reinforces the correct response and no conflict is observed after response. Instead, conflict is observed immediately prior to the response when the distracter or novel stimulus activates a different neural response from target stimuli, resulting in high conflict and large N2 amplitude.

There are several predictions that can be drawn about the development of the ERN and N2 based on the conflict monitoring theory. The literature suggests the possibility of multiple developmental trajectories of EC skills (i.e., Allan & Lonigan, 2014; Blair & Raver, 2012; Montroy, Bowles, Skibbe, McClelland, & Morrison, 2016). In general, EC skills improve with age (e.g., Gerstadt, Hong, & Diamond, 1994; Jacques & Zelazo, 2001; Olson, Schilling, & Bates, 1999; Rothbart & Rueda, 2005). However, its facets (attentional and inhibitory control) may differ in trajectory such that skills specific to regulating affect exhibit a "J-shaped" curve (decreasing in early adolescence when inhibitory control is more problematic) whereas skills specific to regulating attention and cognition exhibit a linear trajectory over development (see Smith, Xiao, & Bechara, 2011).

As children improve their ability to engage EC skills, they also improve in their ability to "correct" their errors, and this error-correcting activity is reflected in a larger ERN. Moreover, children should increase in their ability to filter distracting information and/or inhibit their attention toward irrelevant stimuli. This improvement may result in decreased processing of irrelevant stimuli, which would be reflected in a reduced N2 in affectively-neutral contexts. Therefore, according to the conflict monitoring theory, the ERN should increase linearly with age and N2 decrease linearly with age between childhood and adolescence. These hypotheses are outlined in Appendix Table B.1.

Measurement traditions in research on effortful control

There is consensus among researchers across temperament and developmental cognitive neuroscience literatures that EC skills are central to understanding both typical and atypical developmental trajectories; however, there is considerable confusion over how to define, label, and measure this construct. As a result, research on EC suffers from jangle fallacies (Block, 1996; Duckworth & Kern, 2011; Kelley, 1927) that are worth acknowledging prior to reviewing the current literature base. Jingle fallacies refer to instances when the same term is used to describe different underlying constructs. For example, "self-regulation" may be used to describe the ability to inhibit impulses or to shift attention flexibly. Jangle fallacies refer to instances when different terms are used to describe similar constructs (e.g., effortful control, executive functioning). The tendency for each research tradition to prefer certain terms (i.e., temperament literature favoring "effortful control" and developmental cognitive neuroscience favoring "executive functioning") makes it difficult for integration of these literatures. In an effort to reduce jangle fallacies, I will hereafter use the term "effortful control" (EC) to refer to the set of skills responsible for controlling dominant responses in favor of selecting less dominant ones. In an effort to reduce jingle fallacies, the term "attentional control" will be used throughout the review when referring to the ability to effectively allocate attention in a flexible manner and regulate attention given certain task demands. The term "inhibitory control" will refer to the ability to regulate and resist pre-potent behavioral impulses.

Contemporary models of temperament propose a multidimensional structure from early childhood through adolescence, with primary dimensions centering on variation in expressive or motivational aspects of positive and negative emotions, and in dimensions related to EC (e.g., De Pauw & Mervielde, 2010; Goldsmith and Alansky, 1987; Halverson et al., 2003; Rothbart, Ahadi, Hershey, & Fisher, 2001). Examinations of parent-reports, teacher-reports, and experimenter ratings of child temperament (e.g., De Pauw, Mervidelde, & Leeuwen, 2009; Presley & Martin, 1994; Vroman, Lo, & Durbin, 2014) reliably uncover at least three higher order factors: positive emotionality, negative emotionality, and EC. Variation in positive emotionality emerges first in infancy, when infants reveal clear differences in approach, activity level, and positive affect. Later in the first year of life, variation in fear emerges alongside inhibition of approach tendencies. Fear acts as one the earliest internal and inhibitory control mechanisms, followed by the emergence of EC in the second and third year of life when children can better engage in voluntary attentional control and thus begin to regulate their impulses and reactive emotions.

EC in children has primarily been examined using three methods: (1) self- and/or informant-report; (2) naturalistic observation or behavioral assessment, and (3) cognitive, computer-based tasks. Only recently have researchers begun to discuss and explicitly integrate these different levels of analysis to study the development of EC (Posner, Rothbart, Sheese, & Voelker, 2014; Rothbart et al., 2007; Rueda, Posner, & Rothbart, 2005). This recent effort toward integration is grounded in the basic connections between emotion and cognition that are thought to be central to EC (Bush, Luu, & Posner, 2000; Rothbart, 2004; Rueda et al., 2005). Specifically, evidence from the temperament literature suggests that variation in emotional reactivity and regulation arises from early differences in basic affective and cognitive systems (Rothbart, 2004). The developmental cognitive neuroscience literature has provided evidence that successful mastery of EC skills is dependent on the integration of brain processes underlying affective-cognitive neural systems (e.g., Casey, Jones, & Hare, 2008; Somerville & Casey, 2011). Empirical studies of EC typically use only a single methodology, with questionnaire methods dominating the temperament literature and tests of cognitive function dominating the developmental cognitive neuroscience literature. Each of these methods may lend itself more readily to the assessment of either more affectively salient or cognitively relevant aspects of EC. For example, even though commonplace measures of "hot" EC are used to elicit emotionally significant events in the developmental cognitive neuroscience literature, the typical administration via computer may reduce the degree to which the child is motivated to engage compared to a behavioral task such as delay of gratification. Few studies have effectively integrated lines of research method from the temperament and neurocognitive traditions to capture a more nuanced and multi-faceted understanding of EC and its development. Therefore, a major goal of developmental researchers is to use empirical approaches that assess both affective and cognitive components of EC.

Developmental cognitive neuroscience methods provide a promising direction for this area of research. Specifically, neurophysiological measures allow for a noninvasive measurement of brain activity with high temporal resolution, permitting researchers to study how reactive and regulatory processes may work together to meet specific task demands. Moreover, the use of simple tasks with identifiable demands on EC processes (relative to the greater complexity of naturally observed environments) is advantageous for elucidating which EC components are being measured.

Study aims and hypotheses

The aims of the current review are to (1) examine evidence for the claim that the ERN and N2 are measures of EC and (2) to draw upon this evidence to inform a developmental perspective on the conflict monitoring theory that best explains the nature and function of the ERN and N2 in childhood and adolescence. I hypothesize that as children improve their EC skills, their ability to "correct" their errors and ability to focus on target stimuli should increase, which will be reflected in a larger or more negative ERN. Moreover, children should increase in their ability to filter distracting information, leading to decreased processing of irrelevant or distracting stimuli, which I hypothesize will be reflected in a reduced N2 in affectively-neutral contexts.

The current review will test these hypotheses by first conducting the first comprehensive meta-analytic review of providing a critical review of mean-level amplitude differences in the ERN and N2 from early childhood to adolescence. Meta-analytic procedures provide a useful method to quantify age-related change in the ERN and N2; the results of this analysis can then inform an evaluation of the extent to which mean amplitude changes in the ERN and N2 are consistent with expected increases in EC skills during this developmental period (Rothbart & Rueda, 2005). To complement this quantitative analysis, existing studies examining the ERN and N2 as they relate to EC skills will be summarized in a qualitative review. Finally, limitations of this research area and implications for future research will be discussed.

Meta-analysis of age-related associations of the ERN and N2

Current findings suggest that the ERN increases with age, but very few studies have been conducted that focus on elucidating basic developmental changes (Davies, Segalowitz, & Gavin, 2004). Therefore, despite the proliferation of studies examining the ERN in the last decade, we have a very limited understanding of basic developmental changes in the ERN across childhood and adolescence. The relationship between the N2 and age are equivocal. A majority of studies report that N2 decreases with age, reflecting a reduced need for either the detection of or signaling for increased EC. However, there are several studies reporting no differences between children and adolescents and increases in the N2 with age (Cragg, Fox, Nation, Reid, & Anderson, 2009). Reported increases in N2 with age are suggested to reflect better conflict detection and EC skills. Rather than a review of individual findings across different age groups, a meta-analysis was conducted to test the hypotheses that ERN increases with age and N2 decreases with age.

Method

Literature search

Published studies examining the ERN in child and adolescent populations were initially identified using Google Scholar and Elsevier's Scopus databases using the terms "children", "adolescent", "development", "performance monitoring", "error-related negativity", and "ERN". Searches were crossed using children/adolescent/development with performance monitoring with error-related negativity/ERN. Additional studies were identified using reference sections of empirical and review articles obtained from database searches. Published studies examining the N2 in child and adolescent populations were initially identified using Google Scholar and Elsevier's Scopus databases using the terms "children", "adolescent", "development", "conflict monitoring", "inhibition", "N2" and "N200". Searches were crossed using children/adolescent/development with conflict monitoring/inhibition with N2/N200. Additional studies were identified using reference sections of empirical and review articles obtained from database searches.

Inclusion/Exclusion criteria

Appendix Fig. C.1 depicts the study selection process used for the ERN meta-analysis. The following criteria were used to include/exclude studies from the meta-analysis: (1) the study was published in the English language prior to February 2015; (2) the study included either children or adolescents who were 18 years old or younger; (3) the study measured the ERN; (4) the study reported sufficient information to calculate the ERN mean amplitude and standard deviation. For studies that collected the ERN but did not report enough information to calculate the ERN mean amplitude and standard deviation, the corresponding author was emailed a request for the necessary data to satisfy this inclusion criterion. If a sample was reported on twice in multiple publications, the study reporting the largest sample size was used and the others excluded. These criteria resulted in 26 studies (see Appendix Table D.1) that consisted of 51 independent samples for the ERN ($N = 1{,}519$; $M = 9.77$ years, $SD = 2.25$ years). Of these studies, 10 (38%) studies included children under 8 years of age. Half of the selected ERN studies used clinical or at-risk samples ($k = 13$; 50%).

Appendix Fig. C.2 depicts the study selection process used for the N2 meta-analysis. The following criteria were used to include/exclude studies from the meta-analysis: (1) the study was published in the English language prior to February 2015; (2) the study included either children or adolescents who were 18 years old or younger; (3) the study measured the N2; (4) the study reported sufficient information to calculate the N2 amplitude and standard deviation on high conflict trials. For studies that collected the N2 but did not report enough information to calculate the N2 mean amplitude and standard deviation, the corresponding author was emailed a request for the necessary data to satisfy this inclusion criterion. If a sample was reported on twice in multiple publications, the study reporting the largest sample size was used and the others excluded. These criteria resulted in 19 studies (see Appendix Table D.2) that consisted of 45 independent samples for the N2 (N = 1095; *M* = 8.04 years, *SD* = 2.79 years). Of these studies, 15 (79%) out of the 19 studies included children under 8 years of age. Approximately 37% of N2 studies used for analysis used clinical or at-risk samples (k = 7).

Analytic procedures

Ages of samples were determined by reported mean age and transformed from years to months. Since very few studies reported the correlation between age and the ERN, the means and standard deviations of the ERN were recorded for each study and age was tested as a predictor of ERN amplitude. Few studies included the means and standard deviations of the CRN, and therefore the difference between the ERN and CRN (ERN effect) could not be evaluated. Instead, the mean amplitude of the ERN, itself, was subjected to meta-analytic procedures. Analyses were also conducted to evaluate the extent to which the ERN amplitude differed based on sex, task paradigm, and diagnosis. When interpreting the results of the present analyses, it is important to note that the ERN is a negative deflection; thus, a more negative ERN indicates its amplitude is larger whereas a less negative ERN indicates its amplitude is smaller. Coding procedures of variables and ERN amplitude are described in Appendix E. Interrater reliability for all categorical variables ($\kappa > 0.85$) and dimensional was high (ICC = 0.88). Meta-analytic computations were conducted using Comprehensive Meta-Analysis Software Version 2 (Borenstein, Hedges, Higgins, & Rothstein, 2005).

Similar to ERN studies, very few studies reported the correlation between age and the N2. Therefore, means and standard deviations of the N2 were recorded for each study and age (in months) was tested as a predictor of N2 amplitude. Importantly, few studies provided descriptive statistics for the N2 amplitude on both high and low trials, and N2 congruence effects could not be evaluated. However, a majority of studies provided the descriptive statistics for the N2 amplitude on high conflict trials. Therefore, the high conflict N2 was subjected to meta-analytic procedures. When interpreting the results of the present analyses, it is important to note that, like the ERN, the N2 is a negative deflection; thus, more negative values indicate a larger amplitude and less negative values indicate a smaller amplitude. Interrater reliability for all categorical variables ($\kappa > 0.82$) and dimensional variables was high (ICC = 0.98). Meta-analytic computations were also conducted using Comprehensive Meta-Analysis Software Version 2 (Borenstein et al., 2005). Studies that did not meet inclusion criteria are incorporated into relevant qualitative review sections of the ERN and N2 below.

ERN results

A majority of studies examining the ERN in children and adolescents (42 studies) have been conducted in children above the age of 8 (87% of studies). Of the early childhood studies which included children under the age of 8 (13%), only 45% of these studies included children who were 6 years of age or younger. Overall, the average age of samples across all studies was 11.1 years (range = 3.3–17.05 years). Approximately half of these studies examine the ERN in community samples while the remaining half examine the ERN in clinical/special populations and healthy control groups.

The meta-analysis indicated that approximately 93% of between-study variability was not solely attributable to sampling error (Q (50) = 719.09, $I^2 = 93.41$, 95% CI [91.62, 94.23], $p < .001$). The random-effects model results are reported given that this model permits a more conservative estimate in such situations and allows for studies to be weighted more equally (Cumming, 2012). Across the 51 samples ($n = 1519$) included in the analysis, the ERN was significantly more negative relative to zero ($M = -4.00$, $SE = 0.41$, 95% CI [−4.81, −3.19] $Z = -9.69$, $p < .001$). The size of the ERN effect could not be tested meta-analytically because a majority of included studies did not provide sufficient information for correct trial CRN calculation.

Age

Consistent with hypotheses, age significantly predicted the ERN such that a 1-month increase in age was associated with a 0.02 μV increase in the ERN ($Q_{\text{model}}(1, 50) = 47.63$, slope = −0.02, intercept = 0.14, $p < .001$).[1] A scatterplot of the relationship between age and ERN is depicted in Fig. 1.

Sex

Proportion of male participants predicted the ERN such that increases in the proportion of males was associated with increases in the ERN ($Q_{\text{model}}(1, 50) = 70.23$, slope = −0.04, int = −0.16, $p < .001$). This finding is consistent with studies in adults that suggest larger ERN amplitudes in males compared to females (Fisher et al., 2016; Larson, South, & Clayson, 2011).

