



Electrophysiological activity underlying inhibitory control processes in normal adults

Mariana Schmajuk^a, Mario Liotti^b, Laura Busse^a, Marty G. Woldorff^{a,*}

^a Center for Cognitive Neuroscience, Duke University, Durham, Box 90999, NC 27708, USA

^b Department of Psychology, Simon Fraser University, Burnaby, BC, Canada

Received 28 March 2004; received in revised form 18 May 2005; accepted 8 June 2005

Abstract

In a recent ERP study of inhibitory control using the Stop-Signal Task [Pliszka, S., Liotti, M., Woldorff, M. (2000). Inhibitory control in children with attention-deficit/hyperactivity disorder: Event-related potentials identify the processing component and timing of an impaired right-frontal response-inhibition mechanism. *Biological Psychiatry*, 48, 238–246], we showed that in normal children (age 10–12 years) the Stop Signals elicited a robust, right-frontal-maximal N200 (latency ~200 ms) that was strongly reduced in children with ADHD. To further investigate the mechanisms of response inhibition, this paradigm was applied to 11 healthy young adults. To better distinguish response-inhibition-related activity from early attentional effects, a “Stop-Signal-Irrelevant” condition was added, in which subjects performed the task while ignoring the Stop Signals. In the Stop-Signal-Relevant condition, the right frontal N200 to the Stop Signals was larger for Successful inhibition (SI) than for Failed inhibition (FI) trials. The timing and distribution of this effect was strikingly similar to that of the right-frontal ADHD deficit reported in Pliszka et al. (2000), supporting this activity being related to successful normal inhibitory control processes. In contrast, a posterior N200 was larger for Stop-Relevant than for Stop-Irrelevant trials, likely reflecting enhanced early sensory attention to the Stop Signals when relevant. Two longer-latency failure-specific ERP effects were also observed: a greater frontopolar negative wave (370–450 ms) to Failed than Successful inhibitions, and a greater parietal positive slow wave (450–650 ms) for Failed inhibitions than ignore-stop trials, likely reflecting differential recruitment of error detection and correction mechanisms following Failed attempts to inhibit a response.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Response inhibition; Stop-Signal Task; N200; Nogo-P3; ADHD; Frontal cortex

1. Introduction

Inhibitory control is a central aspect of executive functioning (Barkley, 1998; Schachar & Logan, 1990), and it is generally believed that deficits related to such control processes are core symptoms of many developmental disorders, including attention deficit/hyperactivity disorder (ADHD) in particular (APA, 1994; Barkley, 1998). ADHD is a common behavioral syndrome, estimated to occur in 3–5% of school-aged children (Barkley, 1998). Symptoms include low levels

of attention and concentration and high levels of activity, distractibility, impulsivity, and the inability to inhibit actions (APA, 1994).

Two behavioral paradigms that tap into the inhibitory control symptoms of ADHD (impulsiveness and inattention) are the continuous performance test (CPT) and the Stop-Signal Task (SST). Both the CPT and the SST are varieties of “Go-NoGo” tasks, requiring subjects to occasionally inhibit an ongoing action or response. In the C-X version of the CPT, subjects are presented with rapid sequences of letters. Twenty percent of the stimuli are the letter C, which is followed 50% of the time by an X, and 50% of the time by another letter (e.g., R, V, T, etc). Subjects are instructed to withhold their response when they see an X following a C

* Corresponding author. Tel.: +1 9196810604; fax: +1 9196810815.

E-mail address: woldorff@duke.edu (M.G. Woldorff).

(“NoGo stimulus”) but to respond when any other letter follows the letter C (e.g., C-R, C-V, etc., “Go stimuli”; [Barkley, 1998](#))

The Stop-Signal Task is an even more direct task for measuring inhibitory control, in that subjects have to be prepared to withdraw a response on *each* trial ([Logan, Cowan, & Davis, 1984](#); [Schachar & Logan, 1990](#)). In a visual version of the SST (e.g., [Pliszka, Borcharding, Spratley, & Irick, 1997](#)), subjects are presented with a series of trials that begin with either the letter A or the letter B. On each of these, subjects perform a two-choice reaction time (RT) task, responding to the A with one button and the B with a second button. On 25% of the trials a Stop Signal (the letter S) follows the A or B by a variable time interval (e.g., 200–600 ms, Stop-Signal interval), and the subject must withhold his/her response on that trial. For typical healthy subjects, for the shorter Stop-Signal intervals (e.g., 200–400 ms) it is easier to inhibit responding, while at the longer Stop-Signal intervals (400–600 ms) it is substantially more difficult to do so and the probability of inhibition is much lower. A number of studies have shown that ADHD subjects perform more poorly on the Stop-Signal Task, including showing a significantly different slope of the inhibitory function (i.e., the function of the probability of successfully inhibiting as a function of the Stop-Signal interval) when compared to age-matched control subjects, due to a difficulty withholding a response regardless of the Stop-Signal latency (e.g., [Pliszka et al., 1997](#)).

Neural mechanisms underlying inhibitory processes can be studied with a high degree of temporal resolution by recording event-related potentials (ERPs) from the scalp. A frontally distributed ERP component, the N200, that peaks at about 200 ms post stimulus has been associated with response inhibition in Go-NoGo paradigms, with greater amplitude for NoGo relative to Go stimuli ([Eimer, 1993](#); [Falkenstein, Hoormann & Hohnsbein, 1999](#); [van Boxtel, van der Molen, Jennings, & Brunia, 2001](#)). N200 amplitude was shown not to be modulated by manipulations of probability of the NoGo stimulus, discounting interpretations based on salience or arousal ([Eimer, 1993](#)). However, N200 amplitude has been shown to be modified by speed-accuracy trade-offs, with a greater response when the emphasis was on speed rather than accuracy ([Jodo & Kayama, 1992](#)). Conversely, subjects with a high false alarm rate were found to have smaller and delayed NoGo-N200s than subjects with a low false alarm rate ([Falkenstein et al., 1999](#)). Based on these findings, it has been proposed that the NoGo-N200 indexes a process of response inhibition that is a reflection of a “red flag” signal generated in prefrontal cortex to trigger the inhibitory process ([Kok, 1986](#)), consistent with the role of the frontal lobes in executive functioning, conflict monitoring, and the control of inappropriate responses (e.g., [Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003](#); [Botvinick, Braver, Barch, Carter, & Cohen, 2001](#); [Liddle, Kiehl, & Smith, 2001](#)).

In a recent study, [Pliszka, Liotti, and Woldorff \(2000\)](#) compared ERPs elicited by the Stop Signal in a visual version of the Stop-Signal task in ADHD and healthy children. This

study reported that the amplitude of the N200 was markedly reduced in ADHD children compared to control subjects, with the group effect sharply focused over the right frontal scalp ([Pliszka et al., 2000](#)). This localization is consistent with that of the N200 to NoGo trials in healthy adult subjects ([Bokura, Yamaguchi, & Kobayashi, 2001](#)), and with the results of fMRI studies of inhibitory control in healthy subjects ([Garavan, Ross, & Stein, 1999](#); [Konishi, Nakajim, Uchida, Kiyo, Kameyama, & Miyashita, 1999](#); [Liddle et al., 2001](#)) and ADHD patients ([Rubia et al., 1999](#)).

