J Abnorm Child Psychol (2008) 36:989–998
DOI 10.1007/s10802-008-9230-z

ADHD and Behavioral Inhibition: A Re-examination of the Stop-signal Task

R. Matt Alderson · Mark D. Rapport · Dustin E. Sarver · Michael J. Kofler

Published online: 7 May 2008

Abstract The current study investigates two recently identified threats to the construct validity of behavioral inhibition as a core deficit of attention-deficit/hyperactivity disorder (ADHD) based on the stop-signal task: calculation of mean reaction time from go-trials presented adjacent to intermittent stop-trials, and non-reporting of the stop-signal delay metric. Children with ADHD (n=12) and typically developing (TD) children (n=11) were administered the standard stop-signal task and three variant stop-signal conditions. These included a no-tone condition administered without the presentation of an auditory tone; an ignore-tone condition that presented a neutral (i.e., not associated with stopping) auditory tone; and a second ignore-tone condition that presented a neutral auditory tone after the tone had been previously paired with stopping. Children with ADHD exhibited significantly slower and more variable reaction times to go-stimuli, and slower stop-signal reaction times relative to TD controls. Stop-signal delay was not significantly different between groups, and both groups' go-trial reaction times slowed following meaningful tones. Collectively, these findings corroborate recent meta-analyses and indicate that previous findings of stop-signal performance deficits in ADHD reflect slower and more variable responding to visually presented stimuli and concurrent processing of a second stimulus, rather than deficits of motor behavioral inhibition.

Keywords Attention-deficit/hyperactivity disorder · ADHD · Behavioral inhibition · Stop-signal task

Attention deficit/hyperactivity disorder (ADHD) is characterized by difficulties with attention, hyperactivity, and impulsivity, and occurs in an estimated 3% to 5% of school-age children (Barkley 2006; Szatmari 1992). Presence of the disorder conveys increased risk for several pejorative outcomes including long-term scholastic underachievement and interpersonal peer problems in affected children (for reviews, see Barkley et al. 2006; Mannuzza et al. 1993).

Treatment and prevention of ADHD is dependent on a comprehensive understanding of its underlying mechanisms and core features. Current models suggest that a deficiency in behavioral inhibition—a covert process detectable through the observation of secondary behaviors—is a core feature of the disorder (Barkley 2006; Sonuga-Barke 2002). Anatomical structures such as the prefrontal and frontal cortices are hypothesized correlates of behavioral inhibition (Aman et al. 1998), wherein motoric responses initiated in response to peripheral stimuli (e.g., visual or auditory) are overridden or terminated following commands from these areas. Involvement of the basal ganglia may serve to ensure proper execution of desired motor responses, and the dopaminergic and noradrenergic systems are probable candidates involved in behavioral inhibition at the neurotransmitter level (Rieger et al. 2003).

Performance measures used to index the behavioral inhibition construct typically involve a dual-task paradigm in which children respond to a primary stimulus and withhold a response when presented with a secondary

R. M. Alderson
Department of Psychology, Oklahoma State University, Stillwater, OK, USA

M. D. Rapport · D. E. Sarver · M. J. Kofler
Department of Psychology, University of Central Florida, Orlando, FL, USA

M. D. Rapport (✉)
Children's Learning Clinic-IV, University of Central Florida, P.O. Box 161390, Orlando, FL 32816-1390, USA
e-mail: mrapport@pegasus.cc.ucf.edu

stimulus. Examples include the (a) go-no-go task (Iaboni et al. 1995), (b) change task (Schachar et al. 1995), (c) stroop color–word interference test (Barkley 1997), and (d) stop-signal task (Logan et al. 1984). The stop-signal task is considered the primary measure used in clinic- and laboratory-based research to investigate behavioral inhibition in children with ADHD, due to its unique ability to capture theoretically important cognitive processes by means of the stop-signal reaction time (SSRT) metric.