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[1] Exploratory analyses were conducted to examine whether the ERN-age relationship was moderated by population type (i.e., community versus clinical groups). It should be noted that given the limited number of studies that met inclusion criteria for the meta-analytic portion of this review, theses exploratory analyses were underpowered. The meta-regression analysis for ERN studies conducted with community samples indicated that approximately 94% of between-study variability was not solely attributable to sampling error ($Q(36) = 630.95$, $I^2 = 94.29$, $p < .001$). Across the 37 samples included in the analysis, the ERN was significantly more negative relative to zero ($M = -4.18$, $SE = 0.51$, 95% CI [−5.18, −3.18] $Z = -8.20$, $p < .001$). Age significantly predicted the ERN such that a 1-month increase in age was associated with a 0.02 V increase in the ERN ($Q_{\text{model}}(1, 36) = 56.04$, slope = −0.02, intercept = 0.56, $p < .001$). For ERN studies conducted with clinical samples, results indicated that approximately 90% of between-study variability was not solely attributable to sample error ($Q(17) = 172.18$, $I^2 = 90.13$, $p < .001$). Across the 18 samples included in the analysis, the ERN was significantly more negative relative to zero ($M = -3.44$, $SE = 0.69$, 95% CI [−4.78, −2.10] $Z = -5.03$, $p < .001$). In contrast to ERN studies conducted with community samples, a 1-month increase in age was associated with a 0.03 V reduction in the ERN in clinical samples ($Q_{\text{model}}(1, 17) = 19.77$, slope = 0.03, intercept = −6.60, $p < .001$).

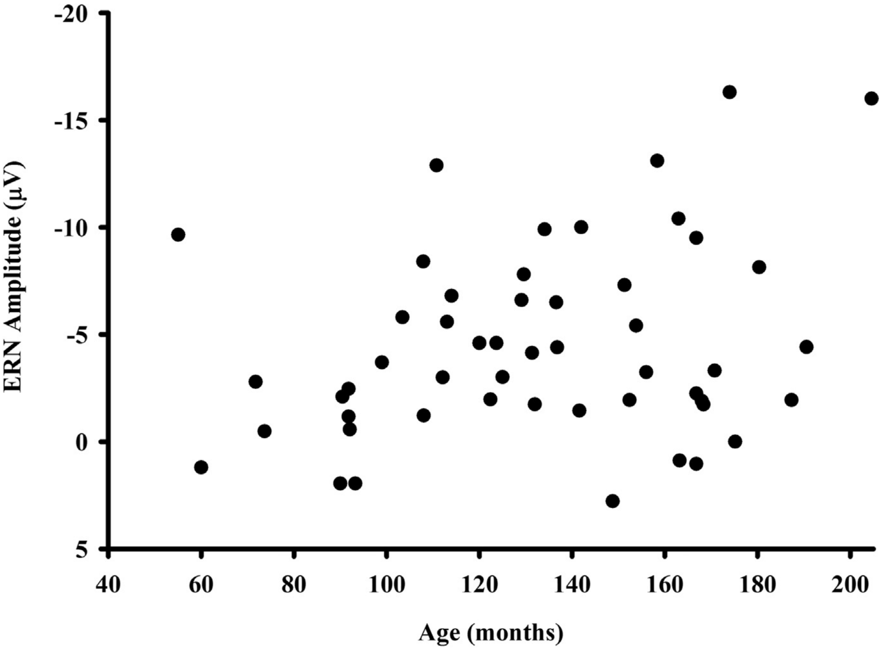

Fig. 1. Scatterplot of the association between age in months and ERN amplitude. Negative amplitudes are plotted up.

Task paradigm

With respect to task paradigm, a total of eight different paradigms were used across the included studies. Appendix Table F.1 includes a detailed description of task paradigms. Approximately 46% of the studies (k = 12) used an arrow flanker task, and the next most commonly used task was a go/no-go task (k = 4). Task types that were only used in one study were grouped into an "other category". Overall, the ERN amplitude did not differ by task type ($Q(4) = 6.14, p = 0.19$). Additional comparisons were conducted to test the effects of specific tasks on the ERN. There were four different Flanker tasks that differed based on stimuli (i.e., arrow, letter, fish, and robot figures). Results suggested that the ERN was not significantly different between these different Flanker tasks ($Q(3) = 1.17, p = 0.76$). In contrast, the ERN was significantly more negative when assessed using the arrow flanker ($M = -4.56$, $SE = 0.63$) compared to the go/no-go task ($M = -1.40$, $SE = 1.36$), suggesting that there may be systematic differences in the ERN based on task type.

Diagnosis

Within clinical samples, the ERN was significantly reduced in participants with internalizing problems ($M = -1.60$, $SE = 1.11$) compared to those with externalizing problems ($M = -5.12$, $SE = 0.84$; $Q(1) = 10.2$, $p = .001$). The ERN did not differ between externalizing and non-clinical populations ($M = -4.15$, $SE = 0.54$), but there was a trend-level effect of a reduced ERN in internalizing compared to non-clinical populations ($Q(1) = 3.66$, $p = 0.06$). This latter result will be discussed further in sections to follow.

N2 results

Similar to studies examining the ERN, a majority of studies investigating N2 in children and adolescents (52 studies) have been conducted in children older than 8 years of age (83% of studies). Overall, the average age of samples across all studies was 10.04 years (range = 3.62–16.53 years). Approximately 56% of these studies included in the qualitative synthesis examine the N2 in clinical populations, and the remaining studies examine the N2 in community samples.

The meta-analysis indicated that approximately 93% of between-study variability was not solely attributable to sampling error ($Q(45) = 598.62$, $I^2 = 92.65$, 95% CI [90.80, 93.85], $p < .001$). Therefore, the random-effects model results are reported given that this model permits a more conservative estimate in such situations and allows for studies to be weighted more equally (Cumming, 2012). Across the 45 samples (N = 1095) included in the analysis, high conflict N2 was significantly more negative relative to zero ($M = -5.37$, $SE = 0.44$, 95% CI [-6.23, -4.51], $Z = -12.25$, $p < .001$). The size of the N2 effect could not be tested meta-analytically since a majority of studies did not provide sufficient information for low-conflict N2 calculation.

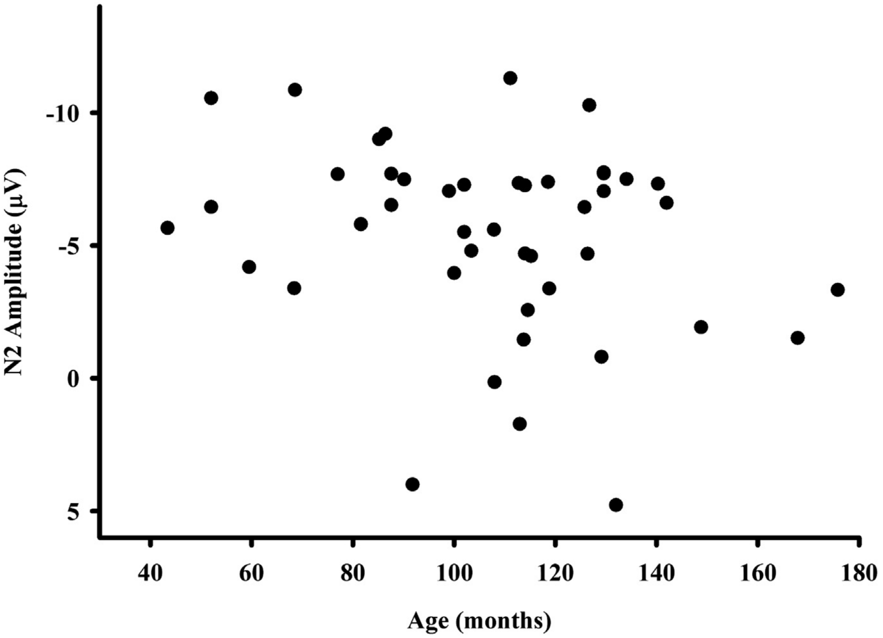

Fig. 2. Scatterplot of the association between age in months and N2 amplitude on high conflict trials. Negative amplitudes are plotted up.

Age

Consistent with hypotheses, age significantly predicted the high conflict N2 such that a 1-month increase in age was associated with a 0.02 μV reduction in the high conflict N2 ($Q_{\text{model}}(1, 44) = 32.15$, slope = 0.02, intercept = −7.22, $p < .001$).[2] A scatterplot of the relationship between age and high conflict N2 amplitude is depicted in Fig. 2.

Sex

The proportion of male participants did not explain significant variation in the high conflict N2 ($Q_{\text{model}}(1, 39) = 0.30$, slope < 0.01, intercept = −5.10, $p = 0.58$).

Task paradigm

With respect to task paradigm, a total of eight different paradigms were used across the included studies. Approximately 26% of the studies (n = 3) used a fish flanker task, and the next most commonly used tasks across studies were the arrow flanker (n = 3) and go/no-go task (n = 3). Unlike the ERN, N2 amplitude differed as a function of task type ($Q(6) = 26.40, p < .001$). The N2 was most negative on the stroop task ($M = -7.13$, $SE = 0.89$). However, given that some tasks were only used in one study, it is possible that this test of effect overestimates the difference in the high conflict N2 between task types (arrow flanker: $M = -2.66$, $SE = 0.86$; CPT: $M = -6.01$, $SE = 0.90$; DCCS: $M = -5.66$, $SE = 2.54$; fish flanker: $M = -7.08$, $SE = 0.91$; go/no-go: $M = -5.27$, $SE = 1.14$; stop signal: $M = 0.81$, $SE = 2.11$).

Diagnosis

The high conflict N2 was not significantly different between externalizing ($M = -5.30$, $SE = 0.76$) and non-clinical populations ($M = -5.41$, $SE = 0.55$). None of the selected N2 studies for quantitative analysis included internalizing populations.

Interim discussion

Meta-analysis results supported developmental hypotheses of the ERN and N2 based on the conflict monitoring theory. From the

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[2] Exploratory analyses were conducted to examine whether the N2-age relationship was moderated by population type (i.e., community versus clinical groups). Similar to the exploratory analyses conducted for the ERN studies, the following results for the N2 studies are underpowered due to the limited number of studies that met inclusion criteria. The meta-regression analysis for N2 studies conducted with community samples indicated that approximately 94% of between-study variability was not solely attributable to sampling error ($Q(29) = 521.92$, $I^2 = 94.44$, $p < .001$). Across the 30 samples included in the analysis, the N2 was significantly more negative relative to zero ($M = -5.41$, $SE = 0.60$, 95% CI [−6.58, −4.23] $Z = -9.04$, $p < .001$). Age significantly predicted the N2 such that a 1-month increase in age was associated with a 0.03 V reduction in the N2 ($Q_{\text{model}}(1, 29) = 40.14$, slope = 0.03, intercept = −7.42, $p < .001$). For N2 studies conducted with clinical samples, results indicated that approximately 80% of between-study variability was not solely attributable to sample error ($Q(14) = 71.12$, , $I^2 = 80.32$, $p < .001$). Across the 15 samples included in the analysis, the N2 was significantly more negative relative to zero ($M = -5.31$, $SE = 0.52$, 95% CI [−6.32, −4.30] $Z = -10.29$, $p < .001$). In contrast to N2 studies conducted with community samples, age did not predict the N2 in clinical samples ($Q_{\text{model}}(1, 14) = 0.004$, slope = 0.001, intercept = −5.44, $p = 0.95$).

26 studies included in the analysis testing age as a predictor of ERN amplitude, results suggested that the ERN increases 0.02 µV with every 1-month increase in age. From the 19 studies included in the analysis testing age as a predictor of N2 amplitudes on high conflict trials, results suggested that the N2 decreases 0.02 µV with every 1-month increase in age. Overall, these findings corroborate research suggesting that the ERN increases from childhood to adolescence, which is assumed to reflect improvement in EC skills and maturation of frontal lobe regions that occurs with age. In terms of the N2, existing evidence suggests that the relationship between N2 and age are equivocal. Consistent with the present meta-analysis, a majority of studies report that the N2 decreases with age, reflecting a reduced need for either the detection of or signaling for increased EC. However, there are several studies reporting no differences between children and adolescents and others still showing increases in the N2 with age (Cragg et al., 2009). Reported increases in N2 with age are suggested to reflect better conflict detection and EC skills.

The present findings support the proposed hypotheses outlined by the developmental account of the conflict monitoring theory. Specifically, as children's ability to correct their errors increases, the discrepancy between error and correct trials when continued processing post-response occurs is larger, and a larger ERN is generated. The N2 amplitude on high conflict trials decreased with age, which is consistent with the notion that as children's ability to ignore distracting information increases, there is decreased processing of irrelevant stimuli. The diminished conflict between irrelevant and target stimuli leads to a reduced N2 on high conflict trials. Taken together, these results suggest that there may be dissociable age effects of the ERN and N2 related to EC in childhood and adolescence.

Qualitative review of ERN and N2 developmental literature

To further test the hypothesis that the ERN and N2 are measures of EC, the qualitative review of literature on the ERN and N2 will be presented in two main sections. The first section will focus on studies examining the association between the ERN and measures of EC in typically developing populations and clinical populations with deficits in EC skills. The second section will focus on studies examining the association between the N2 and measures of EC in typically developing populations and clinical populations with deficits in EC skills.

ERN and effortful control

Correlational studies using typically developing populations

Few studies have investigated the association between behavioral measures of EC and the ERN in typically developing children. One such study investigated associations between the ERN and parent-reported and behavioral measures of EC (Checa, Castellanos, Abundis-Gutiérrez, & Rosario Rueda, 2014). Three groups of children (total N = 47) between the ages 4–6, 7–9, and 10–13 completed a delay of gratification task as the behavioral measure of EC and completed an adapted version of the flanker task (using robot stimuli). The task was adjusted on a trial-by-trial basis for each child such that the duration of the target differed in order to equate the level of task difficulty for all subjects. This permitted the comparison of other behavioral performance measures between age groups controlling for accuracy. Behaviorally, younger children demonstrated a lower percentage of choosing to delay and longer reaction times on incongruent versus congruent trials compared to older children. Children between 4 and 6 years of age did not exhibit an ERN effect. After controlling for age, a significant association was observed between a smaller ΔERN and larger difference in reaction time on incongruent compared to congruent trials, and a larger ΔERN and greater percentage of total delay choices. The authors interpret a larger difference in reaction time between trial type as reflecting poor EC, and conclude that larger ΔERN reflects better EC skills. The authors do not report any data related to the parent-reported questionnaire, which would be helpful to discern dissociable associations between parent-reported, behavioral, and neural measures of EC. It would strengthen the authors' argument that a larger reaction time difference between trial types is evidence of poor EC if this difference were also associated with poor EC as reported by parents and other behavioral measures such as task accuracy.