A longer latency, centrally distributed, positive-polarity ERP component (NoGo-P3, peaking around 300 ms), has also been found to be associated with response inhibition in tasks such as the CPT and the SST, with greater amplitude over central sites for NoGo than Go trials ([Falkenstein et al., 1999](#); [Tekok-Kilic, Shucard, & Shucard, 2001](#)). In contrast, Go trials are associated with a more posterior positive-polarity wave (Go-P3), with the same parietal distribution as the P3b wave found in oddball tasks in response to infrequent task-relevant stimuli (reviewed in [Squires, Squires, & Hillyard, 1975](#)). In the Stop-Signal Task, the central NoGo-P3 has also been found to have greater amplitude for Successful inhibition than Failed inhibition trials in healthy subjects ([Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005](#); [Overtoom et al., 2002](#)). Importantly, this success-enhanced NoGo-P3, whose distribution is consistent with a generator in the anterior cingulate cortex ([Liotti et al., 2005](#)), was also greatly diminished in children with ADHD ([Liotti et al., 2005](#); [Overtoom et al., 2002](#)), suggesting that the NoGo-P3 may index a later stage of evaluation/monitoring of the outcome of the inhibitory process that also may be dysfunctional in ADHD.

In spite of the current interest in inhibitory control and its deficits in ADHD, various aspects of the spatiotemporal organization of response inhibition are still unclear. The current study aims at elucidating the neural functional organization of inhibitory control by recording high-density ERPs in adult healthy volunteers during a visual version of the Stop-Signal Task that was used previously in studying differences in processing between normal children and those with ADHD ([Pliszka et al., 1997, 2000](#)).

To help distinguish effects specifically related to response inhibition from effects due to some other possible cognitive factors, an additional control condition was included. In particular, early ERP differences (e.g., an N200 effect) in the responses to the Stop Signals for Successful versus Failed inhibitions could reflect attention-related modulations due to the varying of attentional focus from trial to trial, rather than activity more specifically related to response inhibition. Thus, a “Stop-Signal-Irrelevant” condition was added, in which subjects performed the Go task while ignoring the Stop Signals. This manipulation was intended to allow us to compare the effects of Successful versus Failed inhibitions to the effects that an explicit manipulation of attention (and task relevance) of the Stop Signals would cause. Thus, the present study recorded high-density ERPs during two versions of the

Stop-Signal Task in adult healthy volunteers, namely Stop-Relevant and Stop-Irrelevant conditions.

2. Methods

2.1. Participants

Fifteen right-handed healthy young adults participated in the study. Two subjects were eliminated due to excessive eye movement artifacts, and the EEG data from two additional participants were unusable due to technical problems. Eleven right-handed healthy young adults (mean age = 22 ± 2.6 years, five female, six male; all enrolled in undergraduate university courses) constituted the final sample. All subjects had normal or corrected-to-normal vision and a negative history of neurological and psychiatric conditions or alcohol abuse. None was under current pharmacological treatment. They gave their written informed consent according to Duke University's Institutional Review Board and received university class credit or were paid a compensation for their participation.

2.2. Stimuli and task

Participants sat in a partially reclined chair with their eyes 65 cm from a computer monitor presenting a visual version of the SST (Pliszka et al., 1997). Subjects' baseline task (Go trials) was a 2-choice RT task, where they had to discriminate between two stimuli (the letter "A" or "B") by responding with the index finger of the left or right hand, respectively. These stimuli were flashed for 150 ms slightly above a fixation dot. On 25% of the trials, the A or B were followed at a variable interval by a Stop Signal (the letter "S", duration 150 ms), appearing slightly below the fixation point. All stimuli were white against a black background, and the letters size were 1° (height) \times 0.7° (width). The time interval between the offset of the A or B and the onset of the Stop Signal (Stop-Signal interval) was varied randomly between 200 and 600 ms. Subjects were instructed to inhibit their manual response when seeing an S. The total interstimulus intervals for the Go stimuli (from onset to onset) varied randomly between 1.5 and 1.8 s.

There were two main conditions: Stop-Relevant and Stop-Irrelevant. The Stop-Relevant condition is described above. In the Stop-Irrelevant runs, the baseline RT task was the same, except that the Go stimuli were the letters C and D and the "Stop Signal" was an N. However, in this condition subjects were instructed to ignore the Stop Signal when it appeared. The experiment included 15 runs lasting 3.5 min each, separated by short pauses, for a total running time of less than 1 h. Each run contained 96 "Go" and 32 "Stop" trials. The order of the run conditions was counterbalanced across subjects.

The Stop-Relevant condition included an on-line adjustment of difficulty of inhibitory performance. For each subject

and run, if the mean Go RT in a run was longer than 700 ms (for example, 770 ms), all Stop-Signal intervals in the following run were increased by the amount of time over 700 ms (+70 ms, see also Pliszka et al., 2000). This effectively prevented the subjects from slowing down to catch all the Stop Signals.

2.3. EEG/ERP recording

Brain electrical activity was recorded continuously (Neuroscan SynAmps amplifiers, El Paso, TX) through a 64-channel custom-built elastic cap (Electro-Cap International, Inc., Eaton, OH), referenced to the right mastoid. Amplifier settings were: band pass filter = .01–100 Hz, gain = 150, sampling rate = 500 Hz. Electrode impedances were maintained below 5 k Ω . Eye movements were monitored by additional skin electrodes at the outer canthi of the eyes (referenced to each other), and below each eye (referenced to the electrode located directly above each eye).

2.4. Behavioral analysis

The following behavioral parameters were measured: mean RT and percent error in the Go trials, probability of inhibition [$P(I)$] for each of the four 100-ms SOA subranges, Stop-Signal reaction time (SSRT) for each SOA subrange (e.g., Logan et al., 1984), and mean RT for Stop-Irrelevant trials. The SSRT provides a measure of speed of the inhibitory process for each SOA subrange. It is calculated as follows. First, correct Go RTs are ranked from the shortest to the longest. In conjunction with this, a probability of inhibition is determined for each SOA subrange, and an RT value is identified in the ranked distribution of the Go RTs corresponding to that probability of inhibition. For example, if probability of inhibition is 80% for a given SOA subrange (i.e., subject quite Successful at inhibiting), that will correspond to the specific value of the Go RTs that is 20% of the ranked Go RT distribution (from the shortest to the longest RT), yielding a quite short SSRT for that SOA subrange. Conversely, if probability of inhibition is 30% for a given SOA subrange (subject quite poor at inhibiting), this would correspond to the value of the Go RT that is 70% of the ranked Go RT distribution (from the shortest to longest RT), and the SSRT will accordingly be longer (Pliszka et al., 1997).

2.5. ERP analysis

Artifact rejection was performed off-line by discarding epochs of the EEG contaminated by eye blinks and other artifacts. Trials with eye blinks were automatically rejected based on peak to peak voltage for the electrodes just above and below the eyes. ERP averages were obtained by time-locking to the onset of the Go signals and to the Stop Signals. After averaging, all channels were re-referenced to the algebraic average of the two mastoid electrodes to derive a hemispherically symmetric reference. After that, the data were digitally

low-pass filtered with a non-causal, smoothing filter consisting of a running average 9 points wide. At our sample rate of 500 Hz, this 9-point running average results in a square-wave filter convolution kernel 18 ms wide, which heavily attenuates activity at and above 56 Hz. Grand averages were then calculated across subjects for each trial type and condition: From Stop-Relevant task: Successful inhibitions (SI), Failed inhibitions (FI); From Stop-Irrelevant task: irrelevant stops (IS). To help in isolating the effects of interest, the following difference waves were calculated: Successful inhibitions minus Failed inhibitions (SI – FI), and Failed inhibitions minus irrelevant stops (FI – IS). To facilitate visualization of the effects, scalp voltage topographic distributions were obtained using spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989).

