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The neural correlates of temperamental inhibitory control in toddlers

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The current study examined the association between effortful control and a well-studied neural index of self-regulation, the N2 event-related potential (ERP) component, in toddlers. Participants included 107 toddlers (44 girls) assessed at 30, 36 and 42 months of age. Participants completed a Go/NoGo task while electroencephalography data were recorded. The study focused on the N2 ERP component. Parent-reported effortful control was examined in association with the NoGo N2 ERP component. Findings suggest a positive association between the NoGo N2 component and the inhibitory control subscale of the wider effortful control dimension, suggesting that the N2 component may index processes associated with temperamental effortful control.

This article is part of the theme issue 'Diverse perspectives on diversity: multi-disciplinary approaches to taxonomies of individual differences'.

1. Introduction

Research on neural biomarkers in early childhood has led to improved understanding of the early correlates of developing psychopathology [1]. Similarly, child temperament—early-emerging, biologically based, individual differences in reactivity and self-regulation—has been shown to be associated with emerging psychopathology [2–4]. However, relatively little research has focused on understanding how these two markers of risk for psychopathology are associated with one another in early childhood. To fill this gap in the literature, this study examines the association between temperamental regulation and a well-studied neural biomarker for dysregulation, the N2 event-related potential (ERP) component, in toddlers.

2. Temperamental effortful control

Temperament describes individuals' tendencies when reacting to changes in their internal and external environment (i.e. reactivity) and their capacity to modulate this reactivity (i.e. self-regulation). Temperament, as measured in childhood, is frequently subdivided into three broad dimensions, including surgency/extraversion and negative affectivity, both of which describe individual differences in reactivity, and effortful control [5], which describes individual differences in the capacity to modulate reactivity. While self-regulatory processes are likely associated with all three dimensions of temperament, individual differences in self-regulation are best described via the dimension of effortful control. Effortful control includes a variety of processes, including the capacity to inhibit a prepotent response, the capacity to execute goal-directed behaviours, and the capacity for strategic allocation of attention. Children with poor effortful control have been shown to be at increased risk for externalizing problems [6,7], academic difficulties [8] and social problems [9].

Temperamental effortful control can be measured using a variety of techniques, including parent-report measures, laboratory or home observations, and laboratory tasks [10]. Effortful control has been shown to improve dramatically across childhood, from reliance on caregivers for regulation in infancy to the more self-initiated deployment of regulatory strategies in childhood [10]. The toddler to preschool years are characterized by particularly rapid improvements in the skills associated with effortful control [10,11]. However, despite mean-level improvements in performance on effortful control tasks across childhood, as an aspect of temperament, it typically shows rank-order stability across development [4].

3. The neural correlates of effortful control

Research suggests that an important root of effortful control is in the executive attention network, a well-specified neural network that underlies the self-initiated deployment of attention and other higher-order cognitive abilities [12,13]. The regions that comprise this network, including the anterior cingulate cortex (ACC) and regions of the lateral prefrontal cortex (PFC), are thought to underlie effortful control abilities [10,13]. These brain regions monitor and regulate activation in the networks of brain responsible for reactivity, emotional expression and motoric behaviours [14,15]. Although the ACC and lateral PFC are active in infancy, it is during the late toddler and preschool period that they begin to take on the regulatory characteristics of what will become their adult functionality [16]. The development of these prefrontal brain regions theoretically underlies improved self-regulation across development. However, empirical studies are needed to assess such processes. To study neural activation in toddlers, the most feasible methodology is electroencephalography (EEG) and corresponding ERPs. ERPs represent large-scale, synchronous neural activity that is time-locked to stimulus presentation. Although ERPs lack the spatial resolution of magnetic resonance imaging, they have high temporal resolution, and are better suited to study rapidly occurring neural processes, like effortful control.

