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RUNNING HEAD: Response Inhibition in Early Childhood

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The temporal dynamic of response inhibition in early childhood:

An ERP study of partial and successful inhibition

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Abstract

Event-related potentials were recorded while five-year-old children completed a Go/No-Go task that distinguished between partial inhibition (i.e., response is initiated but cancelled before completion) and successful inhibition (i.e., response is inhibited before it is initiated). Partial inhibition trials were characterized by faster response initiation and later latency of the lateral frontal negativity (LFN) than successful Go and successful inhibition trials. The speed of response initiation was influenced by the response speed on previous trials and influenced the response speed on subsequent trials. Response initiation and action decision dynamically influenced each other, and their temporal interplay determined response inhibition success.

Key words: response inhibition, executive control, Go/No-Go, event-related potentials, children, lateral frontal negativity.

The temporal dynamic of response inhibition in early childhood:

An ERP study of partial and successful inhibition

Young children must often refrain from engaging in tempting but inappropriate actions, such as petting a stray dog, running across the street, or talking out of turn. The ability to suppress a prepotent, spontaneous, or habitual action when it is not context-appropriate is critical in early childhood, a period when it develops rapidly (Carlson, 2005; McAuley, Christ, & White, 2011; Wiebe, Sheffield, & Espy, 2012) and predicts early academic achievement (e.g. Fuhs & McNeil, 2013). The cognitive processes responsible for response inhibition in early childhood are likely rooted in the maturing brain regions associated with this ability later in development, including the ventrolateral prefrontal cortex, pre- and supplementary motor areas, and basal ganglia (Aron & Poldrack, 2006; Chambers, Garavan, & Bellgrove, 2009; Shaw et al., 2008; Sowell et al., 2004). The present study examines how these cognitive processes temporally interact to determine the success of response inhibition in 5-year-olds.

The passive-dissipation model (Simpson et al., 2012) has attempted to explain response inhibition in early childhood in terms of competition between the to-be-inhibited prepotent response and the action decision (i.e., decision to respond or withhold responding). This competition parallels the horse-race model between Go and Stop processes in the context of the Stop-Signal task (Logan & Cowan, 1984). Specifically, because the activation level of the prepotent response rises faster than that of the correct decision (not to respond), it reaches the threshold for responding before the decision not to respond has been made. Following the passive-dissipation model, if the prepotent response is initiated later, leaving time for the activation level of the prepotent response to rise and fall, the correct decision to not respond should

prevail. Consistent with this hypothesis, Wiebe and colleagues found that faster responses were associated with poorer response inhibition among 3- to 5-year-old children (Wiebe et al., 2012). In their study, children were instructed to quickly respond to frequently occurring Go stimuli by pressing a response button, but withhold responding to infrequent No-Go stimuli. Furthermore, others noted that introducing a delay after stimulus onset before 4-year-old children can respond dramatically improves accuracy on No-Go trials (Simpson & Riggs, 2007; Simpson et al., 2012; see also Diamond, Kirkham, & Amso, 2002).

A key feature of the passive-dissipation model is the difference in activation rise speed between the prepotent response and the action decision. Currently, this difference is thought to account for children's difficulty inhibiting responses when no delay follows stimulus onset, and better performance after a delay. However, even without a delay, 4-year-olds in Simpson et al.'s (2012) study successfully inhibited responding on approximately 50% of No-Go trials. Importantly, this cannot be explained by the prepotent response reaching the activation threshold for responding before the outcome of the decision process. Thus, a necessary assumption is that the relative timing of each process (i.e., the time required to reach the activation threshold) varies across trials. In this way, on some trials the decision process supersedes the prepotent response activation, resulting in a successful response inhibition.

The above assumptions raise questions regarding the timing of these processes. Specifically, does inhibition success depend on the timing of one, or both of these processes? If response inhibition is dependent on both processes, how do these processes dynamically interact with one other? Due to their excellent temporal resolution, event-related potentials (ERPs), are well suited to explore the temporal

dynamics of response inhibition in both children and adults (Johnstone et al., 2007; Todd et al., 2008). ERPs are recorded at the scalp via electroencephalography and are time-locked to specific stimuli of interest. Response inhibition is related to multiple ERPs, including the N2 (a frontal negative deflection typically observed at midline electrodes), P3 (a later-occurring frontal-central positive peak; e.g., Bruin et al., 2001; Smith, Johnstone, & Barry, 2007; Kropotov, Ponomarev, Hollup, & Mueller, 2011), and the lateral frontal negativity (LFN; a left-lateralized negative slow-wave and a possible marker of goal updating in adults; Bailey, West, & Anderson, 2010; Luu, Shane, Pratt, & Tucker, 2009; Luu, Tucker, & Stripling, 2007; West, Bailey, Tiernan, Boonsuk, & Gilbert, 2012).