Due to the short interval between the Go and Stop stimuli, the elicited ERP responses overlapped in time, distorting the final ERP averages (Woldorff, 1993). We used two different approaches for addressing this problem. As predicted by previous behavioral studies, it is more difficult to stop when there is a longer delay between the Go Signal and the Stop Signal. Thus, if simply averaged together across all the Stop-Signal trials, the averaged ERPs for Successful inhibitions (the SI condition) would be comprised of more trials with more recent Go-stimulus events (e.g., 200–400 ms), whereas the ERPs for Failed inhibitions (the FI condition) would be comprised of more trials in which the Go stimulus occurred further back in time (e.g., 400–600 ms). This would then result in differences in the total averaged overlap distortion for the SI and FI conditions due to the preceding “Go” trial. To correct for this differential overlap distortion problem, ERP sub-averages for the SI Stop Signals and for the FI Stop Signals were obtained for each of the four 100 ms time-delay sub-ranges (200–300, 300–400, etc.) for each subject. Then, separately for each condition (i.e., SI and FI), these four sub-averages were collapsed together in an equally weighted way (25% for each sub-average), thereby better equating the overlap from the Go-event ERPs on the SI and FI Stop-Signal ERPs (Pliszka et al., 2000).

Second, to correct for any residual differential overlap for the SI and IS trials, we used the ADJAR technique to directly estimate and remove such overlap (Woldorff, 1993). More specifically, for each condition separately, we shifted the averaged waveforms time-locked to the Go-signal across the –200 to –600 ms GO-stop interval range (2 ms steps) preceding the Stop Signals, weighted by the number of actual occurrences at each interval. This approximated the average of the “Go” signal ERPs that were overlapping upon and distorting the Stop-Signal averages for each of the two conditions. These previous-response overlap estimate averages were then subtracted out of the Stop-Relevant FI and Stop-Irrelevant trials, yielding an estimate of the ERP to these Stop Signals without the overlap distortion due to the preceding Go stimuli (see Fig. 3 below for a comparison of the original waveform averages before ADJAR correction and the corrected waveforms after overlap removal).

Based on previous findings on the N200 and NoGo-P3 in the Stop-Signal Task (Liotti et al., 2005; Overtoom et al., 2002; Pliszka et al., 2000), and after inspection of the grand-average waveforms and scalp topography distributions, we selected time windows around the N200 (200–220 ms) and the NoGo-P3 components (260–280 ms) for detailed analysis. The mean amplitudes of these windows were subjected to repeated-measure analyses of variance (ANOVA). To test for regional differences in N200 amplitude, two regions of interest (ROIs) were selected by collapsing together mean voltage amplitudes over sets of three adjacent anterior electrode sites (corresponding to electrode sites F7, F5, FC5 and F8, F6, FC6). To compare Successful inhibitions versus Failed inhibitions, the following factors were included: inhibition (SI versus FI), anterior–posterior (anterior versus parietal sites) and hemisphere (left versus right). The posterior sites were represented by parietal electrodes: C1p, P3a, P1 and C2p, P4a, P2. For the comparison between Stop-Relevant and Stop-Irrelevant conditions, we included the factors: relevance (Stop-Relevant versus Stop-Irrelevant condition), anterior–posterior (anterior versus parietal sites) and hemisphere (left versus right). Due to the posterior distribution of the N200 amplitude difference between Stop-Relevant and Stop-Irrelevant trials (largest over central-parietal scalp), an additional ANOVA was carried out with the factor of Relevance at the electrode site PCz.

For the analysis of the NoGo-P3 (260–280 ms) of inhibition success (SI versus FI), similar repeated measures ANOVAs were performed. For this focal midline central effect (see topography in Fig. 4), the analysis was performed at site Cz.

Two additional results were not predicted based on previous findings. First, inspection of the waveforms for SI and FI trials and the SI versus FI difference wave revealed a later difference in the 370–450 ms time interval over the frontopolar region (see Fig. 5). Statistical differences for this wave were tested with an ANOVA including four electrode sites in the frontal region (equivalent to Fp1/Fp2 and F3i/F4i in the 10–20 system). Finally, inspection of the waveforms for Stop-Relevant FI trials and Stop-Irrelevant trials revealed amplitude difference of a posteriorly distributed slow wave between 450 and 650 ms. This effect was explored with an additional ANOVA at the midline parietal site Pzi. For all analyses, the critical *p*-value was set at .05 and the corrected degrees of freedom for deviations from sphericity were determined with the Greenhouse–Geisser epsilon method (Greenhouse & Geisser, 1954).

3. Results

3.1. Behavioral performance

In the Stop-Relevant blocks, mean correct GO RT was 619 ± 134 ms; response errors were rare, $2.1 \pm 1.7\%$. In the Stop-Irrelevant blocks, mean correct GO RT was $433 \pm$

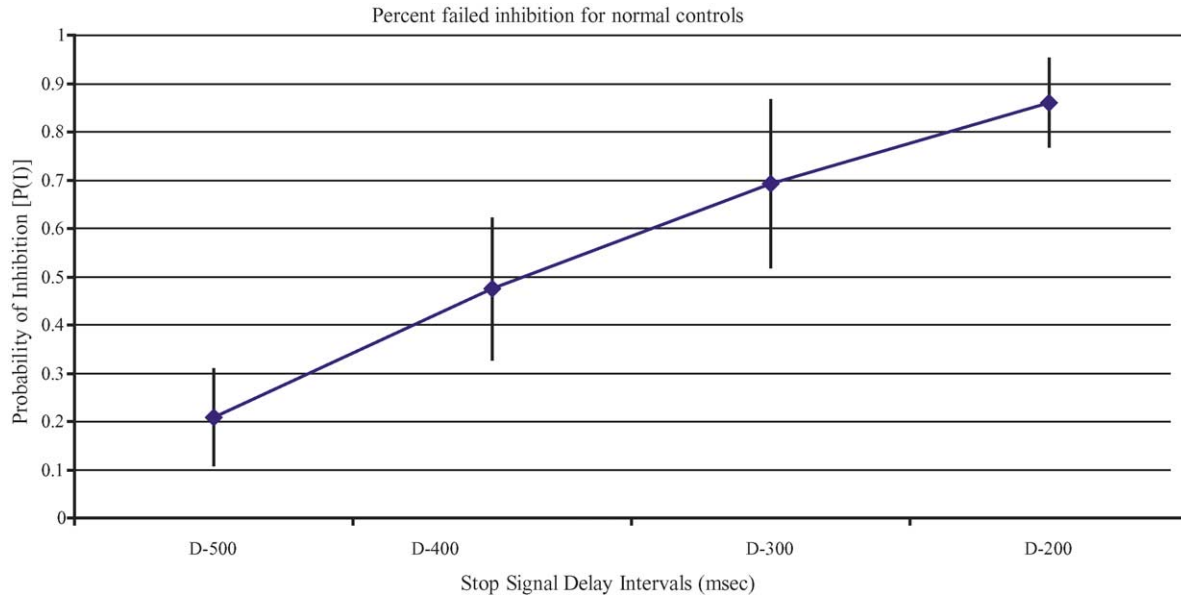


Fig. 1. Probability of Inhibition as a function of Stop-Signal interval. Note that response inhibition is relatively easy at short intervals (200 ms), and relatively hard at long intervals (600 ms).

55 ms. The probability of inhibition [P(I)] for each Stop-Signal interval was: d-500 = 0.21 ± 0.10; d-400 = 0.48 ± 0.14; d-300 = 0.70 ± 0.17; D-200 = 0.87 ± 0.18 (see Fig. 1). The slope of the [P(I)] was very similar to that of previous reported studies of the SST (e.g., Logan et al., 1984; Schachar & Logan, 1990). Mean SSRT for each Stop-Signal interval were the following: d-500 = 228 ± 57 ms, d-400 = 229 ± 43 ms; d-300 = 250 ± 44 ms, and d-200 = 305 ± 54 ms. Overall SSRT was 253 ± 50 ms.