Clinical studies using populations with deficits in effortful control

Given the importance of EC skills in learning to modulate behavioral and emotional reactivity, it is unsurprising that a substantial body of literature has supported the role of EC skills in the development of internalizing and externalizing psychopathology (e.g., Caspi et al., 1996; Kochanska & Knaack, 2003; Moffitt et al., 2011). Moreover, individual differences in ACC-mediated functions and changes in the dopaminergic networks that underlie the ERN likely have psychological consequences (see Holroyd & Umemoto, 2016 for full review). These ramifications may be expressed in the development of affective processes relating to individual differences in the responsiveness of the neural network associated with EC skills. Researchers have theorized that the variation in negative emotionality that emerges in early childhood may be linked to low EC skills. The central basis of this theory is that the ability to shift one's attention toward or away from external and internal stimuli plays a critical role in the ability to regulate affect.

Evidence from the temperament literature support this hypothesis, as demonstrated by a study investigating the role of attentional and inhibitory control at 4 years of age on the relationship between early behavioral inhibition, or the fear of novel stimuli (Kagan, 1994), and later parent-reported anxiety symptoms (White, McDermott, Degnan, Henderson, & Fox, 2011). Laboratory tasks were used to assess attentional control (i.e., DCCS) and inhibitory control (i.e., day/night stroop) at 4 years of age, and behavioral inhibition was assessed at 2 years of age using an adapted stranger paradigm. Attentional control and inhibitory control variables were unrelated to behavioral inhibition, suggesting that these measures tapped independent constructs. Results indicated that the interaction between children's performance on post-switch DCCS trials and early behavioral inhibition explained an additional 9% of variance in anxiety symptoms at 4 years of age. Specifically, high levels of behavioral inhibition predicted higher parent-reported anxiety in children with poor DCCS performance whereas this association was not observed in children with better DCCS performance. The interaction between performance on inhibitory control tasks and early behavioral inhibition explained an additional 10% of variance in anxiety symptoms, such that the association between high levels of behavioral inhibition and later anxiety was only observed in children with high inhibitory control. These results suggest that attentional control and inhibitory control differentially moderate the association between behavioral inhibition and anxiety. Higher attentional control may serve as a protective factor, whereas better control over impulses or predominant responses may place a behaviorally inhibited child at greater risk for developing anxiety symptoms. While these findings support the hypothesis that the ability to shift attention flexibly is important to adaptive regulation of fearful emotional reactivity, the study cannot address the neural processes that may be involved in the relationship between attentional control and reduced affective reactivity in behaviorally inhibited children.

Researchers have turned their attention to the ERN to investigate variation in EC as it relates to emotional reactivity and affect at the neural level. The ERN is hypothesized to be larger in adults who are particularly concerned with making errors and may experience difficulty shifting their attention away from the negative affect and reinforcement associated with making a mistake. In contrast, the ERN is reduced in persons who are less concerned with their performance. There are two competing hypotheses from the adult literature that potentially explain this phenomenon. The threat sensitivity hypothesis proposes that the ERN reflects trait-like differences in threat sensitivity (Proudfit, Inzlicht, & Mennin, 2013), and argues that the ERN may be an endophenotype for psychiatric disorders given evidence of its heritability (Anokhin, Golosheykin, & Heath, 2008; Riesel, Endrass, Kaufmann, & Kathmann, 2011) and moderate test-retest stability (Olvet & Hajcak, 2009; Weinberg & Hajcak, 2011). These hypotheses are based on the primary assumption that individuals with increased threat sensitivity, particularly persons with clinically significant levels of anxiety, are characterized by an increased defensive response to errors and that errors are threatening. However, the threat sensitivity account lacks specific predictions about the mechanism underlying trait-level differences in defensive reactivity and larger ERN, and seems to ignore the effects of EC on anxiety and affect that are equally important in understanding the ERN.

A competing hypothesis to the threat sensitivity account known as the compensatory error-monitoring hypothesis (CEMH; Moser, Moran, Schroder, Donnellan, & Yeung, 2013; Moser, Moran, Schroder, Donnellan, & Yeung, 2014), which is grounded in cognitive theories that emphasize the adverse effects of worry on cognition and performance (Eysenck & Calvo, 1992; Eysenck, Derakshan, Santos, & Calvo, 2007). According to the CEMH, the ERN-anxiety relationship is specific to anxious apprehension/worry rather than anxious arousal, which is supported by a meta-analysis that indicates a stronger relationship between a large ERN and greater anxious apprehension ($r = -0.35$) compared to anxious arousal ($r = -0.09$) (Moser et al., 2013). The CEMH posits that worry interferes with processes that support ongoing goal/performance maintenance, and as a result, increased effort (compensation) is dedicated toward processes to reactivate control when an error occurs to reengage with task goals. Therefore, heightened threat sensitivity in anxious individuals and more distracting worries may make it difficult to maintain proactive, on-task behaviors, leading to an overinvestment in frontally mediated behaviors as manifested by an enlarged ERN (Eysenck & Derakshan, 2011; Moser, Moran, & Jendrusina, 2012).

Both threat sensitivity and CEMH accounts of the ERN reference the importance of developmental considerations in light of increasing evidence that the ERN-anxiety relationship may change with age (Lo, Schroder, Moran, Durbin, & Moser, 2015; Meyer, Hajcak, Torpey-newman, Kujawa, & Klein, 2015; Torpey et al., 2013). Proponents of the threat sensitivity account argue that increased threat sensitivity as characterized by temperamental constructs such as behavioral inhibition develop prior to compensatory processes like worry (Proudfit et al., 2013). Thus, reports of increased ERN in clinically anxious 6-year old children likely characterize enhanced threat sensitivity rather than worry. However, it is important to consider the methodological limitations of measuring cognitions in young children such as reliance on retrospective report or parent report (Alfano, Beidel, & Turner, 2002), as it is unclear whether worry truly does not develop until later in life or if this is an artifact of our inability to measure worry in early childhood.

As argued by Moser et al. (2014), the developmental considerations proposed in the threat sensitivity account do not necessarily contradict the CEMH. For example, a smaller ERN in younger anxious children (Torpey et al., 2013) and association between a smaller ERN and higher defensive reactivity as indexed by a larger startle response (Lo et al., 2015) may reflect findings from research reviewed previously between the association between poor EC skills and higher parent-reported internalizing behaviors. It is possible that children who continue to experience clinically significant levels of anxiety begin developing this compensatory mechanism to maintain a level of functioning similar to their non-anxious peers. Studies investigating associations between the ERN and affective processes will be reviewed below, and the CEMH and conflict monitoring theory will be used to guide discussion of how these findings contribute to our understanding about the functional significance of the ERN in relation to EC.

Adolescents with a history of high levels of laboratory assessed behavioral inhibition averaged across 14, 24, 48 months, and 7 years of age exhibit a larger ERN compared to adolescents with a history of low levels of behavioral inhibition (McDermott et al., 2009). The ERN was assessed using a letter flanker task. Results indicated that the association between the ERN and likelihood of developing an anxiety disorder differed by early levels of behavioral inhibition such that an increased ERN was associated with higher risk for an anxiety disorder in adolescents with high levels of behavioral inhibition in childhood whereas no association was observed between the ERN and risk for anxiety diagnosis in adolescents with low levels of behavioral inhibition. To the extent that the ERN may reflect attentional control, these findings are consistent with the White et al. (2011) study, suggesting that a larger ERN characterizes inefficiency in flexibly shifting attention. Alternatively, a larger ERN could also reflect better inhibitory control, effectively inhibiting the predominant response to respond to flanking letter stimuli instead of responding to the letter in the middle of the array. This interpretation is also consistent with the literature, suggesting that higher inhibitory control may actually increase risk for anxiety problems (Thorell, Rydell, & Bohlin, 2004; White et al., 2011).

One of the first studies to examine the association between increased ERN and concurrent levels of anxiety in children focused on a community sample of 9 year olds (Santesso, Segalowitz, & Schmidt, 2006). The ERN was assessed using a letter Flanker task and obsessive-compulsive behaviors were measured using parent-reported CBCL. Overall, a larger ERN was associated with fewer errors. Results indicated that the relationship between larger ERN and higher parent-reported anxiety was specific to obsessive-compulsive behavior ($r = -0.35, p < .05$). Accounting for gender, the ERN explained 9% of unique variance in obsessive-compulsive behaviors. It is possible that this correlation is an underestimation of the actual relationship since results are based on a restricted range of parent-reported obsessive-compulsive behaviors given that the community population exhibited quite few or mild obsessive-compulsive tendencies.

Since this time, there has been a dramatic increase in researchers using clinical populations to address this concern. The first investigation in a pediatric clinical population focused on 8–14 year olds (n = 9) diagnosed with an anxiety disorder (Ladouceur, Dahl, Birmaher, Axelson, & Ryan, 2006). Age-matched controls (n = 10) were free of any lifetime psychopathology and did not have any first-degree relatives with a lifetime mood or psychotic episode. Assessed using an arrow flanker task, the ERN was significantly larger in children diagnosed with an anxiety disorder. In contrast to Santesso et al. (2006) findings, the ERN was not associated with parent-reported anxiety symptoms. More recent investigations have expanded these findings by examining ERN variation across different anxiety disorders (Carrasco et al., 2013) and the specificity of the ERN to anxiety over depressive symptoms (Bress, Meyer, & Hajcak, 2013). Both studies used an arrow flanker task to elicit the ERN. Results suggested that children between 8 and 16 years of age with any lifetime OCD diagnosis had significantly larger ERNs compared to children with a non-OCD anxiety diagnosis and healthy controls (Carrasco et al., 2013). Follow-up comparisons indicated that compared to healthy controls, youth with a non-OCD anxiety diagnosis also had significantly increased ERN amplitudes. The ERN did not vary based on medication use or psychotherapy, supporting the hypothesis that the ERN may possess trait-like qualities. However, authors did not report data to support this finding. Without information regarding the extent to which medication or psychotherapy reduced symptoms, it is possible that the stability of the ERN across treatment type and no treatment is attributed to minimal treatment effect on anxiety symptoms.

Bress et al. (2013) similarly reported that an increased ERN was specific to higher anxiety 11–13 year olds, such that the ERN predicted higher levels of parent-reported anxious symptoms over and above depressive symptoms. No relation was observed between the ERN and parent-reported depressive symptoms. This finding was also reported in a separate sample of 7–17 year olds using both self- and parent-reported versions of the same depressive symptom measure (Ladouceur et al., 2012). However, while the ERN was not associated with severity of depressive symptoms, youth diagnosed with major depressive disorder (MDD) exhibited a reduced ERN compared to healthy controls. The ERN did not differ between youth with and without co-morbid anxiety disorders, suggesting that the presence of an additional anxiety diagnosis did not influence the ERN amplitude. The ERN was found to increase with age, but only in the healthy control group, indicating that the development of the ERN may be interrupted in youth with MDD. The blunted ERN observed in youth with MDD is inconsistent with studies in adults, which reveal either no differences in the ERN between healthy and depressed adults (Schrijvers et al., 2009) or increased ERN in depressed adults (Pizzagalli et al., 2001). These discrepancies highlight the importance of understanding the influence of age on the development of the ERN in childhood. A reduced ERN in depressed youth may reflect symptoms related to withdrawal, lack of engagement, and poor motivation, all of which likely contribute to poor attentional control and executive attention skills during task performance.

Children who experience difficulty with attentional and inhibitory control also tend to have higher levels of aggressive behavior (Rothbart, Ahadi, & Hershey, 1994) whereas children with good attentional and inhibitory control tend to direct attention away from anger-inducing stimuli, use non-aggressive verbal behaviors to resolve conflict (Eisenberg, Fabes, Nyman, Bernzweig, & Pinuelas, 1994), and demonstrate a sense a responsibility for their behaviors (Derryberry & Reed, 1996; Kochanska, Coy, & Murray, 2001). It has been well documented that damage to the PFC is linked to increased aggression in adults and poor impulse control (as cited in Dahl, 2001), and that the ACC region plays a critical role in processing emotional information and modulating self-regulation of subsequent emotional responses (e.g., Bush et al., 2000; Holroyd & Umemoto, 2016). Thus, researchers have also been interested in examining associations between the ERN and poor affective regulation in the context of externalizing disorders. One study sampled boys between 8 and 12 years of age who were referred to treatment programs for aggressive behavior or were from the community with no parent-reported internalizing or externalizing behaviors as measured on the CBCL (Stieben et al., 2007). Children were divided into externalizing behavior only, internalizing and externalizing behaviors (mixed), and control groups based on CBCL scores on the externalizing and internalizing subscales. Children completed an emotion induction go/no-go task where they were required to click a button for similarly shaped letters and inhibit clicking when a letter was presented a second time. In the first block of the task, children saw their points accumulate, which they could later trade in for a prize that they chose. To induce negative emotion, the second block of the task included a point-adjustment algorithm that caused them to lose all of their points at the end of the second block. During the last block they regained these points back. To test the negative emotion induction, children reported their emotions following each block, which suggested that they experienced higher negative emotionality on the second block compared to the first and last block.

Results indicated that children with primarily externalizing symptoms exhibited less response slowing following negative feedback compared to healthy controls. Prior to the mood induction, children with externalizing symptoms only exhibited the smallest ERN, followed by children in the mixed symptom group and then healthy controls exhibiting the largest ERN. Both children in the externalizing only and mixed symptom group exhibited increases in the ERN during the negative emotion induction block whereas healthy controls did not exhibit any changes in the ERN. Results on the ERN prior to the negative mood manipulation are consistent with previously reported results in children with externalizing or impulsive behavior, suggesting that children with EC difficulties either have deficits in or do not actively engage in processes that would help signal to other brain regions a need for increased attentional control. So while negative feedback is typically used to adjust behavior and signal the need for increased attention to incorrect responses, children with externalizing symptoms only made minimal adjustments to slowing their response time following mistakes compared to healthy controls.

However, the continual loss of points in the negative mood induction appeared to increase their ability to engage in EC, reflected in the increase in the ERN and response slowing. These findings highlight how a small experimental manipulation such as increasing loss probabilities can affect the ERN amplitude, suggesting that the ERN is sensitive to changes in motivation, emotional salience, and mood state. More experimental manipulations such as the one used in this study are important for future research to test the functional significance of the ERN. Overall, the literature suggests that the ERN is a measure of EC, and there is currently not enough evidence to disentangle the extent to which ERN measures these specific facets of EC. This will be an important future direction for research, and has the potential to help determine which intervention or treatment strategies the ERN is most sensitive to, strategies that help increase children's EC and responsiveness to their behaviors through activating neurocognitive processes such as the ERN that in turn activate behaviors related to EC.