4. The N2 event-related potential component

The N2 ERP component is the second negative deflection in the waveform that occurs from approximately 200 to 400 ms post-stimulus across fronto-central electrodes. The N2 component has been elicited in both adults and children and is thought to index aspects of cognitive control [17], particularly response inhibition capacities. The amplitude of the N2 component is larger (more negative) in response to NoGo stimuli (in which inhibition is required) than to Go stimuli (in which activation is required). This feature of the N2 led researchers to theorize that the N2 component reflects response inhibition capacities. Poorer response inhibition, thought to be indexed by larger N2 amplitudes, has been associated with externalizing behaviour problems in childhood [18], leading some researchers to propose that the N2 component is a biomarker for dysregulation.

Go/NoGo (GNG) tasks are frequently used to assess the N2 component. This task includes two stimuli: a Go stimulus, which is paired with response activation (e.g. a button press), and a NoGo stimulus, which is paired with response inhibition. To establish a prepotent tendency to respond, thereby making the inhibition task more difficult, the Go stimuli are often presented more frequently than the NoGo stimuli. Several studies that have used source localization techniques to identify the neural generators of the N2 component elicited during a GNG task have suggested that the N2 component can be localized to the ACC, orbitofrontal cortex, ventral PFC and dorsolateral PFC [19–21]. Both of these prefrontal regions are thought to underlie response inhibition capacities specifically, as well as executive functioning more broadly. There is notable overlap between skills encompassed within executive functions and effortful control, such that differences might actually reflect the different disciplines from which each construct emerged [22]. Hence, it is possible that the N2 component could index the neural correlates of effortful control.

To examine this possibility, several research teams have examined the association between the N2 component and effortful control abilities. Across these studies, a somewhat contradictory pattern of findings has emerged. Using a GNG task, Wiersema & Roeyers [23] found that, in school-aged children, NoGo N2 amplitudes were negatively associated with an aspect of parent-reported effortful control (attentional shifting), such that children with larger, more negative NoGo N2 amplitudes tended to have better attentional shifting skills [23]. Notably, however, parent-reported levels of other types of effortful control, including attentional focusing, impulsivity and persistence, were not found to be associated with N2 amplitudes [23]. Alternatively, using a flanker task, Buss *et al*. [24] found that smaller, less negative N2 amplitudes during incongruent trials in 4–8-year-old children were associated with higher levels of parent-reported effortful control. Similarly, in a sample of preschool-age children, Rueberry *et al*. [23] found that the difference in amplitude between the N2 in the Go and NoGo conditions (Go–NoGo) was positively associated with performance on a battery of effortful control tasks, such that children with a greater difference between Go and NoGo N2 amplitudes performed better on effortful control tasks. As a larger difference between Go and NoGo N2 amplitudes is thought to reflect more advanced conflict detection capacities, this finding aligns with expectations of how the N2 component should theoretically be associated with effortful control. However, the sparse, but conflicting, findings of the studies highlighted above suggest that more research is needed to explore the association between effortful control and the N2 component.

5. Current study

The current study examined the neural correlates of effortful control in toddlers, by examining the association between effortful control and the N2 ERP component. This is the first such study, to our knowledge, to focus on toddlerhood. As the toddler and preschool years are characterized by substantial improvements in executive functioning, this is an especially important era during which to examine the neural correlates of effortful control/executive functioning. Because previous findings with older children have been contradictory, we used theory to guide our hypothesis. Based on findings that suggest that more mature response inhibition capacities are associated with smaller, less negative NoGo N2 amplitudes [17], we expected higher levels of parent-reported effortful control to be associated with less negative NoGo N2 amplitudes.

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6. Methods

For a description of the methods of the current study, see the electronic supplementary material, appendix S1.

7. Results

Descriptive statistics for all variables included in analysis are presented in electronic supplementary material, table S2. Only correlations with the temperament scales for inhibitory control, attentional control and effortful control are presented in electronic supplementary material, table S2; correlations with the two other subscales of the effortful control composite, low intensity pleasure and perceptual sensitivity, were not significant ($-0.01 < r < 0.05$, $p > 0.05$), so they are not considered further.