ERP studies on school-age children found that children often initiate but withhold responses before completion (termed partial inhibition) on No-Go trials (e.g. Cragg & Nation 2008). These partial inhibition trials are associated with delayed onset of the frontal N2 – an ERP marker of response inhibition (Cragg, Fox, Nation, Reid, & Anderson, 2009; Cragg & Nation, 2008). The occurrence of partial inhibition suggests that response prepotency, as reflected by the timing of the response initiation, varies across trials. Most importantly, the later N2 suggests that early response initiation (i.e., stronger prepotency) delays the processes leading to response inhibition. Consistent with this theory, Zhang, Hughes and Rowe (2012) proposed that action decisions are made through an accumulation-to-threshold mechanism by which intention accumulates over time until it reaches the activation threshold. In their study, they observed that previous responses influence the rate of accumulation on subsequent trials in adults, thereby creating a bias toward specific actions.

The present study examined the timing of response initiation and the action decision in 5-year-olds using behavioral and electrophysiological methods. We

adapted the approach introduced by Cragg and colleagues (2009) to measure behavioral response initiation and the neural timing of the action decision with ERPs. Specifically, we assessed whether response inhibition is dependent on the timing of prepotent response initiation, the timing of the action decision, or both of these processes. We also explored whether the timing of the action decision is influenced by the preceding trials and whether it influences subsequent trials.

Method

Participants

Study participants included 40 five-year-old children, recruited from a small city in the Midwestern United States. Ten children were excluded from statistical analyses because their ERP averages included fewer than ten trials per condition, resulting in an inadequate signal-to-noise ratio. Thus the final sample included 30 children with a mean age of 5.7 years ($SD = .5$, range = 5 years 0 months to 6 years 0 months). The sample was composed of 60% girls (18 girls/12 boys), 20 Caucasian, and 10 children from other ethnic/racial backgrounds. Children's mean receptive vocabulary on the Peabody Picture Vocabulary Test-Fourth Edition (PPVT-4; Dunn & Dunn, 2007) was in the average range ($M = 108$, $SD = 17$). For the sake of representativeness, children were recruited from diverse socioeconomic backgrounds. The median household income was \$60,250 ($M = \$63,237$; $SD = \$40,327$) in our sample and \$51,209 in 2011 in the state where the study was conducted (2012 American Community Survey, US Census Bureau). Mean maternal and paternal education was 16.1 years ($SD = 2.8$) and 14.7 years ($SD = 2.7$), respectively. Prior to study enrollment parents completed a telephone screening to ensure that children were not diagnosed with developmental or language delays or behavioral disorders, were born full-term (i.e. ≥ 36 weeks gestation), and were right-handed. Children's

handedness was assessed by asking parents six developmentally appropriate questions from the Edinburgh Handedness Inventory (Oldfield, 1971). Parental informed consent was obtained for all children prior to participation.

Materials and Procedure

The study included two laboratory sessions lasting approximately an hour each where each child was tested individually by one of two trained experimenters. During the first session, children completed the Peabody Picture Vocabulary Test -4th Ed. (PPVT-4; Dunn & Dunn, 2007) to assess verbal skills and an additional ERP task not reported here. The Go/No-Go task was administered at a second visit occurring approximately one week later. Following the completion of each session, the child received a developmentally appropriate toy and the parent received monetary compensation.

The Go/No-Go task was run on a DELL Dimension 5150 PC desktop using E-Prime 1.2 (Psychology Software Tools, Pittsburgh, PA) and a 20-in. monitor (placed about 1 meter away from the participant). On each trial, one of eight different colored cartoon fish stimuli of similar size (about 10 × 13 cm) and visual complexity was presented at the center of the monitor. Children were instructed to respond to six of the fish (i.e. Go stimuli, termed “good fish”) but not to respond when one of the other two fish appeared (i.e. No-Go stimuli, termed “bad fish”). Go and No-Go stimuli were drawn from the same pool of eight fish pictures for all children. The Go or No-Go status of each fish was counterbalanced across participants (Go fish for some participants were No-Go fish for the others). All stimuli were chosen from the same semantic category (fish) to maximize the difficulty of action decision. Children responded with their right thumb using two labeled buttons (about 2-cm wide), located next to each other on a button box. The “home” button was labeled with a

boat picture and the “go” button was labeled with a fishing net. Children were instructed to press and hold the “home” button throughout the task in order to remain on the boat. The task was programmed such that the next trial was not presented unless children were pressing the home button. When a Go stimulus (a good fish) appeared, children were instructed to catch the fish by releasing the “home” button and pressing the “go” button with their thumb, and then quickly return to the home button. Children were instructed not to catch No-Go stimuli but rather to stay on the boat (i.e., keep pressing the home button).