The most commonly studied population with EC deficits include children and adolescents with attention-deficit hyperactivity disorder (ADHD), a disorder characterized by developmentally inappropriate levels of inattention and/or hyperactivity and impulsivity that cause significant impairment in daily functioning (DSM-5; American Psychiatric Association, 2013). Within the last decade, etiological theories of ADHD have begun to emphasize the importance of understanding how EC accounts for decreased regulation of arousal and reactivity in addition to specific cognitive deficits of ADHD that impair attentional and inhibitory control (Douglas, 1999). Using only behavioral performance measures limit the extent to which researchers can posit which neural processes contribute to corrective behavioral responses, so researchers have turned to investigating the ERN to elucidate neurophysiological components related to EC associated with deficits in error detection, performance monitoring, and behavioral adjustments following an error in children with ADHD.

Most investigations have demonstrated that children with ADHD exhibit worse behavioral performance on reaction time tasks and significantly reduced ERNs compared to that of healthy controls (Albrecht et al., 2010; Groen et al., 2008; Groom et al., 2013; Liotti, Pliszka, & Perez, 2005; Rosch & Hawk, 2013; van Meel, Heslenfeld, Oosterlaan, & Sergeant, 2007). However, there are also a number of studies reporting either no group differences or larger ERNs in children with ADHD compared to healthy controls (Burgio-Murphy et al., 2007). For example, a study examining the ERN in children with ADHD and comorbid conditions,[3] reported that children with ADHD exhibited a significantly larger ERN compared to healthy controls (Burgio-Murphy et al., 2007). These findings are somewhat inconsistent with the predictions of the conflict monitoring theory, which would predict that children with ADHD may experience more difficulty engaging in attentional control, decreasing their ability to process target stimuli. Therefore, the discrepancy between error and correct trials should be diminished, which is reflected in a reduced ERN.

However, it is possible that the discrimination task used by Burgio-Murphy et al. (2007) was so simplistic that children with ADHD needed to exert more effort than controls to engage in EC skills. Specifically, the task emphasized both speed and accuracy, and required children to press one button when the letter "X" appeared, and another when "O" appeared. Children with ADHD may have needed to exert greater effort to engage in EC behaviors to achieve similar levels of accuracy as their healthy peers on such a simple task, as evidenced by the increased ERN. If a more difficult task had been used to elicit the ERN, such as one that requires inhibiting a learned response or directing attention away from distracting stimuli, then perhaps task demands would induce greater deficiency in error monitoring. It is important for researchers to focus on investigating how EC skills may break down in the sequence of error detection and subsequent processing that produce observed deficits. Specifically, researchers should conduct within-subject analyses of the ERN and EC skills throughout the entirety of the task. Rather than investigating the ERN averaged across all error trials, it may be particularly useful to examine whether the ERN changes across the duration of the task.

Within-subject analyses may also help account for evidence suggesting that the ERN amplitude is not significantly different between children with ADHD and healthy controls (e.g., Jonkman, van Melis, Kemner, & Markus, 2007; Zhang, Wang, Cai, & Yan, 2009). The heterogeneity of symptoms associated with ADHD may contribute to the inconsistencies in the literature regarding the mean-level differences in the ERN between ADHD populations and controls. Children with ADHD may exhibit symptoms that are more consistent with a predominantly inattentive profile, a predominantly hyperactive/impulsive profile, or both. For children with a predominantly inattentive profile, their major deficiency may be in error detection whereas children with impulse-control deficits may experience more difficulties with later error processing and making behavioral adjustments consistent with task demands.

Taken together, research examining error processing in children with clinically significant deficits in EC suggests that initial error detection (as assessed by the ERN) and later error reflection may be diminished. Greater support for a reduced ERN in populations with EC deficits is consistent with the hypotheses derived from the conflict monitoring theory, that difficulties maintaining attention toward target stimuli reduces the contrast between error and correct trials, resulting in a smaller ERN. It is notable that each study differed in their use of task parameters (e.g., task type, number of trials, task difficulty, task feedback, instructions, task timing) and ERP scoring methods (i.e., mean versus peak amplitude), which introduces a range of methodological issues that likely contribute to the variability in results (Shiels & Hawk, 2010). Moreover, a majority of these studies do not report the CRN on correct trials, which not only makes it challenging to interpret the meaning of the ERN if results of the effect between error and correct trials is not presented, but also increases the possibility that any observed group differences are due to between-subject variability in neurophysiological responses rather than error processing specifically. Therefore, it is important for future research in this area to investigate associations between the ERN and behavioral performance, in addition to conducting within-subject analyses to understand the dynamic changes in EC skills and ERN that likely occur while performing a task.

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[3] Common comorbidities to consider in children diagnosed with ADHD include Oppositional Defiant Disorder, Specific Learning Disorders, and Developmental Coordination Disorder, which have been similarly linked to reduced EC skills in neutral and affectively-salient contexts (e.g., Leonard, Bernardi, Hill, & Henry, 2015; Wahlstedt, Thorell, & Bohlin, 2009).

N2 and effortful control

Correlational studies using typically developing populations

As described previously, the N2 is thought to reflect the processing of irrelevant stimuli (e.g., Yeung, Botvinick, & Cohen, 2004; Yeung & Cohen, 2006). Few studies have investigated the N2 as a measure of EC despite evidence that mastery of EC skills is dependent on the maturation of functional interactions between prefrontal network regions (Somerville & Casey, 2011). Research has suggested that the cortical region responsible for generating the N2 is the ACC, which is located in the prefrontal cortex (Liotti, Woldorff, Perez, & Mayberg, 2000). Evidence suggests that the N2 amplitude on incongruent trials is significantly larger than congruent trials for older children (Buss, Dennis, Brooker, & Sippel, 2011), adolescents, and adults compared to that in younger children (Espinet, Anderson, & Zelazo, 2012; Waxer & Morton, 2011). A larger ΔN2 between incongruent and congruent trials is associated with lower levels of parent-reported EC and longer reaction times on incongruent compared to congruent trials (Buss et al., 2011). Performance on common behavioral tasks used to assess EC skills such as the Dimensional Card Change Sort (DCCS; Zelazo, 2006) has also been used to clarify the functional meaning of the N2. The DCCS is thought to tap multiple cognitive processes by testing children’s ability to apply a set of rules to sorting cards and switching card sorting rules depending on stimulus cues. Longer reaction times on higher conflict DCCS trials is associated with a larger N2 effect (Waxer & Morton, 2011). These findings support the hypothesis that a larger ΔN2 reflects depletion of EC resources. Children who successfully switch card sorting rules depending on stimulus cues exhibit a reduced N2 effect compared to those who fail to switch flexibly (Espinet et al., 2012). It is possible that children who switched flexibly exhibit better EC skills to inhibit their pre-potent response to sort by univalent characteristics and successfully execute a response to sort by bivalent characteristics. Engaging in high levels of EC may therefore be reflected in a smaller N2 amplitude.

The largest study to examine associations between the N2 and other markers of EC skills, such as inhibitory control and attentional shifting, included 215 children between the ages of 7 and 9 years (Brydges, Fox, Reid, & Anderson, 2014). Both structural equation modeling and confirmatory factor analyses indicated that a larger ΔN2 assessed by a modified flanker task was associated with and accounted for 10% of variation in performance on EC behavioral tasks. This finding contrasts conclusions from the studies reviewed above that suggest a reduced N2 is associated with better EC. There are several explanations for inconsistency in the literature, some of which have already been mentioned such as differences in task paradigm. Specifically, the modified flanker task used in the aforementioned study included a “reversed” condition in addition to typical incongruent and congruent trials. The reversed condition required children to respond with the opposite direction of the central fish. It is likely that this modification introduced more complexity and conflict in the task.

Additionally, there is some research to suggest that the reduction in N2 amplitude with age may not directly correspond to improvements in EC depending on where the N2 amplitude is maximal. Specifically, Johnstone, Dimoska et al. (2007) reported that the N2 at centro-parietal sites decreased with age, but frontal N2 amplitude was correlated with behavioral performance. Brydges et al. (2014) reported using a composite N2 amplitude, but method sections were unclear in describing which sites were averaged in the composite amplitude.

In terms of EC performance on behavioral tasks, structural equation modeling results suggested that EC performance loaded onto one factor. This is consistent with developmental findings that the structure of EC is largely unitary in children until the age of 9 (Brydges, Reid, Fox, & Anderson, 2012), at which point EC factors (i.e., inhibition and attentional shifting) are more psychometrically distinguishable from one another (Duan, Wei, Wang, & Shi, 2010). Given that the N2 was observable in this age range, it is possible that ERP components related to inhibitory control emerge before specific behavioral abilities as measured by common EC tasks. One of the ways that this hypothesis could be tested is examining the effects of age on a general or common EC factor (consisting of correlations among different measures of EC) and specific EC facets (i.e., attentional control and inhibitory control). Results would reveal whether there are unique age effects at the level of specific EC factors after accounting for age effects on the common EC factor.

Clinical studies using populations with deficits in effortful control

Similar to studies on the ERN, the most commonly studied clinical population with deficits in EC includes children with ADHD. Poor behavioral performance in children with ADHD has consistently been reported during motor response inhibition tasks such as the go/no-go task (e.g., Pliszka, Liotti, & Woldorff, 2000; Rubia, 2011), which is typically used to elicit the N2 given its posited association with EC. Research on the N2 in clinical populations with deficits in EC began several decades earlier compared to research on the ERN in these populations, and is therefore more extensive. However, findings on N2 variation between clinical and healthy populations are highly inconsistent. Several studies have reported a reduced N2 effect in children with ADHD (e.g., Brandeis et al., 1998; Broyd et al., 2005; Johnstone, Watt, & Dimoska, 2010; Pliszka et al., 2000), ASD (Tye et al., 2014), and unaffected siblings of children with ADHD (Albrecht et al., 2010) whereas others have reported no N2 differences between clinical populations with EC deficits and healthy controls (e.g., Cao et al., 2013; Fallgatter et al., 2004; Johnstone & Galletta, 2013; Rosch & Hawk, 2013; Spronk, Jonkman, & Kemner, 2008). In addition, there are studies reporting the opposite effect, a larger N2 amplitude in children with ADHD compared to healthy controls (Jonkman et al., 2007; Senderecka, Grabowska, Szewczyk, Gerc, & Chmylak, 2012; Smith, Johnstone, & Barry, 2004). Two extensive reviews have been published on the variability of these findings (Barry, Johnstone, & Clarke, 2003; Johnstone, Barry, & Clarke, 2013). Therefore, this section will focus on more recent attempts to address limitations of previous studies investigating the N2 in clinical populations with EC deficits.

Some researchers have examined the effect of stimulant medication on the N2 using within-subjects designs (e.g., Groom et al., 2010; Pliszka et al., 2007; Sunohara, Voros, Malone, & Taylor, 1997; Wilson, Cox, Merkel, Moore, & Coghill, 2006). Common stimulant medications such as methylphenidate are typically used in ADHD populations and believed to increase dopamine available in the striatum, thus enhancing the saliency of task-related stimuli. Groom et al. (2010) observed a significantly larger N2 in the on-medication condition compared to off-medication in children diagnosed with ADHD. Given the lack of reported behavioral performance data, the assumption that larger N2 reflects greater activation of attentional and inhibitory control processes is not fully supported. One would expect that greater activation of attentional and inhibitory control processes would manifest behaviorally in task performance, and if not, the divergence between neural and behavioral measures of EC has important implications for the functional meaning of the N2.

Examining differences in N2 across multiple types of task paradigms is another method of elucidating the meaning behind changes in N2 amplitude and variability of reported directionality (i.e., larger, reduced, no change) in clinical populations with EC deficits. There have been several experiments investigating the effect of manipulating task parameters (e.g., modality, timing, frequency of trial type) on neural activation or ERPs associated with EC processes in adults (e.g., Dimoska & Johnstone, 2008; Falkenstein, Hoormann, & Hohnsbein, 2002; Rubia et al., 2001) and few studies in children (Johnstone, Barry, & Clarke, 2007). Two commonly used response inhibition paradigms are binary-choice reaction time tasks including the go/no-go and stop signal tasks. While both tasks involve purposefully suppressing a predominant motor response, inhibitory processes likely act at different stages in executing a response. For instance, the go/no-go task requires the response inhibition in the preparatory phase whereas the stop signal task requires inhibition of responses already activated in ongoing processing. It is possible that the N2 assessed from each task type may capture a different aspect of inhibitory processing, and evidence suggests that the N2 measured in the go/no-go and stop signal tasks are not correlated and have different scalp distributions in children (Johnstone, Barry et al., 2007).

One study investigated the N2 response to visual go stimuli compared to an auditory stop signal in children with ADHD between 8 and 14 years of age and healthy age-matched controls (Johnstone, Barry et al., 2007). Children with ADHD of the Predominantly Inattentive type committed more omission errors compared to healthy controls and exhibited larger N2 on go trials. Surprisingly, ADHD inattentive children exhibited a *smaller* N2 amplitude in response to stop signals. The extent to which these group differences are driven by the primary go task or presence of stop signals, which may affect how the go stimuli are processed, cannot be determined in the present study since the effects of the go stimuli and stop signals cannot be isolated. However, these results do provide support that differences in the direction of N2 abnormality may be attributed to differences in the stage of inhibitory control processing activated by go/no-go and stop signal tasks (Rubia et al., 2001). This has yet to be explored further in the literature, but is of critical importance to interpreting the inconsistent reports of atypical N2 directionality in clinical populations and understanding how these results inform our study of EC in children.

A limited number of studies have begun to examine both the ERN and N2 as neural measures of EC in clinical populations (Samyn, Wiersema, Bijttebier, & Roeyers, 2014; Wild-Wall, Oades, Schmidt-Wessels, Christiansen, & Falkenstein, 2009). One study examined associations of the ERN and N2 with parent- and child-reported EC in typically developing children and children with ASD or ADHD between the ages of 10–15 years (Samyn et al., 2014). A battery of different questionnaires was used to assess facets of EC such as the Early Adolescent Temperament Questionnaire-Revised (EATQ-R; Ellis & Rothbart, 2001), which includes attentional control and inhibitory control scales. The N2 did not differ across groups whereas the ERN was reduced in children with ADHD. Associations between ΔN2 and parent- and child-reported EC differed by diagnosis. Specifically, there was no relationship between ΔN2 and EC in typically developing children. In contrast, a smaller ΔN2 was modestly related to higher parent- and child-reported attentional control and lower inhibitory control in children with ADHD. In children with ASD, a smaller ΔN2 was strongly associated to parent- and child-reported attentional control. Results indicated that a larger ΔERN was robustly related to parent- and child-reported attentional and inhibitory control regardless of diagnosis. These findings provide evidence that a larger ΔERN reflects better EC, which is further supported by the reduced ERN effect observed in children with ADHD. The authors propose that a smaller ΔN2 may reflect less conflict, implying that better EC skills results in a decreased N2 effect. However, the relationship between the ERN and N2 is unexplored in this study. Given that results suggest a larger ΔERN, and in contrast, a reduced N2 effect is associated with better attentional and inhibitory control, it is possible that the ERN and N2 have dissociable effects.