3.2. N200: Successful versus Failed inhibitions

In the Stop-Relevant blocks, the ERP to both SI and FI trials showed a temporally sharp negative wave peaking at 200 ms after the Stop Signal (N200; see Fig. 2; see also Table 1 for N200 mean amplitude values for each ROI and condition), which appeared to be larger for SI trials than for FI trials over right frontal scalp sites. In the ANOVA analysis, a main effect of the factor anterior–posterior was found, (F(1, 10) = 8.46, p < .02). Such main effect was qualified by the significant interactions of anterior–posterior X inhibition (F(1, 10) = 15.55, p < .003), and inhibition X anterior–posterior X hemisphere (F(1, 10) = 15.28, p < .003), which reflected that the SI-FI N200 amplitude difference was particularly local-

ized over right frontal scalp. This effect was confirmed by local analyses carried out on the individual scalp regions separately, revealing that a regional difference in inhibition (SI versus FI) was present only over right lateral frontal scalp (F(1, 10) = 5.54, p < .04; see Fig. 2).

The scalp distribution of the right frontal effect for Successful versus Failed inhibitions in the present study is very similar to the distribution we previously reported for the group difference between normal and ADHD children in responses to both Successful and Failed inhibitions (Pliszka et al., 2000; see comparison between the two studies in Fig. 2A and B).

3.3. N200: Stop-Relevant versus Stop-Irrelevant trials

The ERP waveforms for Stop-Relevant trials and Stop-Irrelevant trials are shown in Fig. 3, before and after Adjard overlap correction (see Section 2 (Methods); Woldorff, 1993). Mean N200 amplitude value for each ROI and condition are shown in Table 2. A comparison of the Stop-Relevant (Failed inhibitions) and irrelevant stop responses (after Adjard correction) revealed an N200 difference with a distinctly different scalp distribution, being largest over posterior scalp sites.

Table 1

N200 mean amplitude values in microvolts and standard deviations for Successful inhibition (SI) and Failed inhibition (FI) trials at each of the selected ROIs

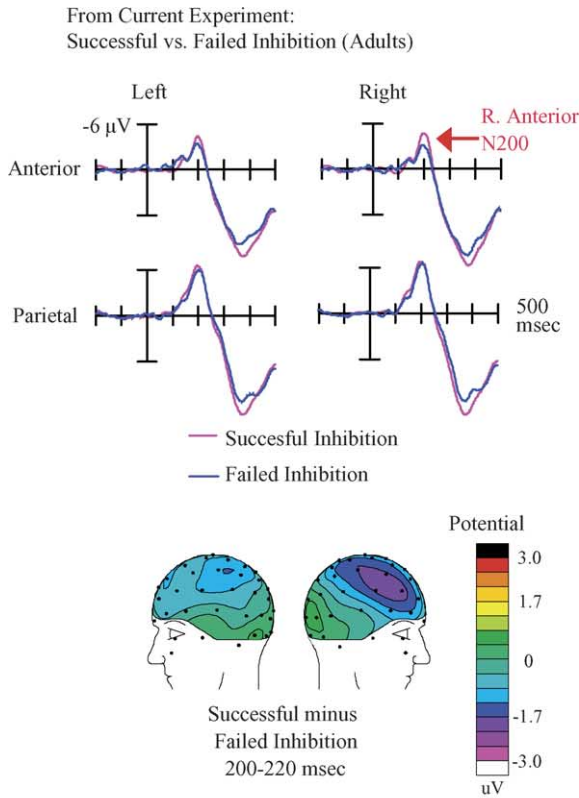
Wave N200	Topography	SI mean uV (S.D.)	FI mean uV (S.D.)
(200–220)	Ant Left	-3.74 (3.54)	-2.87 (2.78)
	Ant Right	-4.29 (4.79)	-2.64 (3.46)
	Post Left	-6.05 (2.75)	-5.77 (2.76)
	Post Right	-6.45 (3.00)	-6.35 (3.12)

Table 2

N200 mean amplitude values in microvolts and Standard Deviations for Failed Inhibition (FI) and Stop-Irrelevant trials at each of the selected ROIs

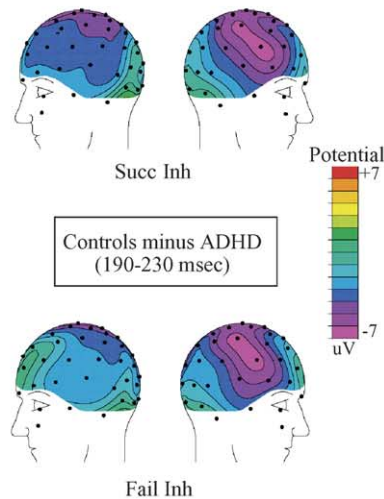
Wave N200	Topography	FI mean uV (S.D.)	Stop-Irr mean uV (S.D.)
(200–220)	Ant Left	-2.72 (2.53)	-0.89 (2.21)
	Ant Right	-2.74 (3.24)	-0.84 (2.82)
	Post Left	-5.14 (2.64)	-0.85 (2.42)
	Post Right	-5.78 (3.43)	-1.03 (3.49)

In the ANOVA analysis, the main effect of relevance was significant ($F(1, 10) = 12.61, p < .006$). This main effect was qualified by the interaction of relevance X anterior–posterior topography ($F(1, 10) = 15.93, p < .003$), showing that the N200 amplitude was greater for Stop-Relevant than stop irrelevant trials over posterior scalp regions. This was further confirmed by a local analysis carried out at the midline parietal



(A)

From Pliszka, Liotti, & Woldorff (2000):
Controls vs. ADHD (Children)



(B)

Table 3

NoGo P3 mean amplitude values in microvolts and standard deviations for Successful inhibition (SI) and Failed inhibition (FI) trials at the vertex (electrode Cz)

Wave Nogo P3	Topography	SI mean uV (S.D.)	FI mean uV (S.D.)
(260–280)	Cz	7.89 (5.88)	5.26 (5.66)

Table 4

Fp400 mean amplitude values in microvolts and standard deviations for Successful inhibition (SI) and Failed inhibition (FI) trials at four frontopolar sites

Wave FP400	Topography	SI mean uV (S.D.)	FI mean uV (S.D.)
(370–450)	FP1 left	6.31 (7.26)	2.96 (6.19)
	FP2 right	7.20 (6.90)	3.49 (6.12)
	F3a left	6.34 (6.07)	3.96 (6.49)
	F4a right	7.32 (6.33)	4.30 (5.50)

site of greatest N200 amplitude (relevance: $F(1, 10) = 28.84, p < .0004$).

3.4. Longer latency effects: Successful versus Failed inhibitions

Two components at longer latencies also appeared to differentiate Successful and Failed inhibitions. First, a focal increase in mean amplitude of the NoGo-P3 wave over mid-line central scalp (at Cz) was present for SI than FI trials $F(1, 10) = 22.37, p < .0009$; Fig. 4. This effect was maximal during the ascending phase (between 260 and 280 ms) of the centroparietal P3b wave, whereas the P3b itself peaked somewhat later (~380 ms) (see waveforms in Fig. 3 and see Table 3).

Second, a later slow wave (370–450 ms) with a medial frontopolar distribution, appeared to be a greater negativity to FI than SI trials, $F(1, 10) = 9.59, p < .015$ (results of local analysis at frontopolar sites FP1 and FP2, see Table 4). The topography, along with the relevant traces, of this effect is shown in Fig. 5. It should be noted that this very anterior effect did not invert at the eye channels located below the eye, indicating that it likely reflects a genuine neural source in prefrontal cortex and not an artifact of eye movement activity. Moreover, it does not appear to invert polarity over posterior regions of the scalp.

Fig. 2. (A) The N200 to the Stop Signal: Successful inhibition versus Failed inhibition (200–220 ms). (Top) Grand average event-related potentials (ERPs) of regions of interest comparing Successful inhibition (SI; pink) and Failed inhibition (FI; blue) during active trials for the lateral-anterior and lateral-parietal regions. (Middle) Topographic maps of the ERP difference of SI and FI trials. Note the right-anterior N200 difference for Successful versus Failed inhibition. (B) The N200 to the Stop Signal from Pliszka et al. (2000): control versus ADHD children (190–230 ms). Topographic maps of controls minus ADHD subjects of ERP differences for Successful inhibition (top) and Failed inhibition (bottom) trials, showing the strong right anterior N200 difference for control children versus ADHD children. Note the striking similarity in topography of this N200 group effect in (B) and the SI – FI difference in the present study in (A), pointing to a common, critical role of the right frontal region in response inhibition across health and disease.