Stimuli were presented at the center of the monitor on a white background for 1000 ms or until children pressed the response button (see Figure 1). A feedback screen was presented immediately after children pressed the “go” button. If children correctly responded to a Go stimulus within this interval (Successful Go response), a picture of the same fish inside of a fishing net appeared for 1000 ms accompanied by the sound of bubbling water. If they incorrectly caught a No-Go stimulus (Failed Inhibition response), a picture appeared with the fish swimming away from a broken fishing net for 1000 ms accompanied by a buzzer sound. No feedback was presented when children did not press the “go” button (Failed Go and Successful Inhibition responses), even if they released the “home” button (i.e., following Partial Go and Partial Inhibition responses, see below). Children were told the fish just swam away. A 1000-ms blank, white screen preceded all stimuli (whether or not feedback was presented on the previous trial). Children completed 15 practice Go trials, an additional 24 practice trials with both trial types (50% No-Go to ensure proficiency), and seven test blocks, each containing 40 trials (25% No-Go, 75% Go to increase response prepotency).

Data recording, processing, and statistical analysis

Following Cragg and Nation's study (2008), responses on No-Go trials were categorized as follows: (a) *Successful Inhibition*: children did not release the "home" button or press the "go" button; (b) *Partial Inhibition*: children released the "home" button but did not press the "go" button; (c) *Failed Inhibition*: children released the "home" button and pressed the "go" button. Similarly, Go trials were categorized as follows: (d) *Successful Go*: children released the "home" button and pressed the "go" button; (e) *Partial Go*: children released the "home" button but did not press the "go" button; and (f) *Failed Go*: children did not even release the "home" button (Figure 1).

Children were fitted with a 128-channel Hydrocel Electrical Geodesic Sensor Net, and their electroencephalogram (EEG) was recorded at a sampling rate of 250 Hz. The computer software Net Station 4.3.1 (Electrical Geodesics Inc, EGI) was used to record ongoing EEG on an Apple Power Mac G5 computer. Impedances were maintained below 50 k Ω at the beginning and midpoint of the task by re-wetting electrodes with electrolyte solution. Recording in every channel was vertex-referenced. The continuous EEG data was digitally filtered using a 30 Hz low-pass filter and trials were segmented into 850 ms time windows (including a 100 ms pre-stimulus baseline period). EEG data were segmented separately for the following response types: Successful Go, Partial Inhibition, and Successful Inhibition. Trials with response times faster than 200 ms (1.7% of trials) were discarded because they were unlikely to reflect purposeful behavior. Eye blinks were removed with an automated independent components analysis (ICA) using EP Toolkit 2.23 (Dien, 2010). ICA components that correlated at least .9 with the scalp topography of the blink template were removed and the data were reconstituted from the remaining ICA components. A channel was considered bad for a specific trial if its amplitude varied by over 100 μ V within that trial or its maximum difference from the most similar

neighboring electrode was over 30 μ V. Channels were rejected for the entire task if they were marked as bad on at least 20% of the trials, and trials were rejected if 10% or more channels were bad. Bad channels were replaced using spline interpolation based on neighboring channels. Following artifact correction, data were re-referenced to the average reference and baseline corrected using the 100 ms pre-stimulus period.

Results

Behavioral analyses

As shown in Table 1, children correctly responded to 83% of Go trials (Successful Go), initiated a response but failed to complete it on 12% of Go trials (Partial Go), and failed to initiate a response on 5% of Go trials (Failed Go). On No-Go trials, children successfully withheld response initiation on 47% of trials (Successful Inhibition) incorrectly, initiated but did not complete the response on 34% of trials (Partial Inhibition), and responded on 19% of trials (Failed Inhibition). (These proportions were slightly distorted by the criterion of at least 10 good segments per trial type for inclusion in the final sample. For the entire sample ($N = 40$), percent correct on Go and No-Go trials was 84% and 75%, respectively. On No-Go trials specifically, Successful, Partial, and Failed Inhibitions accounted for 42%, 33%, and 25% respectively.) Response times (time to press the “go” button) were faster for Failed Inhibitions than Successful Go responses (595 ms vs. 718 ms), $t(30) = 11.47$, $p < .001$, $r = .67$ (Table 1). Home button release times significantly varied across response types (Successful Go, Partial Go, Partial Inhibition, Failed Inhibition), $F(3, 87) = 157.77$, $p < .001$, $\eta^2_p = .85$. Release times were fastest for Failed Inhibition (428 ms), followed by Partial Inhibition (473 ms), Successful Go (531 ms), and Partial Go responses (733 ms), all $ps < .01$.

Correlations among the behavioral variables are provided in Table 2.