The conventional stop-signal task requires children to respond differentially to two distinct go-stimuli (e.g., the letters X and O) using left and right response buttons. On a predetermined number of trials (most often 25%) children are instructed to stop themselves from responding to a visually presented go-stimulus—the X or O—if it is followed by a specific signal such as an auditory tone. The onset asynchrony between the go-stimulus and stop-stimulus may be manipulated, providing a range of stop-signal delays. Contemporary stop-signal studies typically utilize dynamic stop-signal delays that increase or decrease after each stop-trial, depending on inhibitory success. Reaction times to the primary stimulus (i.e., mean reaction time: MRT) are computed by measuring the latency between the presentation of the go-stimulus and the child's response. Stop-signal reaction time is the most commonly reported measure of stop-signal behavioral inhibition—it refers to the latency between the presentation of the stop-signal and the initiation of the stop process, and is typically calculated by subtracting the mean stop-signal delay from mean reaction time. According to Logan et al.'s (1984) race model of behavioral inhibition, response inhibition depends on whether the stop process can overtake the go-process when go- and stop-processes are activated in close temporal sequence (i.e., go-signal activation followed by stop-signal activation). A slow reaction time to a stop-stimulus (SSRT) decreases the probability that the stop-process will overtake the go-process. The relationships among MRT, stop-signal delay, and SSRT are depicted graphically in Fig. 1.

Extant research of behavioral inhibition using the stop-signal task indicates that children with ADHD have slower and more variable choice reaction times (MRT) and stopping reaction times (SSRT) relative to typically developing (TD) children. These findings have been replicated in laboratories in Europe (Overtoom et al. 2002), Canada (Schachar et al. 2000), and the United States (Walcott and Landau 2004) using samples of carefully diagnosed children with ADHD. Despite strong inter-study reliability, recent meta-analytic reviews identified problems with the calculation of MRT from go-trials presented adjacent to intermittent stop-trials, and non-reporting of the stop-signal delay (SSD) metric that collectively threaten the construct validity of SSRT as a measure of behavioral inhibition (Alderson et al. 2007; Lijffijt et al. 2005).

The practice of calculating children's basic motor response speed (i.e., MRT) by averaging extracted non-stop trials (i.e., go-trials) presented before and after stop trials within an experimental block represents a potential methodological confound in past studies examining behavioral inhibition in ADHD by means of the stop-signal paradigm. This methodology implies that children's MRT to the go-stimulus is uninfluenced by exposure to stop signals on previous trials or by the anticipation of stop-signals on future trials, and is contrary to the well-documented effects of intermittent tones on reaction time. For example, stimuli that momentarily capture the attention of a participant (i.e., singleton distracters) often exert a slowing effect on reaction time (Dalton and Lavie 2004), even when the distractor is minimally associated with the task or target stimulus (Mason et al. 2004, 2005). Studies of negative priming reveal a similar effect, wherein implicit memory of a stimulus previously associated with a meaningful stimulus creates a response conflict and slows reaction time on subsequent trials (Fox 1995; May et al. 1995).

Two studies have directly examined the effects of intermittent stop-signals on reaction time to a go-stimulus. Schachar et al. (2004) reported that children with ADHD and typically developing children both slowed their go-response on trials following unsuccessful inhibition (referred to as error monitoring), although children with ADHD slowed significantly less relative to control children. Their estimate of error monitoring may have been inadvertently deflated, however, by including the same go-

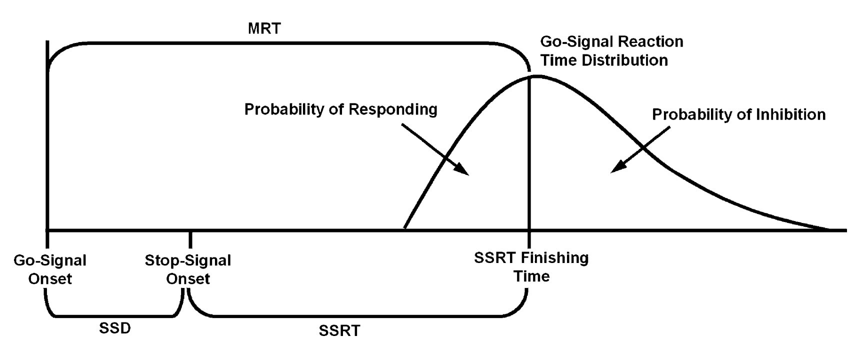

Fig. 1 A visual schematic portraying the relationship among mean reaction time (MRT), stop-signal delay (SSD), and stop-signal reaction time (SSRT) in the context of a traditional stop-signal paradigm

trial reaction time data (following unsuccessful inhibition) in the standard-task/error-monitoring contrast metrics. The second study examining intermittent stop-signal effects on reaction time also reported a slowing effect on MRT, and failed to find motor inhibition differences in children with ADHD after controlling for baseline reaction time (Rommelse et al. 2007). Their ten-option go-response, stop-signal paradigm and use of visuospatial rather than traditionally used phonological text-based stimuli, however, may limit the generalization of their findings.