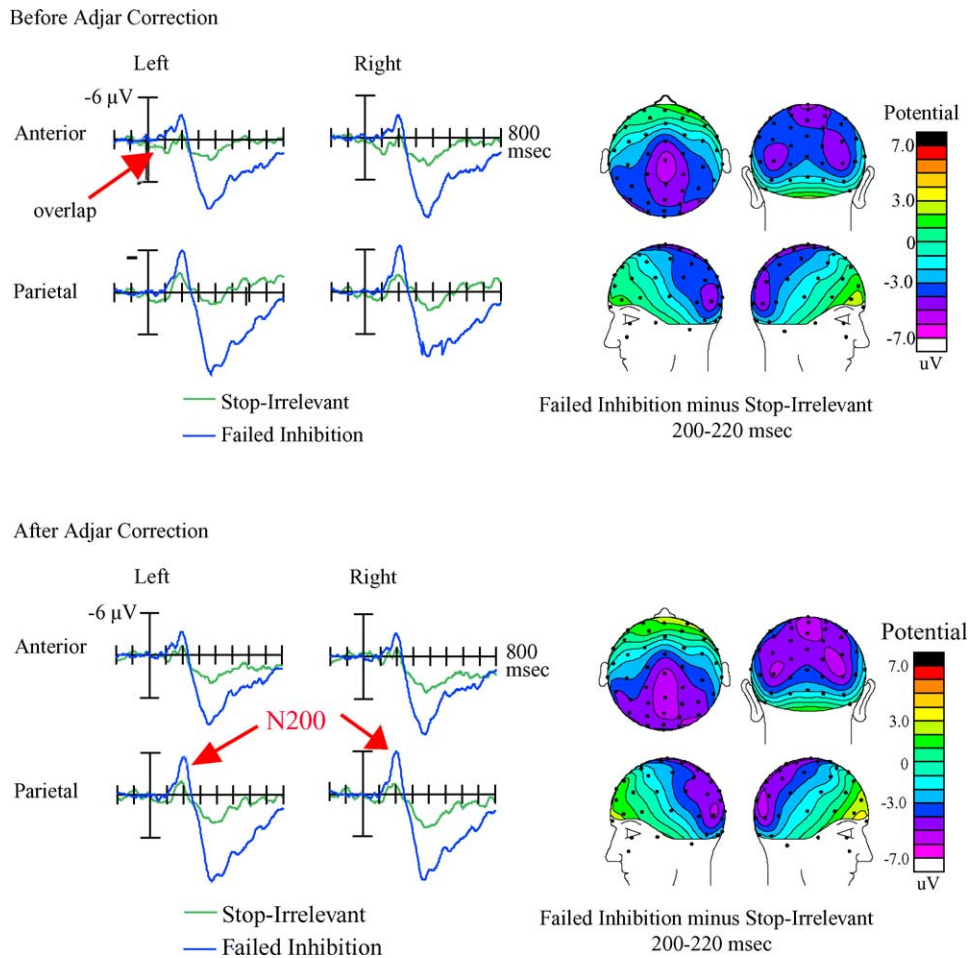


Fig. 3. Responses to the Stop Signals for the Stop-Relevant (FI trials) vs. Stop-Irrelevant conditions, shown before (Top) and after (Bottom) Adjar correction for overlap. (Top left) Grand average ERPs *before* Adjar for the Failed inhibition (Stop-Relevant; blue) and Stop-Irrelevant trials (green) for the lateral-anterior and lateral-parietal regions. Note the enhanced N200 for the Stop-Relevant trials, especially for the posterior sites. However, also note that there is some overlap distortion (from the previous Go stimulus) in all channels, beginning at or before time zero (e.g., arrow labeled “overlap”). (Top right) Topographic maps of the N200 ERP difference of the Stop-Relevant vs. Stop-Irrelevant trials shown in top left panel. (Bottom left) Grand average ERP responses *after* Adjar correction, which has effectively eliminated the previous ERP overlap distortion. Note that the N200 is still clearly larger for the Stop-Relevant trials. (Bottom right) Topographic maps of the ERP difference of Stop-Relevant and Stop-Irrelevant trials after the Adjar correction. Note that the N200 enhancement for Stop-Relevant trials is most prominent over parietal (and occipital) areas.

3.5. Longer-latency results: comparison of Failed inhibition and Stop-Irrelevant trials

An even longer latency positive slow wave difference (450–650 ms), with posterior distribution and a midline parietal maximum, was evident in the contrast of Failed inhibitions and Stop-Irrelevant trials (see Fig. 6, and Table 5), as well as in the contrast of Failed inhibitions and Successful

inhibitions, although this activity partly overlapped with the late portion of the NoGo-P3 (data not analyzed, but see Fig. 2, right, 550–600 time window). An ANOVA of this activity was performed at the midline inferior parietal site (Pzi) for the factor trial type, showing this difference to be highly significant, $F(1, 10) = 50.26, p < 0.001$. The topography of this effect, along with the relevant traces is shown in Fig. 6.

Table 5

Late slow wave mean amplitude values in microvolts and standard deviations for Failed inhibition (FI) and Stop-Irrelevant trials at the midline inferior parietal site (Pzi)

Wave late SW	Topography	SI mean uV (S.D.)	Stop-Irr mean uV (S.D.)
(450–650)	Pzi	11.13 (3.59)	2.76 (2.76)

4. Discussion

In this study, we used ERPs to elucidate the spatiotemporal organization of inhibitory processes in the Stop-Signal Task in young healthy adults. In the evoked response to the Stop Signal, several effects appeared to differentiate Successful and Failed attempts to inhibit the motor response.