Response times for Successful Go and Failed Inhibition responses were positively correlated ($p < .001$). All release times were positively correlated with one another ($ps < .01$), with the exception of release times for Partial Go responses and release times for Failed Inhibitions ($p = .153$). Response times were positively correlated with release times ($ps < .050$), except between response times for Failed Inhibitions and release times for Partial Go responses ($p = .108$). All response and release times were negatively correlated with the proportion of Successful Go responses ($ps = .04$). They were positively correlated with the proportion of Successful Inhibitions (all $ps < .04$, with the exception of release times for Partial Go responses and release times for Partial Inhibition responses). The proportion of Partial Inhibitions was negatively correlated with all release times (all $ps < .03$), except for release times for Partial Go responses ($p = .099$), showing that faster response initiation was associated with a higher number of Partial Inhibition responses. These results suggest that a faster response speed enhanced performance on Go trials but was detrimental to performance on No-Go trials. Conversely, a slower response speed facilitated inhibition but made it more difficult to respond in time.

These correlation analyses also highlight the relation between response speed and the behavioral outcome on No-Go trials, especially the proportion of Partial Inhibitions. To further investigate this relation, release and response times on Go trials that preceded Failed, Partial or Successful Inhibitions were analyzed with ANOVAs (see Table 1). Go trials preceding Failed, Partial and Successful Inhibitions differed in both release and response times, $F(2, 58) = 9.44, p < .001, \eta^2_p = .25$, and $F(2, 58) = 10.28, p < .001, \eta^2_p = .26$, respectively. Release times on Go trials were faster before Partial Inhibitions (509 ms) and Failed Inhibitions (505 ms) than before

Successful Inhibitions (552 ms; $ps < .002$). Similarly, responses on Go trials were faster before Failed Inhibition (690 ms) and Partial Inhibition (709 ms) than before Successful Inhibitions (736 ms, $ps < .02$). These results confirm that faster responding on Go trials is associated with an increased likelihood of inhibition failure on the subsequent No-Go trial.

Finally, we explored whether the outcome of No-Go trials influenced response timing on subsequent Go trials. T-tests were performed to compare Go trial release and response times as a function of previous No-Go trial success. Go trials following Failed Inhibitions were not included because Failed Inhibitions were followed by a 1000 ms negative feedback that affected the length of the response-stimulus interval. These analyses revealed that Partial Inhibitions led to a slower response speed on subsequent Go trials. Specifically, Go trial release times were slower after Partial than Successful Inhibition (546 ms vs. 523 ms, respectively), $t(29) = 2.65, p = .01, r = .13$, whereas the difference was not significant for response times ($p = .07$).

Lateral frontal negativity (LFN)

Preliminary inspection of the ERP data showed that a left-lateral frontal negativity (LFN) concomitant with a posterior positivity dominated the waveforms. The topography of this component (Figure 2) was similar to those observed in adults (Bailey et al., 2010; West et al., 2012). The LFN was analyzed in three steps: (1) a spatial principal component analysis (PCA) identified the peak electrodes contributing to the LFN; (2) peak amplitudes and latencies were extracted by averaging across these electrodes; and (3) ANOVAs examined the effect of response type on peak amplitude and latency.

First, the spatial PCA was estimated using a covariance matrix and promax rotation. Based on the scree plot (Cattell, 1966), ten spatial factors were retained.

They accounted for approximately 91% of the spatial variance in the ERPs. The first spatial factor, which accounted for 25% of the variance, closely represented the large LFN in the data. Second, visual inspection of the data showed that the LFN was most pronounced between 350 and 650 ms after stimulus onset. Therefore, this window was used to extract the peak amplitudes and latencies, averaging across the 13 electrodes with a factor loading greater than .6 (Dien, 2010) (Figure 2).

Third, the effect of response type (Successful Go, Partial Inhibition, Failed Inhibition) on peak amplitude and latency was examined with two repeated-measures ANOVAs. Response type had a significant effect on both amplitude, $F(2, 58) = 14.75$, $p < .001$, $\eta^2_p = .34$, and latency, $F(2, 58) = 10.68$, $p < .001$, $\eta^2_p = .27$. The LFN amplitude was more negative for Partial (-12.3) and Successful Inhibitions (-12.8 μV), compared to Successful Go responses (-9.3 μV , $ps < .001$). Partial and Successful Inhibitions however did not differ from one another ($p = 1.00$). Longer LFN latencies were observed for Partial Inhibitions (521 ms) relative to Successful Inhibitions (469 ms) and Successful Go responses (453 ms; all $ps < .001$). Latency did not differ between Successful Inhibitions and Successful Go responses ($p > .99$).

Correlations between behavioral and ERP indices are provided in Table 2. The proportion of Successful Go responses was negatively correlated with latency of the LFN for Partial Inhibition and Successful Go responses ($p = .042$ and $p = .006$, respectively). That is, children with slower-resolving LFNs had more difficulty responding in time on Go trials. Response and release times for all response types were positively correlated with the latency of the LFN for Successful Go responses (all $ps < .03$). This finding suggests that children with longer LFN latencies on Successful Go trials showed a slower response speed (slower “home” button release and “go” button press).