A second potential confound identified by both meta-analytic reviews involved the non-significant stop-signal delay effect size (Alderson et al. 2007; Lijffijt et al. 2005). These findings suggest that the between-group SSRT variability reported in past studies comparing children with ADHD to typically developing controls reflects baseline differences in MRT rather than true inhibitory deficits. The meta-analytic results, however, were based on derived estimates that relied on unconventional effect size calculations (i.e., unstandardized mean gain scores or pooling pooled standard deviations) due to the non-reporting of stop-signal delays and associated standard deviations in the literature. No published, experimental study to date has directly examined and reported stop-signal delay differences between children with ADHD and typically developing children. In the current study, behavioral inhibition differences between children with ADHD and typically developing control children were examined directly based on the stop-signal delay metric.

The primary aim of the current study was to investigate whether distinctive types of intermittent auditory tones—meaningful (associated with stopping) and non-meaningful (not associated with stopping)—exert an overall or differential (between-group) effect on children's MRT and MRT variability. If meaningful tones significantly influence children's reaction time or MRT variability, past estimates of MRT based on extracted go-trial reaction times likely bias the overall calculation of behavioral inhibition deficits (i.e., the SSRT metric). This is because variability in SSRT is derived from three potential sources: (a) variability in stop-signal delay if MRT is held constant; (b) variability in MRT if stop-signal delay is held constant; and (c) variability in both MRT and stop-signal delay based on Logan et al.'s (1997) formula (SSRT=MRT−SSD). The occurrence of a biased effect, if present, is expected to slow children's MRT relative to a non-meaningful tone or no-tone condition based on extant literature. This is also the first experimental study to directly compare stop-signal delay between children with ADHD and typically developing control children in the context of a conventional stop-signal paradigm. A non-significant or small stop-signal delay effect is expected based on the results of recent meta-analytic findings (Alderson et al. 2007; Lijffijt et al. 2005), which would suggest that children with ADHD do not differ from typically developing children with respect to motor behavioral inhibition processes.

Method

Participants

The sample was comprised of 23 male children aged 8 to 12 years (M=9.04, standard deviation (SD)=1.36), recruited by or referred to the Children's Learning Clinic–IV (CLC-IV) through community resources (e.g., pediatricians, community mental health clinics, school system personnel, self-referral). The CLC-IV is a research-practitioner training clinic known to the surrounding community for conducting developmental and clinical child research and providing pro bono comprehensive diagnostic and psychoeducational services. Its client base consists of children with suspected learning, behavioral or emotional problems, as well as typically developing children whose parents agreed to have them participate in developmental/clinical research studies. A psychoeducational evaluation was provided to the parents of all participants.

Two groups of children participated in the study: children with ADHD, and typically developing children without a psychological disorder. All parents and children gave their informed consent/assent to participate in the study, and Institutional Review Board approval was obtained prior to the onset of data collection.

Group Assignment

All children and their parents participated in a detailed, semi-structured clinical interview using the Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS). The K-SADS assesses current and past episodes of psychopathology in children and adolescents based on Diagnostic and Statistical Manual of Mental Disorders (DSM-IV) criteria. Its psychometric properties are well established, including interrater agreement of 0.93 to 1.00, and test–retest reliability of 0.63 to 1.00 (Kaufman et al. 1997).

Twelve children met the following criteria and were included in the ADHD group: (1) an independent diagnosis by the CLC-IV's directing clinical psychologist using DSM-IV criteria for ADHD based on K-SADS interview with parent and child; (2) parent ratings of at least two SDs above the mean on the attention problems clinical syndrome scale of the child behavior checklist (CBCL; Achenbach and Rescorla 2001), or exceeding the criterion score for the parent version of the ADHD-combined subtype subscale of the child symptom inventory (CSI;

Gadow et al. 2004); and (3) teacher ratings of at least two SDs above the mean on the attention problems clinical syndrome scale of the Teacher Report Form (TRF; Achenbach and Rescorla 2001), or exceeding the criterion score for the teacher version of the ADHD-combined subtype subscale of the CSI (Gadow et al. 2004). The CSI requires parents and teachers to rate children's behavioral and emotional problems based on DSM-IV criteria using a four-point Likert scale. The CBCL, TRF, and CSI are among the most widely used behavior rating scales for assessing psychopathology in children. Their psychometric properties are well established (Rapport et al. 2008). All children in the ADHD group met criteria for ADHD-combined type, and six were comorbid for oppositional defiant disorder (ODD).