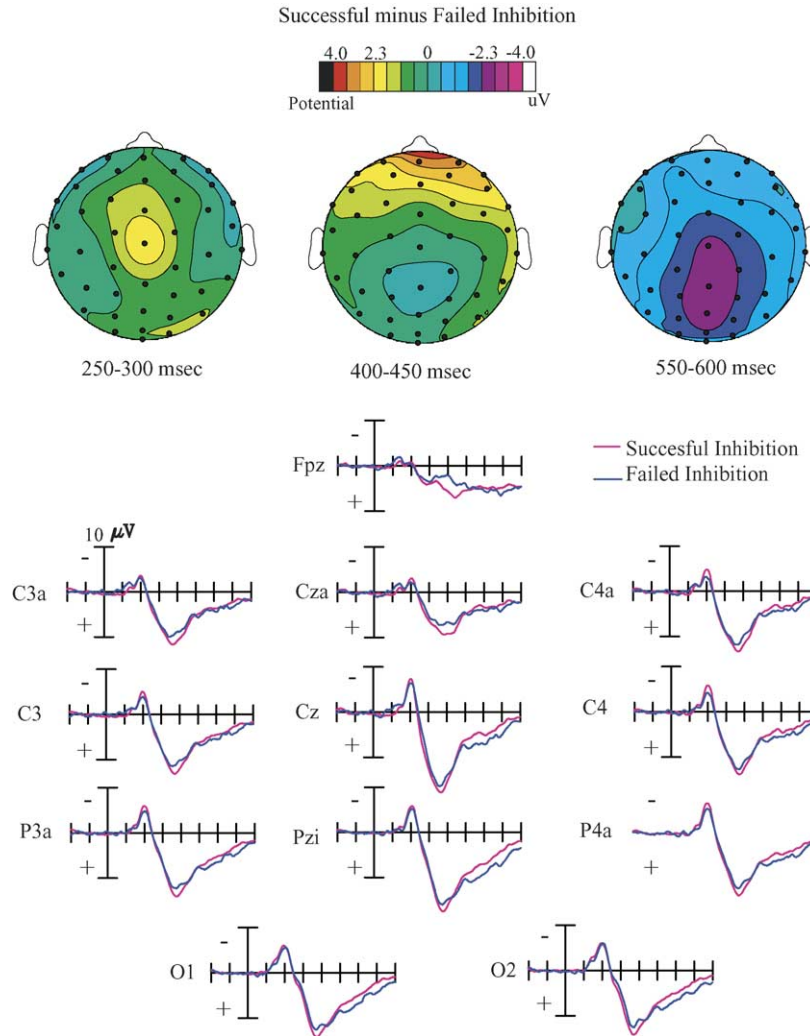


Fig. 4. (Top) Grand average ERP responses for Successful and Failed inhibition trials over 12 representative electrode sites. (Top) Topographic maps of the ERP difference of Successful vs. Failed inhibition trials at 260–280 ms (NoGo-P3), 370–450 ms (Fp400), and 550–600 ms (late SW). Note that the polarity of the Fp400 and late SW are inverted relative to Figs. 5 and 6, due to the direction of the contrast.

4.1. N200 effects

A new finding of particular importance is that the N200 elicited by the Stop Signal was significantly greater for Successful inhibitions than Failed inhibitions over right inferior frontal scalp, suggesting that the amplitude of this early right-frontal N200 wave, besides reflecting the triggering of the inhibitory process, it is also enhanced when there will be successful implementation of the inhibitory process. The N200 success-related enhancement cannot be explained by differences in stimulus salience or probability (same stimuli involved) or differences in early sustained attention (which would have resulted in effects distributed over posterior extrastriate regions, as in the comparison with Stop-Irrelevant trials). This effect is in line with other findings on the relationship of the NoGo-N200 to response inhibition that have indicated that N200 amplitude varies with the speed-accuracy trade-off, being greater when responses are most accurate

(and relatively slower) and smaller when responses are faster but less accurate (Falkenstein et al., 1999; Jodo & Kayama, 1992). Thus, the results of the present study adds further evidence that a right frontal mechanism, reflected in the N200 wave, plays a central role in response inhibition as indexed by the Stop-Signal Task. Consistent with this conclusion are also recent findings of involvement of right middle and inferior frontal gyrus in inhibitory control from fMRI studies of Go-NoGo and Stop-Signal Tasks in healthy adults (Garavan et al., 1999; Konishi et al., 1999; Liddle et al., 2001), and a lesion-behavior correlation study showing that impairment in the Stop-Signal Task is associated with selective lesions in the pars triangularis of the right inferior prefrontal cortex (Aron et al., 2003).

No doubt the most interesting implication of the present finding is its relevance toward understanding impaired inhibitory control mechanisms in ADHD. Previously in Pliszka et al. (2000), using an identical task, we had reported

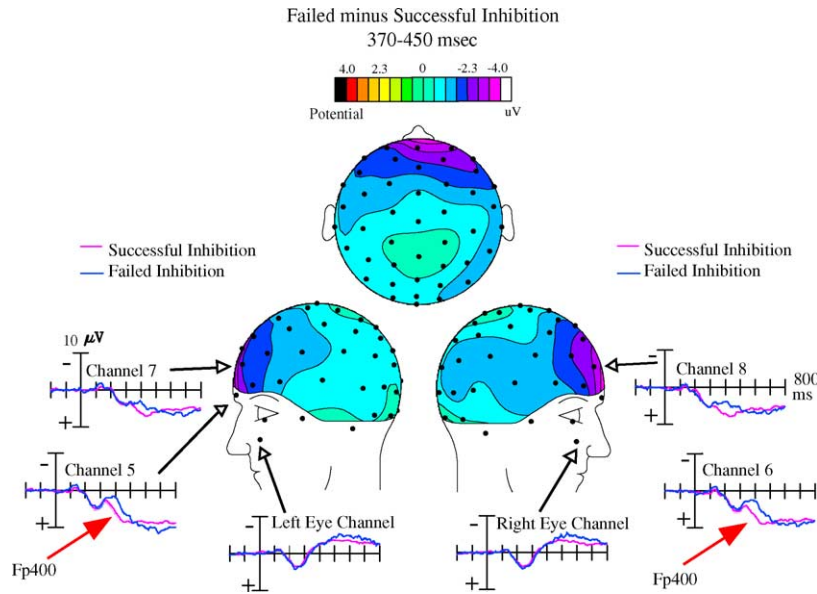


Fig. 5. Prefrontal late positivity (Fp400) to Stop Signal: Failed vs. Successful inhibition. Grand average event-related potentials (ERPs) for Successful and Failed Inhibition in frontal channels. (Center) Topographic maps ERP difference of Failed minus Successful inhibition trials at 370–450 ms. Note that this negativity does not invert in the eye channels (i.e., the VEOG sites below the eyes), indicating that the source of this very frontal activity is neural, rather than eye artifact.

that ADHD children had a markedly reduced N200 to Stop Signals when compared to control children, with the distribution of this effect being over the same right inferior frontal region (see Fig. 2A and B for a comparison of the two studies). In Pliszka et al. (2000), however, no difference in the amplitude of the N200 was observed between SI and FI trials, whether in the healthy control children, or among the ADHD children. This led the authors to speculate that the right frontal N200 is involved in the initiation/triggering of the inhibitory process, independent of its outcome (Liotti et al., 2005). The current results suggest that, at least in healthy adults, the amplitude of the right frontal N200 is also sensitive to the *outcome* of the inhibitory process. However, this discrepancy may reflect differences in statistical power between the two studies. Developmental differences in frontal mechanisms could also explain the discrepancy, i.e., with the

efficiency of the inhibitory mechanism improving in adults relative to children. It is possible that the N200 effects in adults for Successful versus Failed inhibition may reflect, in addition to the triggering of the inhibitory process, the maturation of cognitive control operations involving planning a strategy or applying and maintaining an adequate mental set, functions often attributed to the lateral prefrontal cortex.

An important, second novel finding of the present study derives from the possible isolation of aspects of the response to the Stop Signal previously not characterized. The comparison between the Stop-Relevant Failed inhibitions and the Stop-Irrelevant trials revealed an N200 difference with a quite different scalp distribution—namely, over posterior (parieto-occipital) scalp. These conditions are matched for sensory stimulation, motor requirements and probability of occurrence, and *neither* involves Successful response inhibition (however, detection and evaluation of an error is present only in the FI trials). We propose that this posterior N200 effect reflects the activity of a distinct N200 subgenerator (or set of subgenerators) involved in other aspects of the evoked-response to Stop-Relevant Stop Signals, including enhanced sensory and perceptual processing due to their being attended and relevant. Based on previous ERP and fMRI studies of early sustained visual attention and attentional cuing (e.g., Woldorff, Liotti, Seabolt, Busse, Lancaster, & Fox, 2002; Woldorff, Hazlett, Fichtenholtz, Weissman, Dale, & Song, 2004), this posterior scalp distribution is consistent with generators in extrastriate visual cortex, as well as possibly superior parietal cortex. It is important to note that this posterior N200, which is a sensory/perceptual component apparently sensitive to attention and task relevance, was *not* impaired in ADHD children in the Pliszka et al. (2000) study, whereas the

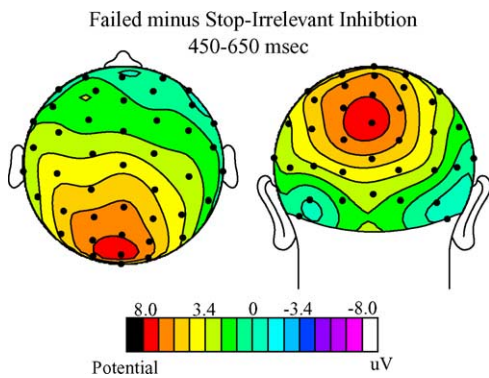


Fig. 6. Late slow wave (450–650 ms) for Failed inhibition vs. Stop-Irrelevant trials. Note the focus over midline posterior scalp. This effect has opposite polarity from Fig. 4, due to the opposite direction of the subtraction.

right frontal N200 subcomponent, reflecting response inhibition, was. Further studies in ADHD subjects would be helpful to further delineate and localize the critical portions of this 200-ms-latency brain activity that are impaired in ADHD.