Discussion

The present study addressed how the timing of prepotent response initiation (as indexed by release times) and action decision (as indexed by the LFN) contributes to 5-year-olds' response inhibition, using a Go/No-Go task that discriminated between successful and partial inhibitions. Partial Inhibition responses were common among 5-year-old children (approximately one third of No-Go trials) and were characterized by earlier release times than Successful Go trials. Children also showed a later LFN for Partial Inhibition responses compared to Successful Go responses and Successful Inhibitions. Furthermore, release and response times were related to prior and subsequent trials. Together, these findings suggest that both response initiation and the action decision varied across trials.

The conjunction of early response initiation and late action decision led to inhibition failures, whereas late response initiation and early action decision resulted in successful inhibition. Specifically, we observed that release times increased across Failed Inhibitions, Partial Inhibitions and Successful Go trials. In addition, greater successful inhibitions were associated with slower release and response times. These findings suggest that the speed of response initiation is a major, perhaps even the primary, contributor to the success of 5-year-olds' response inhibition. If the response is initiated too quickly, response inhibition will likely fail. If the response is initiated moderately fast, it will likely be cancelled prior to completion, resulting in partial inhibition. If the response takes longer to be initiated, the decision to inhibit will likely be reached before the motoric action begins (successful inhibition).

The contribution of action decision timing was examined with ERPs. The ERP data were dominated by a LFN that was most pronounced between 350-650 ms after stimulus onset. A similar LFN component was found in adults who showed greater

amplitudes on trials with greater inhibition demands (Bailey et al., 2010; West et al., 2012; Luu et al., 2007, 2009). In adults, the LFN seems to be generated by the ventrolateral prefrontal cortex, a region critical to response inhibition (e.g., Aron & Poldrack, 2006). These findings suggest that the LFN reflects inhibition-related processes, however, the exact function of the LFN to inhibition is unclear. The LFN has been interpreted as a marker of task goal updating (Bailey et al., 2010). Goal updating is closely related to the action decision because the relevance of an action is dependent upon the goal. The slow-wave nature of this component is consistent with progressive evidence accumulation towards a specific goal and goal-relevant actions, which is a critical feature of action decision in the passive-dissipation model of response inhibition. Finally, in some situations, the relevant goal has to be updated based on feedback information, in anticipation of subsequent actions. Consistently feedback-related LFN has also been reported in adults (e.g., Luu et al., 2009).

In the present study, the LFN occurred later for Partial Inhibitions, relative to Successful Inhibitions. Consistent with past research (Cragg et al., 2009), this finding suggests that the decision to inhibit occurred later and/or took longer on these trials. Therefore, partial inhibitions appear to be characterized by both fast response initiation *and* delayed action decision. Response initiation and action decision may not be two independent phenomena. Instead, early response initiation may erroneously bias the action decision process toward a decision to respond, delaying the time required to reach the correct decision to inhibit responding on No-Go trials. On Go trials, early response initiation may facilitate performance, as suggested by the positive correlations between release/response times and LFN latency for Successful Go responses.

In addition, the timing of response initiation on Go trials influenced response initiation on subsequent No-Go trials. Specifically, Partial Inhibitions followed faster Go responses, whereas Successful Inhibitions followed slower Go responses. This finding is consistent with previous research showing that the speed of responding on Go trials influences subsequent No-Go performance (Wiebe et al., 2012; Liddle et al., 2009) and, in particular, that inhibition success depends on the response time on the *previous* trial (Garavan, Hester, Murphy, Fassbender, & Kelly, 2006; Zhang et al., 2012). Further, response initiation on No-Go trials was positively correlated with the LFN latency on Go trials. Although causality cannot be ascertained, it is reasonable to argue that faster action decision to respond to Go trials leads to faster response initiation on subsequent trials. When response prepotency is strong, the action decision likely occurs after response initiation, because only a limited amount of contextual information processing is needed to trigger the response (in anticipation of a final decision to respond). When such trials are Go trials, early response initiation may facilitate the action decision to press the response button (with which it is compatible), leading to even quicker response initiation and decision on subsequent Go trials. However, on No-Go trials, continued processing may lead to a final decision to inhibit. This decision takes even longer to reach because it conflicts with early response initiation, resulting in either Failed or Partial Inhibition. Finally, slower release times on Go trials following Partial relative to Successful Inhibitions suggest that a near-miss slows down response initiation on subsequent Go trials, in a phenomenon akin to post-error slowing.

Together, the present findings are consistent with Simpson et al.'s (2012) passive-dissipation model of response inhibition in early childhood and, more importantly extend this framework in three important ways. First, they support the

claim that the timing of the prepotent response initiation varies across trials, and that fast activation rise of the prepotent response (i.e., early response initiation) is the cause of inhibition failure. However, it remains unclear whether such variation in prepotent response initiation relates to varying activation levels, activation rise speed, and/or activation rise onset. Second, our findings extend the passive-dissipation model by showing that the timing of action decision also contributes to inhibition success. Finally, they reveal that these two processes are mutually influential, and most importantly, provide an account for how they dynamically interact over time to yield various inhibition outcomes.