Grand-averaged waveforms for the Go and NoGo conditions are presented in figure 1*a*. The N2 elicited to NoGo trials ($M = -2.96$ µV) was significantly more negative than the N2 to Go trials ($M = -0.51$ µV; $t[156] = -2.56$, $p = 0.01$). We calculated the N2 effect by subtracting Go N2 amplitudes from NoGo N2 amplitudes (i.e. NoGo–Go), such that a larger difference between NoGo and Go N2 amplitudes was represented by a more negative N2 effect score. Correlations between Go and NoGo N2 amplitude, the N2 effect, behavioural performance on the Fish–Sharks task, and child temperament are presented in electronic supplementary material, table S2.

Behavioural performance on the Fish–Sharks task, as indexed by the per cent of correct NoGo trials, was correlated with N2 effect ($r[157] = 0.25$, $p = 0.002$). Findings suggest that better performance on the inhibition trials of the Fish–Sharks task was associated with a smaller difference between Go and NoGo N2 amplitudes. In a follow-up test, we found a negative association between Go N2 amplitudes and behavioural performance ($r[157] = -0.27$, $p = 0.001$), such that enhanced Go N2 amplitudes were associated with better performance on the Go/NoGo task. As the Go N2 component is not thought to be associated with response inhibition, this correlation was not investigated further.

The inhibitory control and attentional control subscales of the children's behaviour questionnaire (CBQ) were significantly, positively associated with NoGo N2 amplitudes ($r[142] = 0.23$, $p = 0.007$ and $r[142] = 0.17$, $p = 0.04$, respectively), such that children with higher levels of parent-reported inhibitory and attentional control showed less negative (smaller) NoGo N2 amplitudes. As less negative NoGo N2 amplitudes have been associated with more mature response inhibition [17], these findings suggest that better temperamental inhibitory and attentional control is associated with a neural response pattern indicative of better response inhibition capacities. Given that the higher-order effortful control scale comprised both the inhibitory control and attentional control subscales, but also the low intensity pleasure and perceptual sensitivity subscales, it is understandable that a trend association emerged between the effortful control scale and NoGo N2 amplitude ($r[142] = 0.16$, $p = 0.056$). Although worth mentioning, we did not further investigate this association because it did not meet traditional thresholds for statistical significance. No significant association was found between the N2 effect and child temperament. Additionally, in a follow-up test, we found no association between Go N2 amplitudes and child temperament.

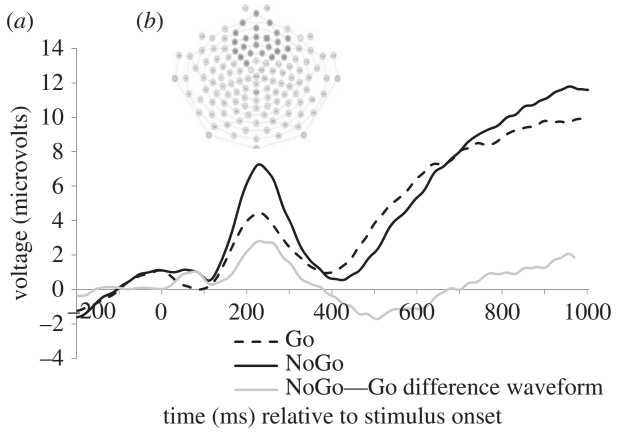

Figure 1. (*a*) Grand-averaged N2 waveforms across the (*b*) fronto-central electrode group determined via temporospatial principal component analysis (PCA) to correspond with the N2 component. The waveform depicted represents the mean waveform from those electrodes with a 0.4 or greater factor loading onto the PCA component reflecting the N2; electrodes were averaged with equal, unit weighting.

The three significant associations (behavioural performance and the N2 effect; temperamental inhibitory control and NoGo N2 amplitudes; attentional control and NoGo N2 amplitudes) were further tested using multiple regression, controlling for the number of trials kept in the NoGo condition, child age (in months) and child sex. These associations are presented in table 1. When these associations were further examined using nested regression to account for the longitudinal dependency in the data, two effects (behavioural performance and the N2 effect; temperamental inhibitory control and NoGo N2 amplitudes) remained significant. However, the association between attentional control and NoGo N2 amplitudes became a trend rather than statistically significant when accounting for longitudinal dependency ($p = 0.054$).