With regards to internalizing populations, the first study in adults to document the influence of anxiety-related threat bias on the N2 used a modified Attention Network Task and reported that subjects with high trait anxiety exhibited a reduced ΔN2 response following threat (i.e., fearful faces presented during intertrial intervals) (Dennis & Chen, 2009). As anxiety increased, N2 amplitudes on congruent flanker trials only (low conflict) increased following fearful faces, which in part explained the reduced ΔN2 among high trait anxiety individuals. Importantly, Dennis and Chen explored associations between the N2 and behavioral performance to clarify whether N2 modulation reflected compensatory resource preservation in support of task performance or inefficient resource allocation that reduces task performance.

Larger N2 amplitude on high and low conflict trials predicted poor alerting efficiency (RT no cue – RT double cue), a smaller difference between the reaction time on cued versus non-cued trials. A larger ΔN2 was also associated with slower RT on incongruent trials, potential evidence of compromised performance. The authors suggested that these results provided evidence that a reduced ΔN2 and enhanced N2 on low conflict trials reflected a compensatory mechanism in trait anxious adults related to threat bias. When threat bias interferes with attention, the ability to distinguish between low and high conflict may be compromised in anxious individuals and they are expending more resources in a low conflict situation. Thus, a reduced N2 following potentially threatening information may be an indicator of better EC skills, suggesting that persons with reduced N2 may have fewer difficulties inhibiting threatening information or distracting information since they are better regulated affectively.

This finding in adults seems somewhat consistent with research on the N2 and internalizing processes in children. Henderson (2010) recruited children between 9 and 13 years of age from the community to complete an arrow flanker task and several self-reported questionnaires of anxiety. A shyness composite was derived from a self-reported temperament measure that consisted of scores on items related to pleasure derived from novel activities subtracted from scores on items related to inhibition in response to novelty or social challenges. Results indicated that self-reported shyness and social anxiety were unrelated to behavioral performance and N2, highlighting the distinct indices of emotional reactivity and EC regulatory processes. Regression analyses suggested that variation in N2 amplitude on high conflict trials moderated the relationship between shyness and self-reported social anxiety, such that higher levels of shyness predicted higher self-reported social anxiety but only for children who exhibited larger N2 amplitudes on high conflict trials. This pattern was also observed for the N2 amplitude on congruent trials, but not for the N2 difference between trial types. The lack of specificity of results by trial type may reflect engagement in EC processes on both types of Flanker trials, which may be due to the difficulty of the task or equal probability of each trial type. The moderating effect of the N2 on the relationship between shy temperament and social anxiety is analogous to the reported moderating effects of high inhibitory control on the association between behavioral inhibition and anxiety (White et al., 2011). White et al. demonstrated that high attentional control has the opposite effect, potentially serving as a protective factor that enables a behaviorally inhibited child to engage in flexibly shifting attention, which may buffer against risks associated with fearful emotional reactivity.

Children between the ages of 8–12 years with a primary anxiety disorder confirmed using a clinical parent interview, and aged-matched peers free of any psychological disorder completed an emotional go/no-go task (Hum, Manassis, & Lewis, 2013). Children were instructed to respond as quickly as possible to facial stimuli with an emotional expression (i.e., angry, calm, and happy) and inhibit their response for the opposite gender (the gender specified as the no-go stimulus was counterbalanced across participants). Both the N2 and ERN were assessed using the emotional go/no-go task. Behavioral performance did not differ between groups. Results indicated that children with an anxiety disorder exhibited a larger N2 and ERN on both low and high conflict trials compared to healthy peers. However, an N2 effect (larger N2 on no-go compared to go stimuli) was only observed in the healthy controls, whereas the anxiety disorder group had a similar N2 response regardless of whether the trial required that they inhibit a learned response. Healthy controls exhibited a larger N2 in response to angry facial stimuli compared to calm and happy facial stimuli. In contrast, the anxiety disorder group had similar N2 responses regardless of the type of emotional expression. The association between the high conflict N2 in response to calm faces in the anxiety disorder group explained 8% of the variance in self-reported anxiety levels.

The authors suggested that these results provided evidence that anxious children allocate more attentional resources toward emotion regulation. However, this conclusion assumes that viewing images of different valenced adult facial expressions not only aroused the child's baseline emotional state, but also activated the need for regulating the induced emotional state. The authors do not include any measures testing whether their task paradigm produced these responses that are central to their primary research question. However, these findings do suggest that children with clinical levels of anxiety appear to exhibit higher N2 activation overall compared to healthy controls while viewing emotional expressions, whereas healthy controls only reach this level of N2 activation in response to angry emotional expressions. Thus, children with anxiety disorders may fail to discriminate between negative, positive, and neutral emotional expressions, consistent with literature suggesting that anxious individuals have a tendency to overgeneralize threatening stimuli and perceive neutral stimuli as equally threatening as other negative-valenced stimuli. Furthermore, based on hypotheses derived from the conflict monitoring theory, the lack of difference in N2 between trial types in the anxiety disorder group may suggest decreased processing of distracting information and reflect higher EC skills. This hypothesis is supported by research suggesting that children with anxiety disorders are overcontrolled and display higher levels of inhibitory control (Fox, Henderson, Marshall, Nichols, & Ghera, 2005).

A strength of the investigation was measuring the ERN and N2 within the same sample. However, the authors did not take advantage of this strength by exploring the association between these two ERP components. Given that the behavioral performance between anxiety disorder and healthy control groups were similar, the larger N2 and ERN response across trial type and emotional stimuli in anxious children may suggest that they are devoting unnecessary cognitive resources to signaling the need for increased EC. In other words, anxious children may be working harder for similar results and allocating resources toward nonessential cognitive processes as compared to non-anxious peers. However, understanding the relationship between the ERN, N2, and behavioral data in this sample could help further test this hypothesis. If the ERN and N2 were positively correlated and predicted behavioral performance, this would suggest that these ERPs index similar EC processes that anxious children may unnecessarily recruit to engage in EC behaviors. If the ERN and N2 were unrelated, this may provide evidence that these ERPs reflect distinct EC processes and support the hypotheses outlined by the conflict monitoring theory about the dissociable effects of the ERN and N2. It is critical for future studies to examine the associations between the ERN, N2, behavioral performance, and other measures of EC to directly test the hypotheses.

Another study that included measures of the ERN ($n = 16$) and N2 ($n = 29$) used an arrow flanker task on children between the ages of 9–17 years (Ladouceur, Conway, & Dahl, 2010). Children also completed self-reported measures of attentional control from the early adolescent temperament questionnaire (Ellis & Rothbart, 2001), and self-reported negative affect from the positive and negative affect schedule (Laurent et al., 1999). The study tested the hypothesis that children with high self-reported negative affect and low attentional control would have a larger ERN and N2. This hypothesis is grounded in the assumption that higher negative affect may increase the emotional saliency of conflict such as an error, and children with poor attentional control may have difficulty modulating their attentional resources necessary to respond to the conflict, and therefore produce larger ACC-mediated ERPs to signal for greater control. Bivariate correlations indicated that higher self-reported negative affect was associated with a larger N2 and ERN whereas self-reported attentional control was unrelated to both ERPs. Contrary to the hypothesized results, regression analyses revealed that self-reported attentional control moderated the relationship between negative affect and N2 amplitude, such that children reporting higher levels of attentional control and negative affect had a larger N2. While not significant, a similar relationship was found for the ERN; children reporting higher levels of attentional control and negative affect had a larger ERN.

A possible explanation for the observed results can be derived from the conflict monitoring theory, which posits that the sensitivity of conflict detection depends on specific threshold levels determined by various factors such as the amount of attentional resources allocated toward monitoring performance. Accordingly, attending to task-specific demands and goals may lower the threshold level for detection and thus increase sensitivity to detect conflict, resulting in a larger ERN and N2. Extending this to the present results, children with higher negative affect and tendency to attend to task-specific goals may have experienced increased sensitivity to detecting conflict, and this focused attention was reflected in larger ACC-mediated ERPs. It is also important to consider the specific factors indexed by the self-reported attentional control measure. Specifically, the attention subscale used in the present study assessed both the ability to focus one's attention and shift attention flexibly. While these two types of attentional control are related, they likely have differential associations to one's ability to modulate or regulate negative affect. The tendency to focus attention may lead to an over-focusing or biased attention toward threatening/negative stimuli, making it increasingly difficult to flexibly shift one's attention to help modulate negative affect. Thus, the present findings may reflect the influence of high attentional focusing and excessive concern about the possibility of making a mistake, which may result in allocating an unnecessary amount of attentional resources to maintain more persistent performance and conflict monitoring. This enhanced effort to maintain optimal performance likely contributes to increased neural activity that may be captured by the larger N2 and ERN. Unfortunately, the authors did not test the extent to which the N2 and ERN may index similar or different EC processes, which could have greatly enhanced the interpretation of their findings.

Discussion and integration of present literature

The aim of the present review was to examine evidence that the ERN and N2 are measures of EC, and provide a developmental application of the conflict monitoring theory to elucidate the nature and function of the ERN and N2 in childhood and adolescence. The qualitative review and meta-analysis indicated that the ERN and N2 are quite malleable in childhood, and methodological differences between studies (e.g., task type, sample characteristics, scoring methods) likely influence the ERN and N2. Quantitative meta-analytic results supported hypotheses that as children age and improve in their EC skills, this improvement may be reflected in a larger or more negative ERN and reduced N2. The larger ERN likely reflects increases in their error-correcting abilities and ability to focus on target stimuli while the reduced N2 may reflect improvement in their ability to filter distracting information (and concomitant decreased processing of distracting stimuli). Future research must address these methodological concerns, work to standardize practices in conducting ERP research in children, and develop new methodologies that allow better identification of EC processes. The following section will integrate the main findings of this review, and discuss their implications for understanding the functional significance of the ERN and N2. A discussion of the limitations of the present review as well as the primary limitations of the research field will guide recommendations for future research.

Quantitative analysis conclusions

Results from the meta-analysis of ERN studies ($k = 26$; $N = 1,519$) and N2 studies (k = 19; $N = 1,095$) indicated a 0.02 μV increase per one month in ERN amplitude and 0.02 μV reduction per one month in high conflict N2 amplitude across childhood. Included studies were primarily conducted in middle to late childhood, the age range spanned from 3 to 17 years of age, during which substantial changes in EC as measured behaviorally or via questionnaire methods are observed. The present results suggest changes in ERN and N2 amplitude may occur in concert with improvements in EC skills as measured behaviorally and via informant report across this developmental period. There are several potential explanations and considerations for these results and their implications for understanding the behavioral and neural changes associated with EC development.

First, it is important to consider the differences across studies regarding ERN and N2 scoring method. In the present meta-analysis, studies did not provide enough information to calculate the ERN and N2 difference amplitudes. Therefore, reported developmental effects are with the ERN and N2 mean amplitude. It is possible that developmental changes in the ΔERN and ΔN2 may be a closer estimate of the development of EC skills given that the ΔERN and ΔN2 (difference scores of neural activity on high minus low conflict trials) likely characterize activity unique to error or high conflict processing from activity broadly related to trial-to-trial monitoring (Simons, 2010). For example, the current literature suggests that the ERN and ΔERN exhibit dissimilar relationships with other psychological constructs of interest, but no research group has hypothesized how these measures might capture differing variance across development (Moser, 2017). The ability to distinguish between low and high conflict trial types is an important skill afforded by the improvement of EC and provides information regarding potential compensatory behaviors that either preserve attentional resources in service of performance or allocate attentional resources inefficiently, resulting in performance deficits. Thus, the ΔERN and ΔN2 may exhibit greater maturational changes compared to the ERN and N2 on high conflict trials.

Second, it is also necessary to consider the extent to which age-related changes in the ERN and N2 reflect specific or general changes in brain function that impact EC development. This is an important empirical question for researchers to consider in future studies given that significant changes in brain maturation and mastery of EC skills are occurring over this developmental period and changes in the ERN and N2 may reflect these general developmental phenomena rather than unique age effects. If the ERN and N2 reflect more general developmental changes, then this constrains the theoretical accounts of the ERN and N2 since they must be general enough to account for the differences reported across the diverse set of tasks used to examine these ERPs.

Third, future studies should explore the hypothesis that the association between age and the ERN and N2 may not be linear. There is evidence to suggest that a nonlinear change in the ERN occurs in the beginning of adolescence (Davies et al., 2004), possibly reflecting neuromodulation of dopamine during this age period. No longitudinal study or cross-sectional investigation from childhood to adulthood has examined the N2. However, one would expect that if the ERN and N2 operate on overlapping neural networks, a nonlinear change in the N2 may also occur across development. Research has indicated that EC skills develop rapidly and exponentially in early childhood (i.e., Allan & Lonigan, 2014; Blair & Raver, 2012; Montroy et al., 2016). Others have also suggested that the aspect of EC more directly related to regulation of emotion differs from the development of regulation of cognition and attention (Smith et al., 2011). Smith et al. (2011) assessed children's affective decision-making using the Iowa Gambling task and attentional control skills using common cognitive neuropsychological tasks. Results indicated a "J-shaped" trajectory for affective decision-making skills such that younger school age children performed better than early adolescents, and performance gradually increased again into late adolescence. This documented trajectory contrasted that of attentional control skills as assessed by cognitive tasks, which appeared to increase linearly with age.

Fourth, changes in the ERN and N2 observed in the meta-analysis may be an artifact of temporal inconsistency and "latency jitter" that is typically greater in children. Specifically, latency jitter refers to variability from trial-to-trial. Traditional ERP analyses ignore the impact of this variability on ERP amplitudes. There is preliminary evidence that latency jitter decreases from childhood to adulthood, and is the confounding factor contributing to an attenuation of the ERN in children, such that there is no relationship between age and ERN amplitude after accounting for latency jitter effects. These results suggest that the reported increase in ERN amplitude across development is attributable to the developmental effects of latency jitter (Lin, Gavin, & Davies, 2015). Recent research also suggests that increases in temporal consistency from trial to trial are observable in a short developmental window from 5 to 7 years of age (DuPuis et al., 2015). Therefore, it is likely that the trial-to-trial variability impacts age-related effects in the ERN reported in samples that only consist of children.