Eleven children met the following criteria and were included in the typically developing group: (1) no evidence of any clinical disorder based on parent and child K-SADS interview; (2) normal developmental history by maternal report; (3) maternal rating below 1.5 SDs on the clinical syndrome scales of the CBCL and TRF; and (4) parent and teacher ratings within the non-clinical range on all CSI subscales. Typically developing children were actively recruited through contact with neighborhood and community schools, family friends of referred children, and other community resources.

Children that presented with (a) gross neurological, sensory, or motor impairment, (b) history of a seizure disorder, (c) psychosis, or (d) full scale IQ score less than 85 were excluded from the study. None of the children were receiving medication during the study—seven of the children with ADHD had previously received trials of psychostimulant medication.

Instruments

Stop-signal Tasks The stop-signal task and administration instructions were acquired from Dr. Schachar's research group, and the experiment used task parameters described by Schachar et al. (2000). Go-stimuli were displayed for 1000 ms as uppercase letters X and O positioned in the center of a computer screen. Xs and Os appeared with equal frequency throughout the experimental blocks. Each go-stimulus was preceded by a dot (i.e., fixation point) displayed in the center of the screen for 500 ms. The fixation point served as an indicator that a go-stimulus was about to appear. A 1000 Hz auditory tone (i.e., stop-stimulus), delivered through sound-deadening headphones, was generated by the computer and presented randomly on 25% of the experimental trials. Stop-signal delays were initially set at 250 ms, and dynamically adjusted ±50 ms contingent on children's performance on the previous trial. Successfully inhibited stop-trials were followed by a 50 ms increase in stop-signal delay, and unsuccessfully inhibited stop-trials were followed by a 50 ms decrease in stop-signal delay. The algorithm was designed to approximate successful inhibition on 50% of the stop-trials. A two-button response box was utilized wherein the left and right buttons were used to respond to the letters X and O, respectively. All participants completed five consecutive experimental blocks of 32 trials (i.e., 24 go-trials, eight stop-trials).

Three additional stop-signal task conditions were presented to examine the effect of stop-signals (i.e., auditory tones) on children's primary reaction time. All task parameters were identical to the previously outlined standard stop-signal condition with exceptions noted below.

A no-tone condition was administered without the presentation of an auditory tone. This condition was included to provide a measure of children's pure reaction time to the primary stimulus, uncontaminated by the influence of intermittent stop-signals or previous exposure to meaningful signals.

An ignore-tone condition was administered to determine whether the intermittent presentation of a neutral (non-meaningful) auditory tone exerts an effect on children's reaction time to the go-stimulus, even though the tone has never been paired with stopping. This condition always preceded the standard stop-signal condition. Children were presented with an auditory tone, but instructed to ignore it.

An ignore-tone-2 condition was administered to determine whether the intermittent presentation of a non-meaningful auditory tone exerts an effect on children's reaction time to the go-stimulus, when the tone has been previously paired with stopping. This condition was always administered after the standard stop-signal condition, and was identical to the standard task except that participants were told to ignore the stop-signal.

Procedures Each participant's performance on the stop-signal task was assessed once per week on Saturdays over a 4-week period at the Children's Learning Clinic-IV. The stop-signal task was administered as part of a larger battery of laboratory-based tests that required the child's presence for approximately 2.5 hours per session. Breaks were scheduled between tasks to minimize the effects of fatigue. Each child was administered a total of four stop-signal task conditions: no-tone, ignore-tone, standard-tone, and ignore-tone-2, across the four testing sessions (one each session, 1 week apart). The no-tone and ignore-tone conditions were counterbalanced so that each was administered before the other with equal frequency. The no-tone and ignore-tone conditions always preceded the standard-tone condition to allow for the measurement of reaction time in the absence of experience with a meaningful auditory tone. The ignore-tone-2 condition was always administered during the fourth session, following the standard-tone condition.