8. Discussion

The current study's findings replicate and extend the existing literature on the neural correlates of effortful control. Our findings suggest an association between the NoGo N2 ERP component, an index of response inhibition and temperamental inhibitory control. Less negative NoGo N2 amplitudes were associated with better parent-reported inhibitory control, a scale thought to index a child's ability to suppress inappropriate responses when directed. The association between the attentional control subscale, a scale thought to index the child's capacity to maintain appropriate attention on task-relevant stimuli, and the NoGo N2 ERP component was initially significant, but was no longer significant when accounting for covariates and nested data, so while this suggests that the N2 may also be associated with attentional control, the current study did not show this association at a $p < 0.05$ level. Additionally, the other subscales comprising the effortful control construct (low intensity pleasure and perceptual sensitivity) were not associated with the N2 ERP component, suggesting a potentially unique association between the N2 and the more regulatory aspects of effortful control. This was expected given that the low intensity pleasure and perceptual sensitivity subscales assess preference for lower levels of stimulation and attention to minute environmental details

Table 1. Multiple regression analyses predicting (*a*) NoGo N2 amplitude with inhibitory control, attentional control and control variables and (*b*) the N2 effect (Go−NoGo) with NoGo trials per cent correct and control variables.

(*a*) NoGo N2 amplitude	*B*	*β*	s.e.	*p*-value
CBQ inhibitory control	2.91	0.25	1.09	<0.01
control variables				
# NoGo trials included	−0.16	−0.06	0.23	0.48
Age (months)	−3.07	−0.11	2.70	0.26
Sex[a]	−1.42	−0.07	1.82	0.44
			$F_{4,118} = 2.24$, $p = 0.06$, $R^2 = 0.07$	
CBQ attentional control	1.97	0.21	0.91	<0.05
control variables				
# NoGo trials included	−0.11	−0.05	0.23	0.62
Age (months)	−3.36	−0.04	2.74	0.22
Sex[a]	−0.79	−0.11	1.79	0.66
			$F_{4,118} = 1.62$, $p = 0.17$, $R^2 = 0.05$	
(*b*) N2 effect	***B***	***β***	**s.e.**	***p*-value**
NoGo per cent correct	0.25	0.30	0.09	<0.01
control variables				
# NoGo trials included	−0.40	−0.12	0.36	0.27
Age (months)	−6.27	−0.15	3.56	0.08
Sex[a]	−2.15	−0.08	2.23	0.34
			$F_{4,125} = 3.30$, $p < 0.05$, $R^2 = 0.10$	

[a]0 = male, 1 = female.

(respectively), and such traits are not thought to be related to the N2 component.

Our findings replicate the Buss *et al.* [24] finding that the N2 component indexes some aspects of effortful control in childhood, while supplementing these findings in two important ways. First, our use of a different task to elicit the N2 component suggests that the N2 component, across paradigms, indexes a neural process related to inhibitory control. Additionally, the current study extends the findings of Buss *et al.* [24] to a sample of toddlers. Toddlerhood is a period of rapid improvements in effortful control. Given the importance of toddlerhood for the development of effortful control abilities, the identification of a potential neural biomarker at this age could have important practical implications for both our understanding of the normative development of effortful control as well as our understanding of emerging deficits in effortful control. Our findings did not replicate those of Wiersema & Royers [23], who found a positive association between the NoGo N2 and certain aspects of effortful control in middle childhood, or Ruberry *et al.* [25], who found that conflict monitoring capacities, as represented by the Go–NoGo difference waveform, were associated with effortful control. These divergent findings could be due to differences in the age of the sample [23] or differences in the measurement of effortful control [25]. More research will be needed to understand why contradictory findings characterize this literature. Additionally, our findings provide support for the hypothesis that the executive attention system, which is thought to functionally underlie the N2 component, supports effortful control abilities in very early childhood.