4.2. *NoGo-P3 to Stop-Relevant trials*

A second, somewhat less novel finding of the present study is the greater amplitude of an early positivity (260–280 ms), with a focal distribution over midline central scalp, evident when comparing Successful inhibitions to Failed inhibitions (Fig. 4). This effect has been reported earlier in healthy children, although it tended to peak slightly later, around 300 ms (the NoGo-P3) (Liotti et al., 2005; Overtom et al., 2002). Such success-related NoGo-P3 effect was significantly reduced in ADHD children (Liotti et al., 2005; Overtom et al., 2002). The somewhat longer latency in children could be due to developmental factors. The midline central distribution of the NoGo-P3 in this study suggests a possible generator from dorsal anterior cingulate cortex (dACC) or nearby pre-SMA. An important role of the dACC in tasks of response selection and conflict monitoring (such as the Stroop task) has been firmly established by PET, fMRI, ERP and lesion correlation studies (Botvinick et al., 2001; Carter, Mintun, & Cohen, 1995; Liotti, Woldorff, Perez, & Mayberg, 2000; Swick & Jonanovic, 2002; van Veen & Carter, 2002). Of importance here, effects in the dACC have recently been reported in healthy adults and adolescents during Go-NoGo tasks by event-related techniques, both ERPs and fMRI (Bokura et al., 2001; Casey, Trainor, et al., 1997; Liddle et al., 2001). In addition, Casey, Castellanos, et al. (1997) found a significant correlation between children's performance in a difficult visual search task and the anatomical size of the right dorsal ACC (Casey, Castellanos, et al., 1997). It has been hypothesized that the NoGo-P3 effect in the Stop-Signal Task reflects monitoring of successful outcome of the inhibitory process (Liotti et al., 2005), consistent with a general role of dACC in monitoring conflict and error processing in cognitive control (Botvinick et al., 2001). In contrast, the actual response inhibition mechanism in such a view would reside in the right lateral prefrontal cortex (Konishi et al., 1999; Liddle et al., 2001).

4.3. *Late failure-specific effects*

Another novel finding of the present study was the observation of a robust, longer-latency effect seen at 370–450 ms over frontopolar scalp (Fig. 5). This effect (which we refer to here as the “Fp400”), reflected the ERP to Failed inhibitions being more negative compared to the ERP to Successful inhibitions. Note that this difference did not invert at electrodes below the eyes (Fig. 5), confirming that this very anterior effect is neural in origin and not an artifact of eye blinks or eye movement. Moreover, no distinct polarity inversion was evident for this component over posterior scalp, suggesting a focal source in anterior prefrontal cortex. We propose that this

frontopolar effect may reflect aspects of inhibitory control relating to error detection and correction, consistent with ERP and event-related fMRI studies of error processing showing that response-locked error-related activity (as reflected by the error-related negativity [ERN, Falkenstein et al., 1999]) have generators in the dorsal and even rostral anterior cingulate cortex (Liddle et al., 2001; van Veen and Carter, 2002). This is further supported by recent evidence that the amplitude of the ERN during a Stop-Signal Task is strikingly reduced in ADHD relative to control children (Liotti et al., 2005). The fact that this late Fp400 effect has not been reported in previous studies of the Stop-Signal Task in children may reflect more robust signal-to-noise over inferior frontal regions in this study (due to less ocular artifacts in young adults than in children), removal of pre-Stop Signal overlap in this study, and higher electrode density than in some studies.

Later on in time (450–650 ms), a midline parietal positive slow wave was markedly greater in amplitude for Failed inhibitions than Stop-Irrelevant trials. These conditions are matched for motor requirements, but they differ in that in the demands in terms of error evaluation and correction are absent for the second task. It is proposed that this *late* failure-specific effect corresponds to the response-locked error positivity found in ERP studies of error processing (the “Pe”, Falkenstein et al., 1999, 2000). This is confirmed by the similar scalp distribution over midline posterior scalp of the present slow wave and the Pe, as well as its timing – in ERP studies of error processing, the Pe follows the ERN by about 200 ms. It is worth noting that a failure-enhanced parietal slow wave is also evident from the contrast between Failed inhibitions and Successful inhibitions (see Fig. 2, right, 550–600 ms). However, such statistical contrast was not been carried out (because the two type of trials are not matched for motor activity).

5. Conclusions

The present high-density ERP study allowed the identification of spatially and temporally distinct electrophysiological effects during the unfolding of the Stop-Signal Task. The N200 modulation observed over right lateral frontal cortex, with greater amplitude for Successful than Failed inhibitions, appeared to reflect the triggering and efficient implementation of the inhibitory process. Accordingly, this effect overlapped almost precisely in both scalp distribution and timing with an N200 abnormality previously shown in children with ADHD (Pliszka et al., 2000). This effect dovetails nicely with recent findings from lesion correlation (Aron et al., 2003) and fMRI studies of response inhibition (Garavan et al., 1999; Konishi et al., 1999; Liddle et al., 2001; Rubia et al., 1999) showing that the right middle and inferior prefrontal gyrus are critical for inhibitory control.

Over parieto-occipital scalp, the N200 was enhanced for the Stop Signals in the Stop-Relevant condition versus the Stop-Irrelevant condition. This effect was presumably due to

enhanced sensory and perceptual processing for the Stop Signals in the former condition due to their being attended and task-relevant. This effect is likely produced by N200-latency subgenerators in extrastriate visual cortex and/or parietal cortex (Woldorff et al., 2002, 2004) that are distinct from the right-frontal contributions. Such posterior N200 activity is presumably not related to inhibitory control, as evidenced by it not differing between Successful and Failed inhibitions and by its normal amplitude in ADHD children in the Pliszka et al. (2000) study. Moreover, the combination of the results from that study and the present study helps confirm that the N200 deficit in ADHD children is *not* due to deficits at the level of the sensory and perceptual processing of the Stop Signals.

At longer latencies, a modulation of the NoGo-P3 over medial frontocentral scalp also appeared to reflect activity related to the efficient implementation of the inhibitory process, having greater amplitude for Successful relative to Failed inhibitions. Such a result is consistent with ADHD children showing less success-related activity than control children (Liotti et al., 2005; Overtom et al., 2002). NoGo-P3 activity appears likely to originate, at least in part, from the dACC, a structure believed to be involved in general monitoring of performance and error processing during tasks of cognitive control (Botvinick et al., 2001).

Finally, two late failure-specific ERP effects, a greater frontopolar negative wave (370–450 ms) to Failed than Successful stops, and a greater midline parietal positive slow wave (450–650 ms) for Failed inhibitions than ignore-stop trials were also found in the study. The fronto-polar effect, which we term here the Fp400, likely reflects error monitoring mechanisms perhaps related to the error-related negativity, and possibly originating in the rostral anterior cingulate region (van Veen and Carter, 2002). The later midline posterior positive slow wave (450–650 ms) was due to greater positivity for Failed inhibitions compared to the Stop-Irrelevant trials (but was evident also in the comparison with Successful inhibitions). This latter wave had the same scalp distribution of the error positivity (Pe) elicited when time-locking to a manual response, and follows the Fp400 activity by about the same time lag typically found between the ERN (peaking at 100 ms from the onset of a response) and the Pe (peaking about 300 ms from response onset). It is therefore proposed that the Stop-Signal evoked Fp400 and late parietal slow wave may correspond, respectively, to the ERN and the Pe (time-locked to response onset), both reflecting differential recruitment of error detection and correction mechanisms following Failed attempts to inhibit a response.