Children were seated approximately 0.66 meters from the computer monitor. Prior to the administration of each experimental condition, they were required to complete two practice blocks, each consisting of 32 trials. Children were provided the following instructions during the practice phase of the standard-tone condition: *You are going to divide your time into two parts, practice time and test time. This is your control box. This is the X button, and this is the O button. Your job is to watch the computer screen. At first you will see a dot. It is important to look at the dot because when it disappears, you will see the letter X or O. If the letter is X, press the left button on your gamepad. If the letter is O, press the right button on the gamepad. As soon as you see the letter, push the matching button (i.e., X or O) as quickly as you can. Always use your thumbs to push the X and O buttons. Go as fast as you can without making mistakes. Every once and a while you will hear a beep through your headphones. When you hear the beep, I want you to stop yourself from pushing the button*. Following these instructions, children were asked to explain the task. In the event that a child did not respond correctly, the instructions were read again until the child was able to orally communicate that they understood the directions. Prior to administration of each experimental phase, children were told that they were going to begin the test portion of the session and that it would be longer in duration relative to the practice session. They were also reminded to push the buttons as fast as possible and to always use their thumbs.

Instructions for the no-tone, ignore-tone, and ignore-tone-2 conditions were identical to those of the standard-tone condition except for the explanation of the stop-signal tone. Specifically, the tone was not mentioned in the no-tone condition, and prior to the ignore-tone and ignore-tone-2 conditions, children were administered the following additional instructions: *Sometimes you will hear a beep. When you hear the beep I want you to ignore it*.

Results

Preliminary analysis of power, potential outliers, and demographic variables were followed by a three-tier approach to examine the central experimental questions. SSRT and stop-signal delay for the standard task were examined initially to determine whether children with ADHD exhibit behavioral inhibition deficits relative to TD children. MRT differences in children with ADHD relative to typically developing children across the no-tone, ignore-tone, standard-tone, and standard-tone-2 conditions were examined subsequently to determine (1) whether children with ADHD exhibit slower choice reaction times to the go-stimulus (MRT) relative to TD children, and (2) whether intermittent auditory tones—meaningful (associated with stopping) and non-meaningful (not associated with stopping)—exert an overall or differential (between-group) effect on children's MRT. A final set of analyses examined potential between-group differences in reaction time variability across the four experimental conditions to examine whether intermittent auditory tones—meaningful and non-meaningful—exert an overall or differential (between-group) effect on children's MRT variability.

Data Screening

Power analysis GPower software version 3.0.5 (Faul et al. 2007) was used a priori to determine needed sample size for omnibus tests as recommended by Cohen (1992). A Hedges' g effect size of 0.63 was chosen based on the average magnitude of SSRT differences between children with ADHD and TD children reported in a recent meta-analytic review (Alderson et al. 2007). Power was set to 0.80 (Cohen 1992). For an SSRT Hedges' g effect size of 0.63, $\alpha=0.05$, power $(1-\beta)=0.80$, and two groups, 22 total subjects are needed for a repeated measures analysis of variance (ANOVA) (conditions: standard-tone, ignore-tone-2) to detect differences and reliably reject H_0. A repeated measures power analysis was computed based on the expectation that SSRT metrics would be available for both the standard-tone and ignore-tone-2 conditions (i.e., that children would inhibit responding to some ignore-tones following exposure to the standard-tone task). A nearly identical procedure was used to estimate the needed sample size for MRT and MRT variability (SDRT), based on the average magnitude of MRT and SDRT differences between children with ADHD and TD children (Alderson et al. 2007). The correlation between task conditions was set moderately high ($r=0.75$) because previous studies have assumed that MRT is unaffected by intermittent stop trials and would thus approximate MRT during an equivalent, simple choice reaction time task. For an MRT Hedges' g effect size of 0.45, $\alpha=0.05$, power $(1-\beta)=0.80$, two groups, and four repetitions (i.e., no-tone, ignore-tone, standard-tone, and ignore-tone-2 conditions), 14 total subjects are needed for a repeated measures ANOVA to detect differences and reliably reject H_0. For an SDRT Hedges' g effect size of 0.73, $\alpha=0.05$, power $(1-\beta)=0.80$, two groups, and four repetitions (i.e., no-tone, ignore-tone, standard-tone, and ignore-tone-2 conditions), six total subjects are needed for a repeated measures ANOVA to detect differences and reliably reject H_0. A power analysis for SSD was not calculated due to non-significant effect sizes reported in previous meta-analytic reviews (Alderson et al. 2007; Lijffijt et al. 2005).