Our findings contribute to the development of taxonomies of individual differences based on neurobiological correlates in two ways. First, they provide support for the role of the executive attention network as a neural network underlying effortful control capacities, such that dysfunction in this network might underlie dysregulated behaviour in children with low levels of effortful control. Next, our findings suggest that efforts to develop taxonomies of individual differences can and should incorporate young children, examining the application of developed taxonomies to early childhood.

Among the strengths of this study, it is the first, to our knowledge, to examine a plausible electrophysiological marker for effortful control in very early childhood. Additionally, this study also provides electrophysiological evidence for the executive attention network's role in supporting effortful control in toddlerhood. Additionally, the study has a large sample when compared with many ERP studies of young children, which enables a more stable estimate of covariations between the study's measures. The study also has limitations. Although this study contributes to a literature examining the brain networks underlying effortful control, ERPs do not provide conclusive information about the brain regions underlying the components we examined. Our inferences from source localization studies with older children and adults about the brain regions involved in the N2 and task performance have to be somewhat tentative, because we cannot be sure how applicable these studies are to toddlers. Future studies, using novel imaging techniques with good spatial resolution (e.g. near-infrared spectroscopy), could better articulate the neural regions associated with effortful control.

In summary, the findings of the current study support an association between the N2 ERP component and parent-reported effortful control in toddlers, in which smaller, less negative NoGo N2 amplitudes were associated with better effortful control. These findings add to an existing literature examining the neural correlates of temperament in both childhood, focusing on an understudied age group, and toddlers, for whom effortful control abilities are developing rapidly.

Ethics. All procedures approved and monitored by the Institutional Review Board at Indiana University.

Data accessibility. The datasets supporting this article have been uploaded to Open Science Framework at the following link: https://osf.io/9nzev/ [26].

Authors' contributions. All four authors met all of the requirements for authorship.

Competing interests. We have no competing interests.

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Supplementary Appendix S1. Methods

Participants and Procedures

Participants in the current study include toddlers recruited from a mid-sized, Midwestern city at 30 months of age, and assessed at three time points: 30, 36, and 42 months, as part of a larger, ongoing multi-site longitudinal study. At each age, caregivers were given the option to have their children participate in a laboratory visit during which EEG data were collected. Of the 221 children whose parents were given the option to take part in the EEG visit, 175 children's parents (170 mothers) opted to have their child participate at at least one time point. In the current study, 133 children (61 female) participated in the Fish-Sharks task at 30 months, 99 children (51 female) participated at 36 months, and 90 children (45 female) participated at 42 months. Data from three of these children were excluded because they had a parent-reported history of seizures or serious head injury. The number of children with usable data at each age was 52 (21 female) at 30 months, 50 (27 female) at 36 months, and 59 (25 female) at 42 months. The reasons that participating children did not contribute usable data is presented in Supplementary Table S1. Of our sample, 107 different children provided data at either one time point (*n*=60), two time points (*n*=40), or three time points (*n*=7), with 161 data points in all. These 107 different children comprise the final sample. Children who did and did not provide usable EEG data did not differ in terms of parent education, SES, ethnicity, or effortful control.

The final sample was predominantly Caucasian (90%, 3% Latino, 2% Black, 3% Other, and 2% Unknown, Not Reported, or Missing) and from two-parent households (95%, 2% Single Parent, 2% Other, 1% not reported). The majority of primary caregivers were college educated (87% college degree, 10% some college, 2% high school diploma or less, 1% not reported). SES was calculated using the Hollingshead Four Factor Index (Hollingshead, 1975), which takes into account the parents' educational attainment and occupational prestige. In the final sample, SES estimates ranged from 13 to 66 (*M* = 48.51, *SD* = 13.51), suggesting that our sample was predominantly middle class. All children had parent-reported normal or corrected-to-normal vision and hearing.