In terms of differences in the ERN and N2 in clinical populations with deficits in EC, the meta-analysis results suggested no significant differences in the ERN or N2 between children sampled from the community and children with externalizing disorders. In the qualitative review of individual studies, behavioral performance was compromised in children with ADHD, and there was evidence for children with ADHD to either exhibit a reduced or similar ERN in comparison to children without ADHD. Results were more inconsistent in studies on the N2 given that there was evidence for children with ADHD to exhibit a reduced, increased, or similar N2 in comparison to children without ADHD. A critical component to understanding the variation in the ERN and N2 in clinical populations is the composition of their symptoms, which is an ongoing issue addressed in this area of research (Johnstone et al., 2013). For children with predominantly inattentive symptoms, they may experience more difficulty with attending to target stimuli and exhibit a reduced ERN whereas those with predominantly impulse-control deficits may have more difficulty making behavioral adjustments and may rely more on reactive control leading to an increased ERN. However, these are distinctions that would need to be examined in relation to post-error behavioral performance. Specifically, it would be important to understand how children who have deficits in attention and/or impulse-control adjust their behavior after receiving high conflict information.

There were more studies investigating medication effects in children with ADHD that measure the N2. Results from these investigations suggest that N2 increases with medication use and appears to "normalize" the N2 amplitude of children with ADHD, placing them closer to their same-age healthy peers. This finding calls into question whether the N2, and possibly the ERN, may function in a similar fashion as the Yerkes-Dodson law (Yerkes & Dodson, 1908) wherein performance is optimal when the ERN and N2 fall within an average range and performance begins to deteriorate when the ERN and N2 are either much larger or much smaller than average. This argument also follows the concept of ego resiliency (Block & Block, 1980) and the positive psychological and social-emotional outcomes of being able to flexibly reduce or increase self-control depending on situational demands. In other words, the ERN and N2 will vary as a function of the child's EC skills to maximize behavioral and neural efficiency for optimal task performance – this could mean either responding and attending to distracting stimuli (indexed by a larger N2), or preserving attentional resources and inhibiting responses and attention to distracting stimuli (indexed by a smaller N2). Imbalance between these efforts may impact task performance such that expending too many EC resources on irrelevant stimuli (e.g., enhanced N2 in anxious individuals) may be detrimental, but the lack of engagement with or inability to recruit EC resources (e.g., reduced N2 in ADHD children) may also be detrimental.

It is critical to consider this formulation of the N2 in relation to the ERN, particularly with the difference in when they are generated during task completion. The N2 is elicited immediately following presentation of a stimulus whereas the ERN is elicited immediately following a response. Therefore, there are several patterns between the ERN and N2 (i.e., increased ERN and N2; increased ERN and reduced N2; reduced ERN and N2; reduced ERN and larger N2) that may yield the most efficient and optimal performance. In order to discriminate the patterns that yield optimal behavioral and neural efficiency, it is critical for studies to investigate associations between the ERN, N2, behavioral performance, and other multi-method measures of EC.

In terms of the relationship between the ERN, N2, and internalizing problems, research in this domain has primarily focused on fear and behavior inhibition, common precursors to the development of anxiety disorders. Children older than 8 years of age who have an anxiety disorder or at high risk for developing an anxiety disorder are reported to have enhanced ERN, and while somewhat inconsistent, a larger N2. Younger children under the age of 8 years who have higher levels of anxiety and/or fear have reduced ERNs. Using the conflict monitoring theory and CEMH hypothesis framework (Moser et al., 2013; Moser et al., 2014), the reduced ERN observed in young anxious children may reflect their poor EC skills and inability to shift attention away from anxious worries and attend to target stimuli. As a result, their ERN profile reflects that of a child with poor EC skills. However, over time, children who continue to experience difficulty with anxiety may overcompensate and rely on enhanced reactive control with greater attentional focus on information gathered from their errors, which is reflected in an enhanced ERN. This ERN profile is still evidence of their poor EC and inability to attend flexibly, but manifests differently in terms of ERN amplitude later in development.

Taken together, the proposed hypothesis is that anxious children continue to have poor EC skills, but this deficit manifests differently in the ERN amplitude at different developmental periods. However, this hypothesis is inconsistent with the current meta-analysis results. The meta-analysis suggested that the ERN was reduced in children and adolescents with internalizing disorders ($M = -1.60$, $SE = 1.11$) compared to non-clinical ($M = -4.15$ $SE = 0.54$) and externalizing disorder samples ($M = -5.12$, $SE = 0.84$). This finding remained even when excluding studies on children younger than 8 years of age. Within individual studies comparing internalizing versus control groups, results did suggest that on average, youth with internalizing disorders exhibited a larger ERN compared to their same-age healthy peers. However, meta-analytic results indicated that the average ERN amplitude of internalizing populations across these individual studies was reduced compared to the average ERN amplitude of control and community populations combined. It is possible that differences in task type between studies confounded comparisons between internalizing, externalizing, and non-clinical groups. However, studies including these populations did not appear to differ systematically by task. In order to resolve this inconsistency, it would be important to obtain data from authors on the ΔERN and ERN effect (whether the negativity on error trials was significantly more negative compared to correct trials). Without information on the ERN effect, it is difficult to discern the meaning of the ERN amplitude averaged across multiple samples, particularly if some of those age groups did not exhibit a significant difference between error and correct trials.

It is possible that for children, the difference in negativity between error and correct trials indexes variation in EC skills whereas the ERN amplitude alone may just act as a proximal measure. However, this hypothesis would need to be tested and could be ascertained from researchers providing data on the CRN and ΔERN from previous research and including it in future studies. Lastly, there were no investigations of the N2 in children with internalizing problems that met criteria for the meta-analysis. Moreover, the N2 has not been assessed in children younger than 8 years who have internalizing problems. However, one would expect that if N2 is a measure of EC, young children experiencing difficulties with anxiety may have high levels of inhibitory control given the literature on the association between behavioral inhibition and anxiety, which may be observed as a reduced N2.

Limitations and future directions

Conclusions and implications from the present review should be considered in light of several methodological limitations that may have influenced the present meta-analysis results and, more generally, significantly pervade this area of research. There are several directions for future investigations to address these limitations that will greatly benefit the area of ERP research in the children and adolescents in examining the development of EC. Limitations and associated recommendations for future research will be presented in three primary domains: (1) sample characteristics, (2) methods/procedures, and (3) data analysis.

Sample characteristics

A majority of the studies on the ERN and N2 in children and adolescents primarily focused on middle to late childhood. The average age of all studies on the ERN in this developmental period (including studies that did not meet inclusion criteria for the meta-analysis) was 11.1 years and the average age for studies on the N2 was 10.4 years. The dearth of research on the ERN and N2 earlier in childhood introduces several limitations. First, research suggests that individual differences in EC emerges around 2–3 years of age and accelerates rapidly during the preschool years. Therefore, the lack of investigations on these neural measures of EC during the age range when it initially emerges and develops most rapidly precludes our ability to understand the full developmental progression of the ERN and N2, and examine the impact of their ongoing maturation on the development of EC. Second, the bias toward older samples likely influenced the results of the meta-analysis such that the age effects on the ERN and N2 may be an underestimate. Because there were not enough studies that provided data on the association between age and the ERN/N2, a meta-analysis on reported age effects could not be conducted. As a result, age needed to be averaged for separate samples included in the meta-analysis, which also could have minimized the reported effects of age on the ERN and N2. Lastly, of all the studies on the ERN and N2, there was only one longitudinal examination on the ERN (DuPuis et al., 2015). Although cross-sectional studies are more affordable and less time intensive compared to longitudinal designs, they simply do not afford the advantages of longitudinal studies, especially in the investigation of change over time. Thus, future research should focus on examining the ERN and N2 in early childhood using longitudinal study designs.

Regarding the composition of the samples included in ERN and N2 studies, very few assessed the ERN and N2 in typically developing children. It was more common that this area of research was examined in clinical samples. Although investigating behavioral and neural processes related to EC in clinical populations is important to understanding how these processes may go awry in development, it is difficult to extend findings from these studies to our understanding of normative development. Moreover, given that our current knowledge of the functional significance of the ERN and N2 in childhood is limited, proposed interpretations about observed differences in ERN/N2 amplitude between healthy controls and persons with clinical disorders are hypotheses that need to be tested further. However, it seems that these hypotheses continue to go untested and the number of investigations in clinical samples continue to increase. Therefore, there is a dire need for more studies examining the ERN and N2 in typically developing children in the preschool years to better understand how neural measures of attention influence emotionality, and vice versa, and how this interaction plays a role in the development of EC.

For clinical studies on youth with deficits in EC and/or difficulty with affect regulation, a major limitation of these studies is the heterogeneity within clinical disorder groups. This limitation can be difficult to address when there are periodic changes in the diagnostic criteria to meet specific psychological disorders, and the current diagnostic categories themselves have questionable reliability and validity (see Sanislow et al., 2010). The heterogeneity within clinical disorders such as ADHD likely reduces the consistency and specificity of results. Specifically, the different subtypes of predominantly inattentive symptoms, predominantly hyperactive-impulsive symptoms, or a combination of both likely have differential effects on the ERN and N2 amplitudes. For example, predictions from the CEMH may suggest that predominantly inattentive ADHD children may exhibit reduced ERN, reflecting primary deficits in error detection, and predominantly hyperactive-impulsive ADHD children may exhibit enhanced ERN, reflecting primary deficits in preparatory proactive control and reliance on reactive control. For the N2, it is possible that it may be reduced in both subtypes if both experience difficulties with processing conflicting stimuli prior to making a response. This hypothesis would need to be tested in a future study, but the utility of measuring the ERN and N2 is apparent, as it could reveal the stages at which deficits in EC may interfere during task performance (immediately following stimulus onset, response, or at both time points).

Another major limitation that pervades not only studies on the ERN and N2 in children, but also the broader neurocognitive and psychophysiological research fields, is that samples consist of primarily White European American, upper/middle class participants (Gatzke-Kopp, 2016). It is increasingly apparent that this common sample composition is not a “representative” sample due to the ongoing sociodemographic shift of growing ethnic minority populations. The issue of including a diverse sociodemographic sample should not be taken lightly due to the implications of assuming that results from current studies speak to how early individual differences in EC contribute to normal and abnormal development. Examining the racial/ethnic demographics provided by the studies included in the meta-analyses, the urgency of this issue cannot be ignored. Specifically, only 26.9% (n = 7) of studies examining the ERN in children (n = 26) included any racial demographic information. Of the 7 studies that included any racial demographics, 5 studies only provided the percentage of White European American subjects in the sample. Only 15.8% (n = 3) studies examining the N2 in children (n = 19) included any racial demographics. Including a more representative sample of the general population may be particularly important for future work investigating EC development given research demonstrating that low income, ethnic minority children are at higher risk for experiencing self-regulation difficulties (Raver, 2004). Furthermore, studies have suggested that that models of EC processes do not always match samples of ethnic minority children in the same way as they do for non-minority samples (Hill, Bush, & Roosa, 2003; Maughan & Cicchetti, 2002; Mendez, Fantuzzo, & Cicchetti, 2002).

Methods/procedures

A shocking number of different task types and paradigms were used across the studies on the ERN and N2. No two studies from different research groups used the exact same paradigm – studies that were closest in task type used an adapted version, varying the number of trials and timing of the task itself. None of these variations or even the creation of entirely new tasks was prefaced with a justification of chosen task parameters. This was also the case for ERP scoring methods, data acquisition and filtering rates. The extent to which scoring methods, data acquisition, and filtering rates influence the ERN and N2 amplitude have not yet been tested, but these factors do reduce consistency across studies and make study replication difficult. The present meta-analysis results suggest that ERN and N2 amplitudes may differ depending on task type. Given that much of the literature in this area relies on the comparison of the ERN and N2 amplitude in different groups (e.g., high and low anxiety, ADHD and healthy control), the effect of task type on the ERN and N2 amplitude may be concerning given that there is evidence of inconsistent results between studies that examine similar populations but use different task paradigms. However, no research in children has been conducted to identify the direct link between variations in task parameters and its impact on ERP amplitudes. Using multiple tasks within the same study may be particularly helpful in testing hypothesis about the functional significance of the ERN and N2 since tasks may place different demands on the participant (Johnstone, Barry et al., 2007).

Nearly half of the studies identified in the initial search of ERN and N2 studies in children were excluded from the meta-analysis due to a lack of information. The most common forms of missing data included the standard deviation of the ERN, the mean age of comparison groups, and the mean amplitude of the ERN itself (i.e., only waveforms presented); future studies should routinely include such measures. Moreover, the initial aim of the meta-analysis was to include the all components of the ERN (CRN and ΔERN) and N2 (low conflict N2 and ΔN2), but too few studies reported on the ERN and N2 effect. Therefore, the present meta-analysis results should be interpreted with this limitation in mind, principally, that these results do not provide insight into changes in the ERN or N2 effect across development.

Data analysis

There is an overrepresentation of studies focusing on analyzing group differences in ERN and N2 amplitude. Specifically, a majority of studies reviewed lacked exploration of associations between the ERN, N2, and behavioral task performance, and yet, many of these studies drew conclusions about the directionality of the amplitude difference as it related to behavioral performance outcomes. Investigating the relationship between ERPs and behavioral performance seems to be an effective method for evaluating the functional meaning of reported changes or group differences in the ERN and N2, particularly when the primary outcome of interest is often a behavioral measure (e.g., overall accuracy, post-error accuracy, post-error slowing). Evaluating the convergence of the ERN, N2, and behavioral performance measures could provide tests of dissociable effects of the ERN and N2.

Accordingly, this highlights the importance of multi-method assessment more generally and the value of examining the convergent and divergent validity of different measures of EC across multiple levels of analysis (e.g., informant-report, behavioral, and neurophysiological). The strength of these associations may also vary across development, but this has yet to be examined. Evaluating convergence within method, such as the association between the ERN and N2 within the same sample, would provide a more distinct test of the overlapping and dissociable effects of the ERN and N2 as measures of EC. However, of the few studies that included measures of both ERPs in their investigation, none evaluated the correlation between the ERN and N2. As measures of EC, one possible hypothesis is that the ERN and N2 should be correlated since they are also thought to arise from similar neural networks. If the ERN and N2 were correlated, this would not necessarily negate the hypothesis that they are measures of EC, but rather the overlapping variance shared by attentional and inhibitory control may be reflected in the correlation between the ERN and N2. Given the developmental trends observed in the meta-analysis, it is possible that there would be a negative correlation with increasing age.