To our knowledge, the present study is the first report of the LFN in young children. Because this negative slow-wave is concomitant with a posterior positivity, similar to a P3 component, previous studies may have focused on the posterior positivity, although No-Go P3 usually show a more anterior topography.

Alternatively, the LFN may relate to specificities of the task we used. In particular, Go and No-Go stimuli were drawn from the same semantic category (i.e., common fish). The semantic and perceptual similarity between Go and No-Go stimuli may have yielded greater action decision demands than in studies using more distinct Go and No-Go stimuli (e.g., fish vs. sharks as in Wiebe et al., 2012). Greater action decision demands also seem to characterize the tasks where the LFN was previously documented in adults (e.g., Stroop task, where congruent and incongruent words are drawn from the same semantic categories). When Go and No-Go stimuli belong to the same semantic category, one may have more difficulty detecting the environmental information that indicates which action is required. Monitoring for such information is indeed critical to response inhibition during both childhood and adulthood, and it relates to ventrolateral prefrontal cortex (e.g., Chevalier, Chatham & Munakata, 2014;

Chatham et al., 2012; Dodds, Morein-Zamir, & Robbins, 2011; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Sharp et al., 2010). Alternatively, as the present study also differs from prior ones in the use of a more complex response set-up, one may argue that the LFN could reflect motor activity. If so, the component should have been more pronounced in amplitude on Go trials, for which a motor response occurred, than No-Go trials. However, we observed the reverse pattern, speaking against this interpretation.

Finally, the ERP data showed a midline N2 over anterior channels around 300 ms, but this negative peak did not differ in amplitude or latency between Go and No-Go trials ($ps > .479$). Thus, unlike the more pronounced midline N2 on No-Go than Go trials usually reported (e.g., Bruin et al., 2001; Johnstone et al., 2005; Cragg et al., 2009), the N2 in our study is unlikely to reflect inhibitory processes. Although the lack of a more pronounced N2 is intriguing, other studies have also failed to observe this component in young children (e.g., Buss et al., 2013). An open question is whether the lack of a clear No-Go N2 could relate to the presence of the LFN. The LFN shares some commonalities with the usual midline N2, including (a) presence of the component on both Go and No-Go trials in children, (b) greater amplitude on No-Go than Go trials, and, most importantly, (c) later latency (despite similar amplitude) on Partial relative to Successful Inhibition trials (Johnstone et al., 2005; Cragg et al., 2009). Yet, the LFN shows a later latency and a distinct topography, with a supposedly different brain source in adults (the ventrolateral prefrontal cortex instead of the anterior cingulate cortex). Further research is needed to clarify to what extent the LFN and the midline N2 may or may not be related.

In conclusion, the present study shows that response inhibition relies on the temporal interplay between prepotent response initiation and the action decision in 5-

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year-olds. In particular, fast responding on Go trials leads to quick response initiation on subsequent trials. Such fast response initiation biases the cognitive system towards responding, which delays the correct decision to inhibit responding when the action actually is irrelevant. In turn, a near-miss (i.e., partial inhibitions) leads to slowing on subsequent trials. These findings suggest that the modulation of the response timing based on prior experience is key to successful response inhibition in early childhood. They also emphasize the importance of considering temporal dynamics (both within and across trials) to better account for response inhibition in young children.