We used all available data points across subjects and ages in analysis (*N* = 161). However, because the final sample included children with multiple measurement occasions, this sample would violate the traditional assumption of independence required for correlation analysis. So, in order to retain all 161 data points in our final sample, without violating the assumption of independent observations, nested regression was used to statistically account for potential longitudinal dependency in the data

At each age, children participated in an EEG visit, in which two EEG tasks, a Go/NoGo task and an Oddball task, were administered. Only results from the Go/NoGo task are considered here. At each age, the child's primary caregiver also completed questionnaires about their child's temperament.

Measures

The Fish-Sharks GNG task. During the Fish-Sharks task, children were presented with a series of static stimuli depicting cartoon images of fish (Go stimuli) and sharks (NoGo stimuli). During the Go trials, children were instructed to "catch" the fish on the screen by pressing a response button located on a table in front of them. If a child successfully pressed the button to "catch" the fish, positive feedback (i.e., a picture of the fish in the net and pleasant bubble sounds) was presented. During the NoGo trials, the children were instructed not to catch the sharks, by inhibiting the button press. No feedback was presented if a child successfully inhibited, but if they committed an error by making a response during a NoGo trial, feedback (i.e., a picture of the shark breaking the child's net and an unpleasant buzzer sound) was presented. This task was designed to be used with young children, with the feedback included to improve the child's accuracy on the task [26]. During the 6-minute task, a research assistant sat with the child to ensure compliance. Children were instructed to sit still and make as little movement as possible, while watching the stimuli on a computer monitor. If the child looked away from the monitor, talked, or made excessive movements, the task was paused, and the research assistant gently redirected the child.

Four practice blocks, each including eight practice trials, were presented at the beginning of the task in the following order: Go trials only, NoGo trials only, Go trials only, and a mixed block including both Go and NoGo trials. After the child successfully completed the practice trials, the test trials began. Test trials included 80 trials, 60 Go trials and 20 NoGo trials. For the Go stimuli, 10 different fish exemplars were presented with equal frequency. For the NoGo stimuli, three different shark exemplars were presented with equal frequency. The task was broken up into 10 blocks of eight trials, with each block including 6 Go stimuli and 2 NoGo stimuli that were randomly presented. NoGo trials were always presented after two or four Go trials. Each Go and NoGo stimulus appeared on screen for a maximum of 3000 milliseconds, allowing ample time for the child to make a behavioral response. Behavioral responses occurring less than 200 ms after stimulus onset were rejected, as they were considered to be too fast to be a response to the current stimulus. Although Go and NoGo stimuli could be presented for as long as 3000 ms, they were truncated after the child pressed the response button. Feedback stimuli onset 800 ms after the button press, and were displayed on screen for 750 ms. The task's inter-stimulus interval was 1500 ms. Resulting ERP waveforms were time locked to the presentation of the Go or NoGo stimuli. Behavioral performance on the Fish-Sharks task was indexed using the percentage of NoGo trials to which the child successfully inhibited their response.

The Child Behavior Questionnaire (CBQ). The child's primary caregiver completed the short form of the CBQ [27-28], a temperament assessment for children between the ages of 3 and 7. The short form of the CBQ includes 94 items, divided into 15 subscales that load onto the three dimensions of child temperament: positive emotionality, negative emotionality, and effortful control. Items are rated on a 7-point likert scale, ranging from (1) "extremely untrue of your child" to (7) extremely true of your child. The current study focuses on the effortful control factor, which is made up of four subscales, including low intensity pleasure, inhibitory control, perceptual sensitivity, and attentional control.

Although they each load onto the overall effortful control factor [27], these four subscales assess fairly unique constructs. The inhibitory control subscale includes 6 items assessing a child's capacity to inhibit an approach response when either directed by a caregiver or as necessitated by a situation (e.g., "my child can wait before entering into new activities if s/he is asked to", "my child is good at following instructions", my child can easily stop an activity when s/he is told 'no'"). The attentional control subscale (also referred to as attentional focusing) includes 6 items assessing a child's capacity to maintain focus on relevant tasks (e.g., "when drawing or coloring in a book, my child shows strong concentration"). The low intensity pleasure subscale includes 8 items assessing a child's enjoyment of activities with low levels of stimulation (e.g., "my child enjoys gentle rhythmic activities, such as rocking or swaying", "my child likes being sung to"). The perceptual sensitivity subscale includes 6 items assessing a child's sensitivity to minute details of environmental stimuli (e.g., "my child notices the smoothness or roughness of objects s/he touches", "my child comments when a parent has changed his/her appearance").