Future directions that are essential for research in this area are incorporating alternative ERP analysis strategies to examine variability in behavioral performance measures across the entirety of the task, variability in temporal consistency and latency jitter, and the impact that variability has on the ERN and N2 amplitudes. For example, the Woody filter technique (Woody, 1967) time shifts an ERP waveform on each segment to match the averaged ERP template, and then averages the re-aligned segments (see Lin et al., 2015 for example). Time frequency analyses can then be used to examine the extent to which signals in the theta band (frequency band of the ERN and N2) are synchronized and impact of latency jitter on signal intensity and amplitude. Within-subject analyses can also be used to better understand trial-to-trial variability in behavioral performance and the impact changes in an individual's behavioral performance may have on their own ERN and N2 components.

When examining developmental changes in the ERN, N2, and EC, it is also necessary for researchers to consider the extent to which these changes reflect unique age-related effects or a more general effect of basic development. Future research should use meta-analytic correlation matrices and structural equation modeling to test for age effects at the level of a general EC factor (correlations among different measures of EC) and lower level factors of EC (attentional and inhibitory control). After taking into account any age effects on the general EC factor, then any additional effects at the lower level factors of EC can be examined. These findings would be crucial for guiding researchers in developing an overarching theory that accounts for differences in the ERN and N2 across a number of different domains such as age, task, and disorder type.

Concluding remarks

Decades of research have shown the significance of understanding early individual differences in EC skills and the importance of cultivating the mastery of this skill given its association to long-term outcomes related to the mental, physical, academic, and financial well-being at the individual and societal level (e.g., Caspi, Henry, McGee, Moffitt, & Silva, 1995; Moffitt et al., 2011). Research on the ERN and N2 in children and the implications of this research on our understanding of the development of EC is a burgeoning field. Therefore, scientists are positioned to take advantage of their opportunity to ensure that investigations in this emerging field address some of the existing limitations outlined in the present review. The recommendations provided will help bring the necessary rigor and refinement to future studies to fully capture and assess EC components traditionally separated by different research traditions. The present results are encouraging in terms of elucidating the neural processes associated with EC development and provide a foundation for researchers to further examine developmental mechanisms underlying individual differences in EC and their associations to later psychological adjustment and well-being.

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Contributors

Sharon Lo is the sole author of this study. She conducted analyses, literature review, and wrote the manuscript in its entirety.

Conflict of interest

I have no potential conflict of interest to disclose.

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Appendix A

See Table A.1.

Table A.1
Description of Event-Related Potential (ERP) components and indices.

ERP components	Description
ERN	The error-related negativity (ERN) appears as a negative deflection at frontocentral electrodes approximately 100 ms following the commission of an error. Typically, the ERN is enhanced (more negative) compared to negativities elicited following correct responses (correct-related negativity; CRN)
CRN	The correct-related negativity (CRN) appears as a negative deflection at frontocentral electrodes approximately 100 ms following a correct response. Typically, the CRN is reduced compared to the ERN
ΔERN	The ΔERN refers to the numerical difference between the ERN and CRN and is calculated by subtracting the CRN from the ERN (ERN − CRN = ΔERN). A positive ΔERN would suggest that the CRN was larger compared to the ERN whereas a negative ΔERN would indicate that the CRN was reduced compared to the ERN. The ΔERN is an indicator of the effect of the ERN.
High conflict N2	The high conflict N2 refers to the negativity preceding a correct response, and appears 200 ms following stimulus presentation on trials involving more conflict (e.g, a novel/infrequent stimulus, a trial in which subject needs to inhibit a response). Typically, the high conflict N2 is more enhanced compared to the N2 on low conflict trials. Depending on the task used to elicit the high conflict N2, researchers use different terms specific to the task to distinguish between low and high conflict N2. For example, in the go/no-go task, no-go N2 refers to high conflict trials and go N2 refers to low conflict trials
Low conflict N2	The low conflict N2 refers to the negativity preceding a correct response, and appears 200 ms following stimulus presentation on trials involving low conflict (e.g., a frequently seen stimulus, a trial in which subject does not need to inhibit their response). Typically, the low conflict N2 is reduced compared to the high conflict N2. As mentioned above, researchers may use terms to describe the go N2 depending on the task used to elicit the event-related potential. In the case of the go/no-go task, go trials are frequent and do not require the subject to inhibit their response, and therefore are low conflict trials and the N2 on these trials are referred to as the "go N2".
ΔN2	The ΔN2 refers to the numerical difference between the high and low conflict N2 and is calculated by subtracting the low conflict N2 from the high conflict N2 (high conflict N2 – low conflict N2 = ΔN2). A positive ΔN2 would suggest that the low conflict N2 was larger compared to the high conflict N2 whereas a negative ΔN2 would indicate that the low conflict N2 was reduced compared to the high conflict N2. The ΔN2 is an indicator of the N2 effect between low and high conflict trial types.

Appendix B

See Table B.1.

Table B.1
Hypotheses about the development of the ERN and N2 derived from the Conflict Monitoring Theory.

	ERN	N2
Amplitude and difference between trial types	Determined by post-response conflict processing and the discrepancy between early processing of the stimuli on the initial error and the correcting response	Determined by pre-response processing of distracting information and the difference between processing distracter information relative to target information
Developmental hypothesis	↑ EC skills ↑ Ability to process target stimuli ↑ Discrepancy between error and correct trials ↑ ERN	↑ EC skills ↑ Ability to ignore distracter stimuli ↓ Processing of distracter stimuli ↓ Discrepancy between distracter and target stimuli ↓ N2

Appendix C. PRISMA guide flow charts

See Figs. C.1 and C.2.

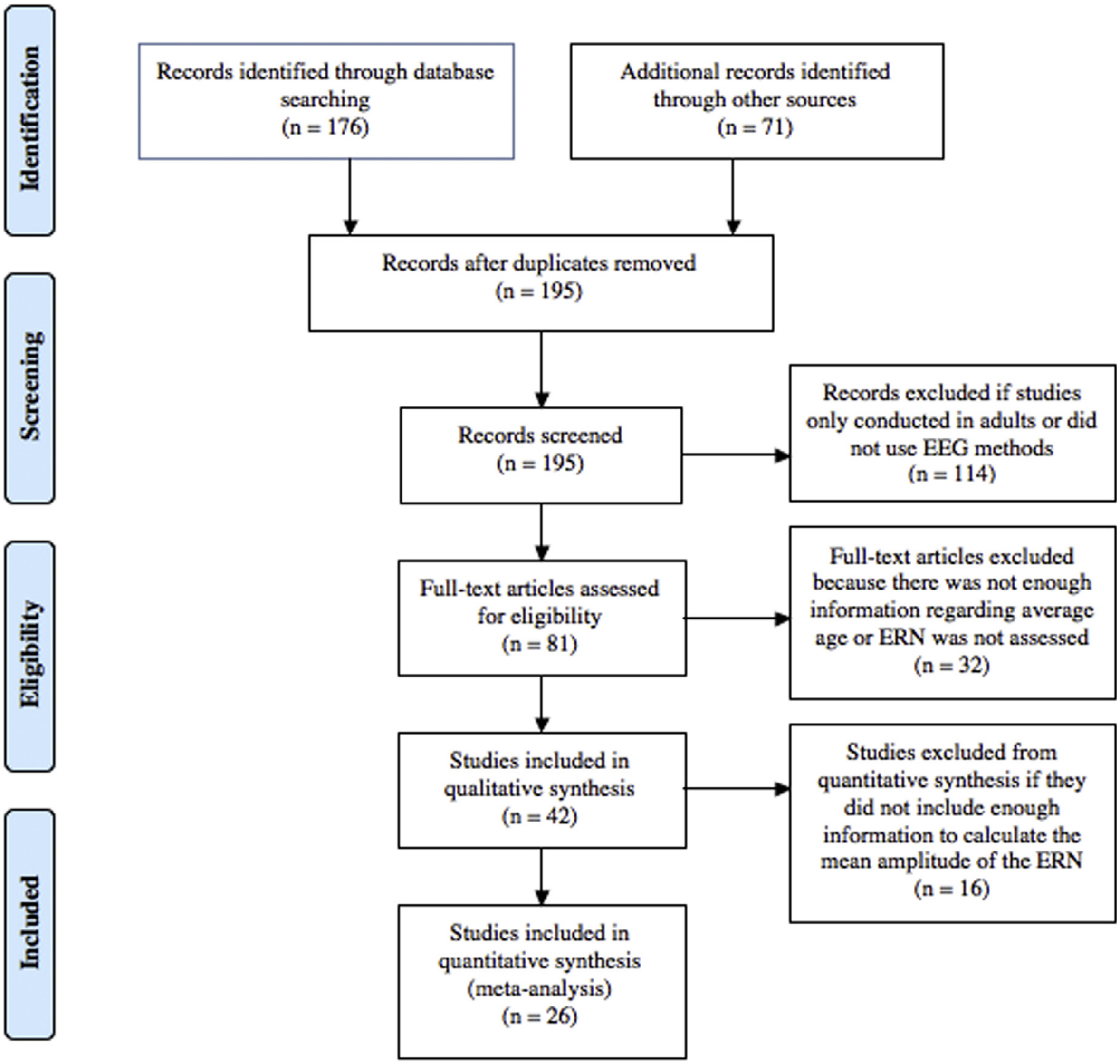

Fig. C.1. PRISMA guide flow chart of ERN studies included in meta-analysis.

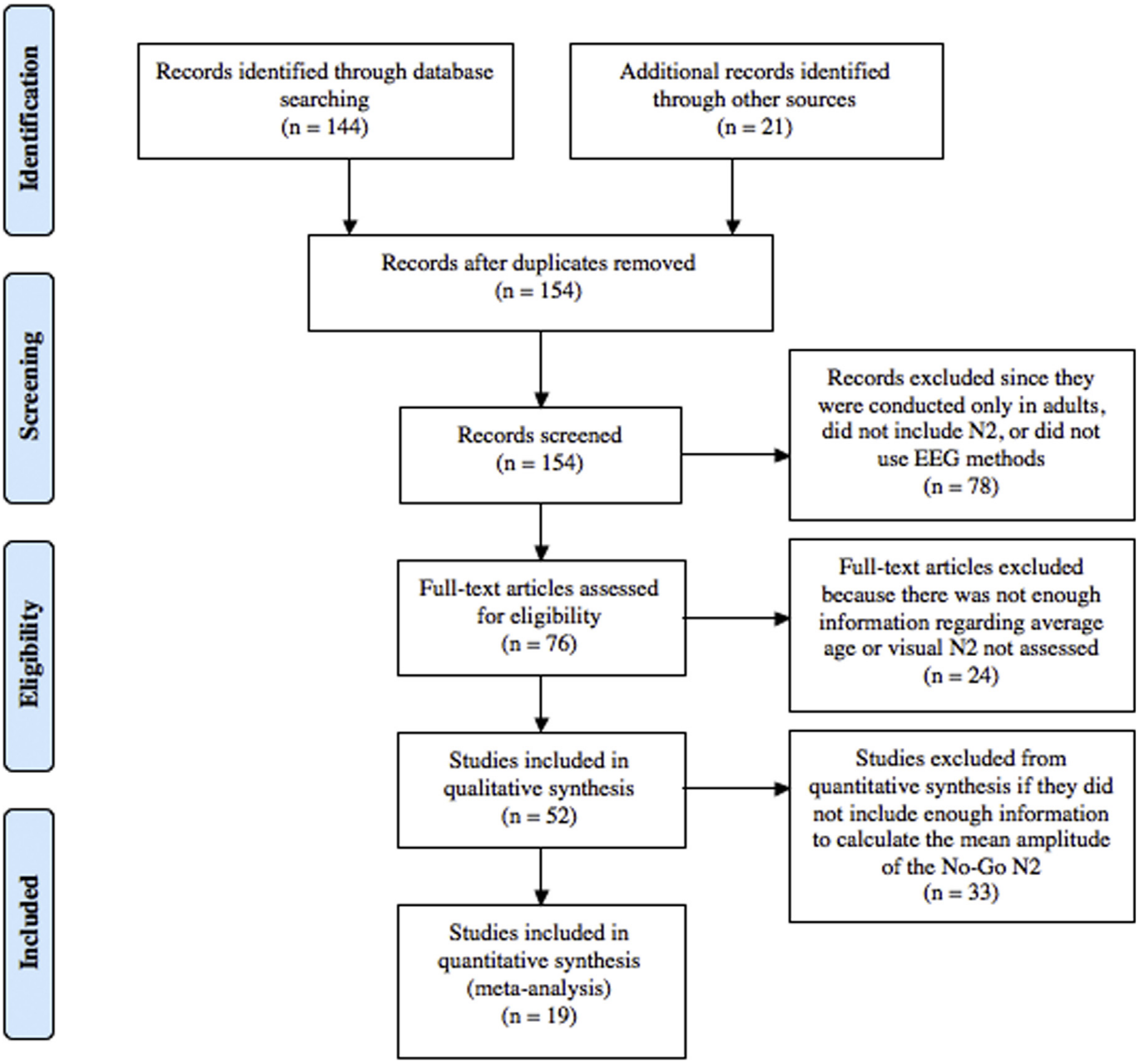

Fig. C.2. PRISMA guide flow chart of N2 studies included in meta-analysis

Appendix D. Studies included in meta-analysis

See Tables D.1 and D.2.

Table D.1

Studies included in the meta-analysis on the ERN. Studies in this table are grouped according to task and then year of publication.