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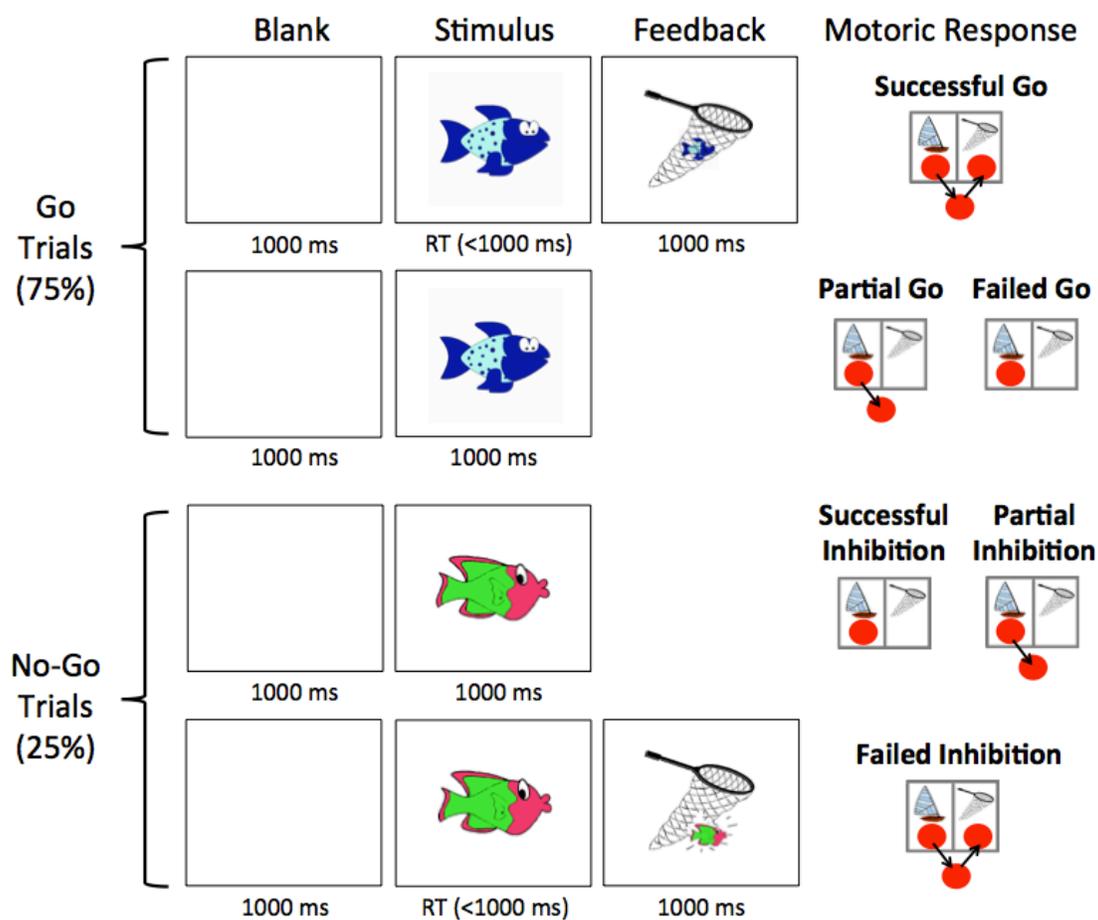


Figure 1. Illustration of the Go/No-Go task and various responses types. Using their right thumb, children were instructed to release the “home” (boat) button and press the “go” (fishing net) button to catch the good fish (Go trials) but not the bad fish (No-Go trials). The red circles and black arrows indicate thumb movements corresponding to each type of response. A red circle located on a button indicates that the button is being pressed. The red circle below the buttons indicates that the “home” button has been released. Children were told to return their thumb to the “home” button quickly after pressing the “go” button. Feedback was presented only if the “go” button was pressed. RT = response time.