In summary, we report a spatiotemporal sequence of differential activity for Successful versus Failed inhibitions during the Stop-Signal Task. This sequence begins with an enhanced N2 wave at 200 ms over right frontal cortex for Successful stops, an effect very similar in timing and distribution to the right-frontal N2 deficiency previously seen in ADHD children, thus helping to confirm that such activity reflects the triggering and efficient implementation of the inhibitory pro-

cess. This was followed by a series of longer latency effects likely reflecting differential recruitment of error detection and correction mechanisms following Failed attempts to inhibit a response, processes which have also been shown to be abnormal in ADHD. These results thus provide insight into both the normal sequence of response inhibition processes in healthy adults and the abnormal ones seen in ADHD.

Acknowledgement

This work was supported by NIMH R01 grant MH-60415 to M.G.W.

References

- American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders—Fourth Edition (DSM-IV)*. Washington, DC: American Psychiatric Association.
- Aron, A., Fletcher, P., Bullmore, E., Sahakian, B., & Robbins, T. (2003). Stop-Signal inhibition disrupted by damage to right inferior frontal gyrus in humans. *Nature Neuroscience*, *6*, 115–116.
- Barkley, R. (1998). *Attention-deficit hyperactivity disorder: A handbook for diagnosis and treatments*. New York: Guilford.
- Bokura, H., Yamaguchi, S., & Kobayashi, S. (2001). Electrophysiological correlates for response inhibition in a Go/NoGo task. *Clinical Neurophysiology*, *112*, 224–2232.
- Botvinick, M., Braver, T., Barch, D., Carter, C., & Cohen, J. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652.
- Casey, B., Trainor, R., Orendi, J., Schubert, A., Nystrom, L., Giedd, J., et al. (1997). A developmental functional MRI study of prefrontal activation during performance of a go-no-go task. *Journal of Cognitive Neuroscience*, *9*, 835–847.
- Casey, B., Castellanos, F., Giedd, J., Marsh, W., Hamburger, D., Schubert, A., et al. (1997). Implication of right frontostriatal circuitry in response inhibition and attention deficit/hyperactivity disorder. *Journal of the Academy of Child and Adolescent Psychiatry*, *36*, 374–383.
- Carter, C., Mintun, M., & Cohen, J. (1995). Interference and facilitation effects during selective attention: An H215O PET study of Stroop task performance. *Neuroimage*, *2*, 264–272.
- Eimer, M. (1993). Effects of attention and stimulus probability on ERPs in a Go/Nogo task. *Biological Psychology*, *35*, 123–138.
- Falkenstein, M., Hoorman, J., & Hohnsbein, J. (1999). ERP components in Go/NoGo tasks and their relation to inhibition. *Acta Psychologica*, *101*, 267–291.
- Falkenstein, M., Hoorman, J., & Hohnsbein, J. (2000). ERP components on reaction errors and their functional significance: A tutorial. *Biological Psychology*, *51*, 87–107.
- Garavan, H., Ross, T., & Stein, E. (1999). *Right hemispheric dominance of inhibitory control: An event-related functional MRI study* (pp. 8301–8306), 96.
- Greenhouse, S., & Geisser, S. (1954). On methods in the analysis of profile data. *Psychometrika*, *24*, 95–112.
- Jodo, E., & Kayama, Y. (1992). Relation of a negative ERP component to response inhibition in a Go/No-go task. *Electroencephalography and Clinical Neurophysiology*, *82*(6), 477–482.
- Kok, A. (1986). Effects of degradation of visual stimulation on components of the event-related potential (ERP) in go/nogo reaction tasks. *Biological Psychology*, *23*(1), 21–38.
- Konishi, S., Nakajim, K., Uchida, I., Kiyoyama, H., Kameyama, M., & Miyashita, Y. (1999). Common inhibitory mechanism in human infe-

- rior prefrontal cortex revealed by event-related functional MRI. *Brain*, 122, 981–991.
- Liddle, P., Kiehl, K., & Smith, A. (2001). Event-related fMRI study of response inhibition. *Human Brain Mapping*, 12, 100–109.
- Liotti, M., Woldorff, M., Perez, R., & Mayberg, H. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia*, 38(5), 701–711.
- Liotti, M., Pliszka, S., Perez, R., Kothmann, D., & Woldorff, M. (2005). Abnormal brain activity related to performance monitoring and error detection in children with ADHD. *Cortex*, 42(3), 1–12.
- Logan, G., Cowan, W., & Davis, K. (1984). On the ability to inhibit thought and action: A theory of act of control. *Psychological Review*, 91, 295–327.
- Overtoom, C., Kenemans, J., Verbaten, M., Kemner, C., van der Molen, M., van Engeland, H., et al. (2002). Inhibition in children with attention-deficit/hyperactivity disorder: A psychophysiological study of the stop. *Biological Psychiatry*, 51, 668–676.
- Perrin, F., Pernier, J., Bertrand, D., & Echallier, J. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology*, 72, 184–187.
- Pliszka, S., Borcharding, S., Spratley, K., & Irick, S. (1997). Measuring inhibitory control in children. *Journal of Developmental and Behavioral Pediatrics*, 18, 254–259.
- Pliszka, S., Liotti, M., & Woldorff, M. (2000). Inhibitory control in children with attention-deficit/hyperactivity disorder: Event-related potentials identify the processing component and timing of an impaired right-frontal response-inhibition mechanism. *Biological Psychiatry*, 48, 238–246.
- Rubia, K., Overmeyer, S., Taylor, E., Brammer, M., Williams, S., Simmons, A., et al. (1999). Hypofrontality in attention deficit hyperactivity disorder during higher-order motor control: A study with functional MRI. *American Journal of Psychiatry*, 156, 891–896.
- Schachar, R., & Logan, G. (1990). Impulsivity and inhibitory control in normal development and childhood psychopathology. *Developmental Psychology*, 26, 710–720.
- Squires, N., Squires, K., & Hillyard, S. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and Clinical Neurophysiology*, 38, 387–410.
- Swick, D., & Jonanovic, J. (2002). Anterior cingulate cortex and the Stroop task: Neuropsychological evidence for topographic specificity. *Neuropsychologia*, 40, 1240–1253.
- Tekok-Kilic, A., Shucard, J., & Shucard, D. (2001). Stimulus modality and Go/NoGo effects on P3 parallel visual and auditory continuous performance tasks. *Psychophysiology*, 28, 578–589.
- van Boxtel, G. J., van der Molen, M. W., Jennings, J. R., & Brunia, C. H. A. (2001). Psychophysiological analysis of inhibitory motor control in the Stop-Signal paradigm. *Biological Psychology*, 58(3), 229–262.
- van Veen, V., & Carter, C. (2002). The anterior cingulate as a conflict monitor: fMRI and ERP studies. *Physiology Behavior*, 77(45), 477–482 (review).
- Woldorff, M. (1993). Distortion of ERP averages due to overlap from temporally adjacent ERPs: Analysis and correction. *Psychophysiology*, 30, 98–119.
- Woldorff, M., Liotti, M., Seabolt, M., Busse, L., Lancaster, J., & Fox, P. (2002). The temporal dynamics of the effects in occipital cortex of visual-spatial selective attention. *Brain Research Cognitive Brain Research*, 15(1), 1–15.
- Woldorff, M., Hazlett, C., Fichtenholtz, H., Weissman, D., Dale, A., & Song, A. (2004). Functional parcellation of attentional control regions of the human brain. *Journal of Cognitive Neuroscience*, 16, 149–165.