Given the content of these subscales, we expected to see the highest associations between the N2 and the two subscales that assess the cognitive aspects of regulation (i.e., inhibitory control and attentional control), but examined each subscale, as well as the overall effortful control dimension, with the N2 component.

Recordings and Data Processing

Electrophysiological data were collected using an Electrical Geodesic, Inc (EGI) 128-electrode Hydrocel Geodesic Sensor Net with a Net Amps 300 series amplifier. Netstation Acquisition Software version 4.4.2 (EGI.: Eugene, OR) was initially used to collect and process the continuous EEG data recorded during both paradigms. However, we upgraded to Netstation Acquisition Software version 5.1.2 (EGI.: Eugene, OR) during the middle of longitudinal data collection. Stimulus presentation was managed using E-Prime 2.0 [29]. Stimuli were presented on a computer monitor that was located approximately one meter in front of the child, and auditory feedback, which was presented at a volume of 75 decibels, was presented on an 8-ohm speaker powered by an 80-watt amplifier that was centered one meter above the child's head.

Throughout the recording session, electrode impedances were adjusted to be at or below 50 kΩ, and continuous EEG data were collected at a sampling rate of 250 Hz. After collection, the continuous waveform was band-pass filtered from 0.3 to 30 Hz, and then segmented into 1200 ms epochs that began 200 ms prior to presentation of each stimulus. Epochs were manually inspected for artifacts, and then automatically examined for artifacts. The automatic artifact detection procedure included identifying and removing channels that contained a voltage shift greater than 150 μV during a given segment of length 80 ms, and removing epochs that contained 20 or more bad channels. Removed channels were then interpolated based on the waveforms of surrounding electrodes. Each individual's epoched data were then re-referenced to an average reference (the average of all scalp electrodes), and baseline corrected by subtracting the average activity from each epoch's 200 ms baseline. Finally, epochs for each condition were then averaged together. For a child's ERP data to be included in analysis, the child had to have at least 8 correct, artifact-free trials in each condition.

After processing, the ERP waveform was statistically decomposed using sequential temporospatial principal components analysis (tsPCA), which objectively and empirically determines the regions of electrodes and time frames that parsimoniously account for the majority of the variance in the waveforms [30]. The factors identified by the tsPCA are thought to correspond with more traditionally-defined ERP components [30], but use a data-driven, empirical technique for identifying components. Sequential tsPCA was conducted using the ERP PCA toolkit [31], a toolkit that is publically available for use within the Matlab software package. In the current study, the temporospatial PCA identified 8 temporospatial factors that accounted for 85% of the variance in the waveform. The temporospatial factor, thought to correspond with the N2, the component of interest for the current study, was selected based on a priori expectations about the latency and topography of the component. The chosen temporospatial factor peaked around 350 – 450 ms post-stimulus and was characterized by a frontocentral negativity (see Figure 1-A). Along with amplitudes for the Go and NoGo trials, we also examined the N2 effect, a difference waveform calculated by subtracting the child's amplitude for Go trials from the child's amplitude for NoGo trials (i.e., NoGo – Go), thought to index activity that is uniquely associated with inhibition processes.