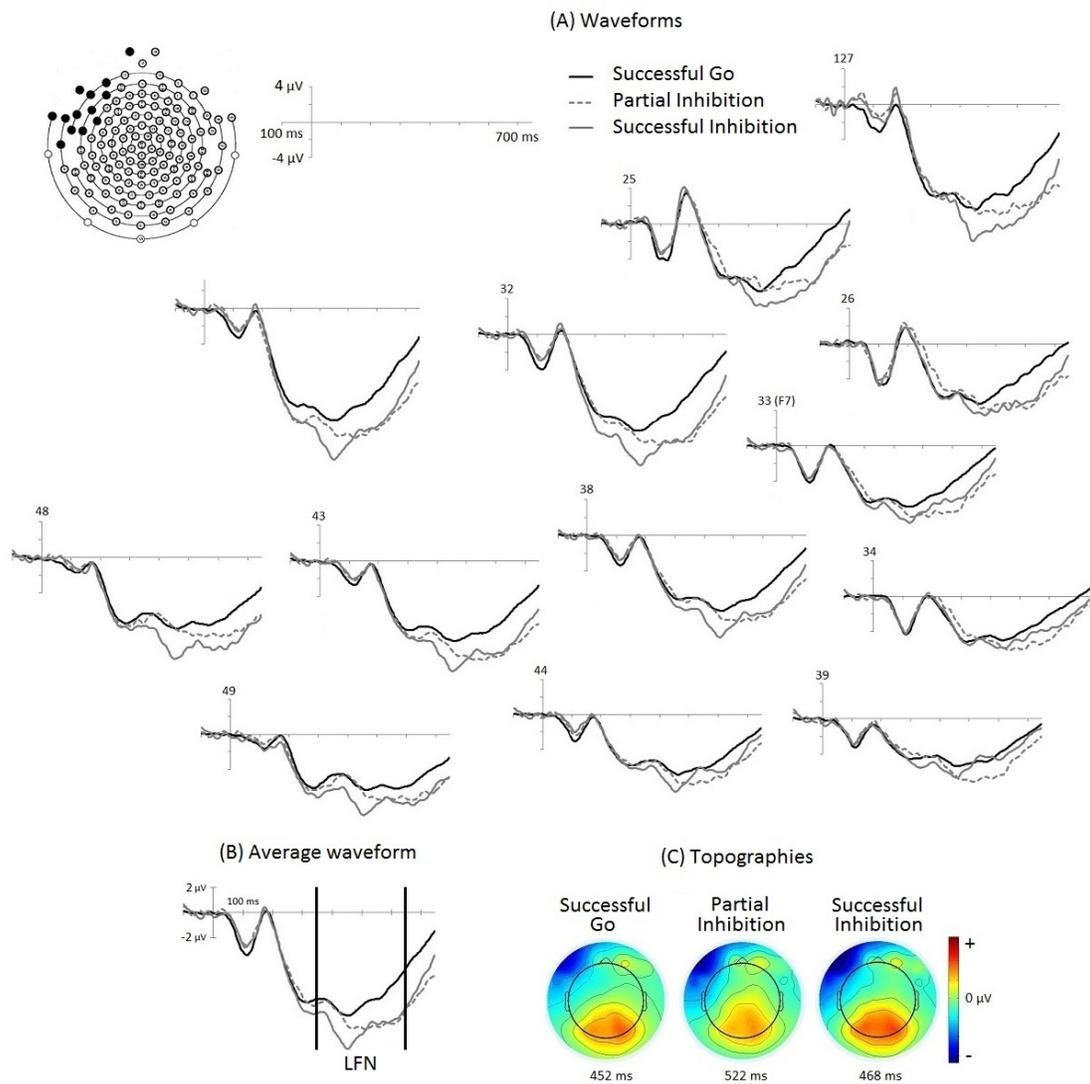


Figure 2. Grand average waveforms for electrodes included in the lateral frontal negativity (LFN) cluster: 25, 26, 32, 33, 34, 38, 39, 43, 44, 48, 49, 127, 128. LFN electrodes are shown in black on the top left net schematic. (A) & (B) average waveforms (the black vertical bars indicate the temporal window used to analyze the LFN) and (C) corresponding topographies.

Response Inhibition in Early Childhood

Table 1

Descriptive Statistics for the Lateral Frontal Negativity and Behavioral Response

Types

	Mean proportion in % (<i>SD</i>)	Mean RIsT in ms (<i>SD</i>)	Mean RT in ms (<i>SD</i>)	LFN	
				Mean amplitude in μ V (<i>SD</i>)	Mean latency in ms (<i>SD</i>)
Successful Go (all)	83 (11)	531 (65)	718 (69)	-9.3 (0.6)	453 (71)
Before Succ. Inh.		552 (68)	736 (72)		
Before Partial Inh.		509 (54)	709 (56)		
Before Failed Inh.		505 (75)	690 (77)		
After Succ. Inh.		523 (82)	720 (93)		
After Partial Inh.		546 (95)	740 (81)		
Partial Go	12 (3)	733 (116)			
Failed Go	5 (3)				
Successful Inhibition	47 (19)			-12.8 (1.0)	469 (87)
Partial Inhibition	34 (12)	473 (70)		-12.3 (1.0)	521 (95)
Failed Inhibition	19 (15)	428 (57)	595 (67)		

Note: RIsT = Release time. RT = Response time. *SD* = Standard Deviation. LFN =

Lateral Frontal Negativity. Succ. Inh. = Successful Inhibition. Partial Inh. = Partial Inhibition. Failed Inh. = Failed Inhibition.

Table 2

Correlations among behavioral and ERP measures.

	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1) Succ. Go-%	.162	.002	-.599*	-.365	-.452	-.399	-.642*	-.507*	-.492	-.373	-.302	-.292	-.384	-.407
(2) Partial Inh.-%		-.625*	-.347	-.302	-.307	-.459	-.415	-.515*	-.252	-.346	-.122	.146	-.049	.108
(3) Succ. Inh.-%			.592*	.396	.333	.430	.158	.687*	.068	.039	-.002	-.247	-.151	.046
(4) Succ. Go-RT				.626*	.583*	.602*	.525*	.886*	.399	.261	.241	-.135	-.025	.067
(5) Failed Inh.-RT					.300	.732*	.366	.496	.493	.325	.280	.022	.140	.279
(6) Partial Go-RIsT						.267	.560*	.622*	.538*	.263	.283	.001	.119	.156
(7) Failed Inh.-RIsT							.487*	.598*	.400	.391	.171	-.161	-.092	.035
(8) Partial Inh.-RIsT								.626*	.564*	.311	.127	-.011	.140	-.033
(9) Succ. Go-RIsT									.494	.302	.103	-.010	.079	.201
(10) Succ. Go-LFN L.										.640*	.262	.211	.304	.133
(11) Partial Inh-LFN L.											.596*	.064	.127	-.018
(12) Succ. Inh.-LFN L.												-.112	.304	.133
(13) Succ. Go-LFN A.													.857*	.718*
(14) Partial Inh.-LFN A.														.721*
(15) Succ. Inh.-LFN A.														

Note: Succ. = Successful. Inh. = Inhibition. % = percent correct; RT = response time; RIsT = release time. L. = Latency. A. = Amplitude.

Significant uncorrected correlations ($p < .050$) appear in bold and significant Holm-Bonferroni corrected correlations (computed separately for behavioral indices, latencies, and amplitudes) are marked with stars.