Study	*N*	Age Group(s)	Task	Feedback	% Male	Sample comparison	Main Results
Henderson et al. (2006)	41	8–18	Arrow flanker	No	87	High Func ASD; Control	Larger ERN in youth with high functioning ASD
Jonkman et al. (2007)	20	8–12	Arrow flanker	No	89	ADHD; Control	No differences in the ERN
Wild-Wall et al. (2009)	39	11–17	Arrow flanker	No	63	ADHD; Control	No differences in the ERN
Albrecht et al. (2010)	70	8–15	Arrow flanker	No	50	Unaffected ADHD sibling	Larger ΔERN in control group as compared to unaffected ADHD siblings
Ladouceur et al. (2010)	16	9–17	Arrow flanker	No	63	None	Adolescents high in attentional control and negative affect exhibited slightly larger ERNs; age did not significantly predict ERN
South, Larson, Krauskopf, and Clawson (2010)	45	8–21	Arrow flanker	No	93	ASD; Control	Reduced ERN in youth with ASD as compared to typically developing youth
Hanna, Carrasco, and Harbin (2012)	88	10–18	Arrow flanker	No	52	Tic OCD; Control	Larger ERN in youth with OCD as compared to youth with Tic OCD and healthy controls; ERN increased with age only in healthy controls
van Meel, Heslenfeld, Rommelse, Oosterlaan, and Sergeant (2012)	47	6–12	Arrow flanker	No	62	None	No age differences in ERN amplitude
Carrasco et al. (2013)	66	8–16	Arrow flanker	No	35	GAD; OCD; Control	Larger ERN in children with anxiety disorder as compared to healthy controls
Liu, Woltering, and Lewis (2014)	40	10–19	Arrow flanker	No	55	OCD; Control	Larger ERN in youth with OCD compared to healthy controls
Meyer, Bress, and Proudfit (2014)	55	8–13	Arrow flanker	No	56	None	Test-retest reliability of ERN $r = 0.34$
Samyn et al. (2014)	65	10–15	Arrow flanker	No	68	ADHD; ASD; Control	Reduced ERN in youth with ADHD compared to healthy controls
Kim, Iwaki, Uno, and Fujita (2005)	9	7–8; 9–11	Go/No-Go	Yes	35	Experiment - effect of observer	Larger ERN observed in 9–11 year olds compared to 7–8 year olds; larger ERN in groups that worked under the observation of a peer
Kim, Iwaki, Imashioya, Uno, and Fujita (2007)	9	7–8; 9–11	Go/No-Go	Yes	45	Age	No ERN difference between younger age groups or compared to young adults
Torpey et al. (2013)	315	5–7	Go/No-Go	Yes	55	Maternal history of anxiety disorder	High negative emotionality and maternal history of anxiety disorders predicted reduced ERN in young children
Grammer, Carrasco, Gehring, and Morrison (2014)	95	3–7	Go/No-Go	No	48	None	Age did not predict variation in the ERN
Richardson, Anderson, Reid, and Fox (2011)	77	7; 9	Fish flanker	No	44	Age	No age group differences in ERN amplitude
Lahat et al. (2014)	113	7	Fish flanker	Yes	46	Low vs. High BI	Larger ERN in 7 year olds with high behavioral inhibition as 4-year olds
Brooker and Buss (2014)	41	4	Fish flanker	Yes	51	Low vs. High Fear	ERN elicited in children with high fear, but children with low fear did not exhibit an ERN effect
Santesso et al. (2006)	39	10	Letter flanker	No	41	Age	Reduced ERN in 10 year olds compared to young adults
Santesso and Segalowitz (2008)	35	15–16	Letter flanker	No	100	Age	Reduced ERN in adolescents (15–16 years) compared to young adults (18–20 years)
Euser, Evans, Greaves-Lord, Huizink, and Franken (2013)	68	12–20	Letter flanker	Yes	43	SUD Risk	ERN somewhat reduced in adolescents at high risk for SUD
Checa et al. (2014)	47	4–6; 7–9; 10–13	Robot flanker[1]	Yes	52	Age	ERN effect was not observed in 4–6 year olds
Hogan, Vargha-Khadem, Kirkham, and Baldeweg (2005)	12	12–19	4-Choice response	No	48	Age	Reduced ERN in adolescents compared to adults on infrequent incompatible trials
Vlamings, Jonkman, Hoeksma, Van Engeland, and Kemner (2008)	27	9–10	Auditory decision	No	97	ASD; Control	Reduced ERN in ASD children compared to controls
Senderecka et al. (2012)	40	7–12	Stop signal	No	80	ADHD; Control	Reduced ERN in youth with ADHD compared to healthy controls

High Func ASD: High Functioning Autism Spectrum Disorder. ADHD: Attention Deficit Hyperactivity Disorder. ASD: Autism Spectrum Disorder. Tic OCD: Obsessive-Compulsive Disorder with Tics. GAD: General Anxiety Disorder. OCD: Obsessive-Compulsive Disorder. BI: Behavioral Inhibition. SUD: Substance Use Disorder.

[1] Robot flanker is a modified flanker task using different shaped robots as stimuli.

Table D.2

Studies included in the meta-analysis on the N2. Studies in this table are grouped according to task paradigm and then year of publication.

Study	*N*	Age Group (s)	Task	Feedback	% Male	Sample Comparison	Main Results
Jonkman et al. (2007)	20	8–12 yr	Arrow flanker	No	90	ADHD; Control	Larger N2 on error trials in ADHD children compared to control
Albrecht et al. (2010)	70	8–15 yr	Arrow flanker	No	50	ADHD risk (sibling with ADHD)	Reduced N2 on incongruent trials in nonaffected siblings with risk for ADHD compared to controls
Ladouceur et al. (2010)	29	9–17 yr	Arrow flanker	No	66	None	Larger N2 in children with higher self-reported negative affect and attentional control; age did not significantly predict N2
van Meel et al. (2012)	47	6–9; 10–12	Arrow flanker	Yes	62	Age	Reduced N2 on incongruent trials in younger children
Fallgatter et al. (2004)	35	7–12 yr	CPT	No	100	ADHD; Control	No group differences in N2 components
Jonkman (2006)	33	6–7; 9–10	CPT	No	30	Age	ΔN2 decreased with age
Spronk et al. (2008)	27	5–7 yr	CPT	Yes	55	ADHD; Control	No group differences in ΔN2
Tye et al. (2014)	92	8–13 yr	CPT	Yes	100	ADHD; ASD; ADHD + ASD; Control	Reduced ΔN2 effect in ASD and ASD + ADHD groups compared to ADHD only and control
Espinet et al. (2012)	45	3–4 yr	DCCS	No	36	None	Reduced N2 for children who passed post-switch versus those who failed
Rueda, Posner, Rothbart, and Davis-Stober (2004)	22	4 yr	Fish flanker	Yes	50	Age (compared to adult)	N2 decreased with age
Rueda et al. (2005)	73	4; 6	Fish flanker	Yes	51	Pre- vs. Post-training	ΔN2 effect observed post-training only in 6 year olds; larger N2 on incongruent trials post-training in 4 year olds
Buss et al. (2011)	26	4–6; 6–8	Fish flanker	Yes	66	Age	ΔN2 effect only found in older age group; Larger ΔN2 was related to a greater difference between RT on incongruent versus congruent trials; Larger ΔN2 and related to lower parent-reported EC
Abundis-Gutiérrez, Checa, Castellanos, and Rueda (2014)	46	4–13 yr	Fish flanker	yes	NI	Age	ΔN2 effect was only observed in adults, not children
Brydges et al. (2014)	215	7–9 yr	Fish flanker	No	51	None	Larger ΔN2 predicts better behavioral performance on executive functioning tasks
Lamm, Zelazo, and Lewis (2006)	33	7–11; 11–16	Go/No-Go	Yes	100	Low vs. High EF task performance	Reduced N2 related to better performance on EF tasks after controlling for age
Cragg et al. (2009)	56	7; 9	Go/No-Go	No	42	Age	Larger ΔN2 and shorter N2 latency observed in older children
Chevalier, Kelsey, Wiebe, and Espy (2014)	30	5–6 yr	Go/No-Go	Yes	40	None	N2 effect not observed in children
Senderecka et al. (2012)	40	7–12 yr	Stop signal	Yes	80	ADHD; Control	Larger N2 on successful stop trials in children with ADHD
Cao et al. (2013)	176	6–11 yr	Spatial stroop	No	70	ADHD; Control	No group differences in N2 components; N2 on incongruent trials increased with age

CPT: Continuous Performance Task. DCCS: Dimensional Card Change Sort. ADHD: Attention Deficit Hyperactivity Disorder. ASD: Autism Spectrum Disorder. ADHD + ASD: Comorbid Attention Deficit Hyperactivity Disorder and Autism Spectrum Disorder. EF: Executive Functioning.

Appendix E. Meta-analysis coding procedures

E.1. Coding ERN and N2 mean amplitudes

When recording mean amplitudes and standard deviations of the ERN and N2, there were several coding decisions that were made based on the following criteria:

(1) When a study reported on the ERN or N2 on multiple tasks, the task more commonly used to elicit the neural marker of interest was included in the meta-analysis (e.g., an arrow flanker chosen over a go/no-go task for measure of the ERN and vice versa for the N2)
(2) When multiple time-points were collected (e.g., pre- and post-intervention or baseline and follow-up), only the first time-point or baseline measure was included in the analysis.
(3) When a study reported on a sample randomly selected into different experimental manipulations (i.e., intervention or treatment), the ERN or N2 measured for the entire sample at baseline was included in the analysis.
(4) When a study manipulated specific aspects of the task (e.g., visual degradation of the stimuli), the ERN or N2 reported on control or baseline trials (e.g., 0% visual degradation) was included in the analysis.

E.2. Coding of variables

We coded several relevant variables (proportion of males, task paradigm, and diagnosis) to test whether the ERN and N2 mean amplitude differed as a function of these variables. Proportion of males was coded as the percentage of males in the study sample. Task paradigm was coded categorically**.** If authors used an adapted version of an original task, it was coded as the original task. For example, if authors reported that they used an adapted version of the fish flanker, this study would have been coded as “fish flanker”. If the adapted task used different stimuli such as letters, or robots, this was coded based on the type of stimuli used (e.g., letter flanker, robot flanker). Diagnosis was coded as “Internalizing”, “Externalizing”, “Community”, and “ASD” groups. Samples were coded in the “Internalizing” category if they had a mental health disorder commonly associated with internalizing psychopathology such as anxiety and mood disorders whereas samples coded as “Externalizing” had a mental health disorder commonly associated with externalizing psychopathology such as attention-deficit hyperactivity disorder and conduct disorder. Samples were coded as “Community” if the researchers did not sample for clinical populations and used community samples. Samples were coded as “ASD” if researchers recruited samples with autism spectrum disorder diagnoses.

Appendix F

See Table F.1.

Table F.1
Description of tasks used to elicit the ERN and N2 from studies included in the meta-analysis.

Tasks	Description
4-Choice response*	Horizontal arrows are presented and subjects are asked to press a response button that corresponds to the direction of the arrows (i.e., left or right). The 4-choice response task presents subjects with either a green-colored arrow or red-colored arrow randomly pointing left or right. When presented with green-colored arrows, subjects are instructed to press the response button that corresponds with the correct direction of the arrow pointing. In contrast, when presented with red-colored arrows, subjects are instructed to respond with the opposite response button. Red arrows appeared 25% of the time while green arrows appeared 75% of the time. There was equal probability that both red and green arrows were pointing right or left.
Arrow flanker	On each trial, 5 horizontally aligned arrowheads are presented, some of which are congruent (> > > > > or < < < < <) and some of which are incongruent (> > < > > or < < > < <). The percentage of congruent and incongruent trials often varies depending on the study, but typically the task contains 50% congruent and 50% incongruent trials. Subjects are instructed to press a button that corresponds to the direction of the middle arrow. Incongruent trials in this task are often more challenging and considered higher conflict than congruent trials.
Auditory decision*	In the first level of the task, subjects were presented with 4 different animal noises binaurally through headphones and instructed to press a right-hand button for the cat noise but press a left-hand button for any other animal noise (cat noises were presented in 50% of the trials while non-cat noises were presented in 50% of the trials). In second level of the task, all animal noises were presented with equal frequency and subjects were instructed to press the right-hand button if the preceding animal noise matched the one following, and press the left-hand button when the noises did not match.
CPT	Subjects are instructed to press a button when a specific letter (e.g., 'X') appears but only when preceded by another letter (e.g., 'A'). This type of trial (e.g., A-X sequence) is a congruent trial whereas trials in which an A was not followed by an 'X', the subject would need to inhibit their response and therefore is an incongruent trial. Researchers use different adaptations for this task and typically vary the sequence letters (e.g., 'O' and 'X'; 'A' and 'X') and the number of non-target letters. The 'A-X' sequence example provided in this description is one of the more common versions used in the developmental literature.
DCCS	Subject is instructed to first sort cards by one feature (e.g., color) and then switch rules to sorts cards by a different feature (e.g., shape). If the subject obtains 5 out of 6 trials correct, they advance to the next portion of the task where they are asked to sort cards by color if they were presented with a card with a border and sort by shape if they were presented with a card with no border.

(*continued on next page*)

Table F.1 (*continued*)

Tasks	Description
Fish flanker	The fish flanker is an adaptation of the arrow flanker and instead of arrowheads uses yellow cartoon fish facing different directions. The primary difference between the fish flanker and arrow flanker is the stimuli (fish versus arrowheads).
Go/No-Go	Subjects are instructed to respond on trials that present a specific stimulus. These trials are known as 'go trials'. Subjects are instructed that when they see a different type of stimulus to inhibit their responses. These trials are known as 'no-go trials“. Similar to the Flanker task, researchers choose different types of go and no-go stimuli, but regardless of the stimuli the principle remains that subjects respond on go trials and must inhibit their response on no-go trials.
Letter flanker	The letter flanker is an adaptation of the arrow flanker and instead of arrowheads uses closely shaped letters (e.g., M and N, or S and H) such that congruent trials may look like 'MMMMM' or 'NNNNN' and incongruent trials may be presented as 'MMNMM' or 'NNMNN'. Subjects are instructed to press a button that corresponds to the middle letter.
Robot flanker*	This task is an adaptation of the Flanker task. Stimuli used in this task were 5 horizontally presented robots that were either shaped like circles or squares. Congruent trials would either be ○○○○○ or □□□□□ while incongruent trials would appear as ○○□○○ or □□○□□.
Stop signal*	Subjects were presented with a cartoon picture of a plane heading left or right. Subjects were instructed to press either left and right arrow buttons according to the plane direction. On a random 25% of the trials, an auditory tone was presented binaurally through headphones, which acted as the “stop signal”. Subjects were instructed that when they heard the stop signal, they needed to inhibit their response to the primary task regardless of the plane direction.
Spatial stroop*	Subjects are instructed to press either a right-hand or left-hand button corresponding with the direction of an arrow pointing up or down that was presented in one of 4 positions surrounding a central fixation cross (left, right, above, below). Congruent trials included those that the position of the arrow was compatible with the response (e.g., right-hand button press and arrow positioned to the right of fixation cross) and incongruent trials included those that the position of the arrow was incompatible with the response (e.g., right-hand button press and arrow positioned to the left of fixation cross).

* These tasks were specific to individual studies included in meta-analyses (i.e., were not used by more than one study) and therefore the specific description of the task used in each respective study was provided here.

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