Analysis Plan

N2 amplitudes were examined in relation to parent reports of child temperament using Pearson correlations, which treated each case as an independent measurement occasion. Significant correlations were further examined using multiple regression, controlling for child age, sex, and the number of trials retained in analysis (control variables commonly included in ERP studies). Because 47 children had more than one measurement occasion, we further investigated significant associations using multiple regression with a cluster variable (i.e. clustered regression)*. Clustered regression is a statistical technique that accounts for dependencies in nested data, in this case, it accounts for the dependency caused by including multiple measurement occasions from the same children. The clustered regression models were fit using the rms package [32] in R 3.0 [33], which calculates robust standard errors using a robust estimator (the Huber-White sandwich estimator) of the covariance matrix [33-34]. Sandwich estimators are widely used to account for data dependency in regression models. We initially examined the association between the features of the N2 thought to be associated with response inhibition (i.e., the NoGo N2 amplitude and the N2 effect) and both performance on the Go/NoGo task and child temperament.

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* We also examined the association between the N2 component and temperament by running the nested regression procedure on all possible combinations of the N2 and temperament variables. This approach yielded identical results to initially running Pearson correlations and further investigating any significant correlations using nested regression.

Because Go N2 amplitudes are not thought to be an index of response inhibition and we had no specific hypotheses about Go N2 amplitudes, we examined the association between the Go N2 amplitude and both performance on the Go/NoGo task and child temperament as a follow-up analysis to the main focus of the current study.

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Supplementary Table S1.

Reasons for Missingness for ERP Data at Each Age

Age	Reason for Missingness	# Missing
30 months (Total *N* cases = 133)	Refused to wear cap	16
	Refused to play Fish-Sharks task	19
	Too many bad channels	3
	Not enough usable trials*	40
	Other technical problem	3
	Total *n* usable cases = 52	
36 months (Total *N* cases = 99)	Refused to wear cap	9
	Refused to play Fish-Sharks task	10
	Too many bad channels	4
	Not enough usable trials*	23
	Other technical problem	3
	Total *n* usable cases = 50	
42 months (Total *N* cases = 90)	Refused to wear cap	5
	Refused to play Fish-Sharks task	5
	Too many bad channels	1
	Not enough usable trials*	14
	Other technical problem	6
	Total *n* usable cases = 59	

Note: * "not enough usable trials" denotes children who did not have at least 8 correct, usable trials in both the Go and NoGo condition

Supplementary Table S2.

Descriptive Statistics and Correlations of Study Variables

	Go N2 Amplitude	NoGo N2 Amplitude	N2 Effect	NoGo % Correct	CBQ IC	CBQ EC	CBQ AC	Age	Sex	# NoGo Trials Included
Go N2 Amplitude (μV)[i]	1									
NoGo N2 Amplitude (μV)[i]	0.22**	1								
N2 Effect (μV)	-0.61***	0.64***	1							
NoGo Percent Correct	-0.27**	0.04	0.25**	1						
CBQ Inhibitory Control	0.12	0.22**	0.08	0.01	1					
CBQ Effortful Control	0.1	0.16^	0.04	-0.02	0.79***	1				
CBQ Attentional Control	0.04	0.17*	0.10	-0.10	0.53***	0.78***	1			
Age	-0.05	-0.04	0.01	0.15^	0.12	0.03	0	1		
Sex[§]	0.08	0.02	-0.05	-0.06	0.32***	0.33***	0.24 **	-0.01	1	
Number of NoGo Trials Included	-0.17*	-0.09	0.07	0.57***	-0.06	-0.09	-0.15^	0.29**	-0.17^	1
N	157	157	157	161	146	146	146	145	160	135
M	-0.51	-2.96	-2.45	86.49	4.49	5.14	4.7	3.16	.46	12.96
SD	9.46	9.73	11.99	14.91	0.82	0.57	0.94	0.43	.50	3.79

Note: IC=inhibitory control; EC=effortful control, AC=Attentional Control

[§] 0=male, 1=female

^$p \leq .10$; *$p \leq .05$, **$p \leq .01$, ***$p \leq .001$

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[i] The N2 amplitude values reflected in this table were calculated from the PCA. In the PCA, all electrodes contribute to the estimation of amplitudes to the extent that they reflect the underlying N2 component (based on factor loadings), accentuating electrodes that are driving the signal. This accounts for the larger, more negative amplitudes in this table than are depicted in Figure 1.