Outliers Each of the dependent variables were screened for univariate outliers, defined as scores of greater than three standard deviations above or below the group mean. This procedure resulted in no outliers.

Preliminary analyses Demographic data are shown in Table 1. Sample ethnicity was mixed with 16 Caucasians (69%), five Hispanics (22%), and two African Americans (9%). All parent and teacher behavior ratings scale scores were significantly higher for the ADHD group relative to the TD group (see Table 1). Children with ADHD and typically developing children did not differ on age, $F(1,21)=2.34$, $p=0.14$, or measured intelligence based on The Wechsler Intelligence Scale for Children (WISC-III or WISC-IV) full scale scores (Wechsler 1991, 2003), $F(1,22)=2.43$, $p=0.13$. A univariate ANOVA revealed that families of children with ADHD had lower average Hollingshead (1985) socioeconomic status (SES) scores than TD children, $F(1,21)=6.31$, $p=0.02$. IQ, age, and SES were not significant covariates of any of the analyses reported below. We therefore report simple model results with no covariates. Means, SDs, and between-group contrasts are presented in Table 2.

Tier I: Behavioral Inhibition

SSRT and SSD were not calculated for the ignore-tone-2 condition because the frequency of response inhibition during "stop-trials" in the ignore-tone-2 condition was insufficient to provide a reliable estimate. With a sample size of 23, effect sizes of 1.098 or higher would be reliably detected by a between-group ANOVA. Sixty-four percent of reviewed studies reported an effect size (ES) confidence interval that included or exceeded this value (Alderson et al. 2007). SSRT and stop-signal delay during the standard-tone condition were analyzed using one-way ANOVAs with group (ADHD, TD) as the fixed factor. There was a significant main effect for group on SSRT, $F(1, 22)=15.64$, $p=0.001$. The main effect for SSD was not statistically significant, $F(1, 22)=2.47$, $p=0.131$ (see Table 2).

Table 1 Sample and Demographic Variables

Variable	ADHD		TD children		F
	$\overline{X}$	SD	$\overline{X}$	SD	
Age	8.75	1.29	9.36	1.43	1.17
FSIQ	100.92	15.22	110.18	13.11	2.43
SES	43.46	12.25	52.50	7.57	6.13*
CBCL					
Attention problems	78.50	10.53	55.64	7.06	36.68***
TRF					
Attention problems	66.25	8.83	48.73	16.92	9.94**
CSI-parent					
ADHD, combined	77.75	9.92	48.73	11.11	9.29**
CSI-teacher					
ADHD, combined	63.08	11.05	49.50	9.57	43.83***

CBCL Child behavior checklist, *CSI* Child Symptom Inventory—symptom severity *T*-scores, *FSIQ* full scale intelligence, *SES* socio-economic status, *TD* typically developing children, *TRF* Teacher Report Form

*$p\leq0.05$, ** $p\leq0.01$, *** $p\leq0.001$

Table 2 Stop-signal Task Dependent Variables

	ADHD ($n=12$)		TD ($n=11$)		Between-group	
	$\overline{X}$	SD	$\overline{X}$	SD	F	p
MRT[a]					9.37	0.006
MRT (NT)	680.01	172.68	517.74	66.22		
MRT (IT)	705.72	223.01	510.78	67.50		
MRT (ST)	836.07	286.80	669.70	149.35		
MRT (IT-2)	807.01	265.53	488.29	77.26		
SDRT	322.39	118.11	169.97	59.15	21.80	<0.001
SSD	169.60	333.53	346.56	173.86	2.47	0.131
SSRT	666.48	259.19	323.14	130.08	15.64	0.001

ADHD Attention-deficit/hyperactivity disorder, *IT* ignore-tone condition; *IT-2* ignore-tone-2 condition, *MRT* mean reaction time, *NT* no-tone condition, *SDRT* mean reaction time variability (standard deviation of reaction time), *SSD* stop-signal delay, *SSRT* stop-signal reaction time, *ST* standard-tone condition, *TD* typically developing children

[a] MRT in the standard-tone condition was significantly slower than MRTs in the no-tone, ignore-tone, and ignore-tone-2 conditions ($p<0.05$), which did not differ from each other.

Tier II: Mean Reaction Time

A group (ADHD, TD) by condition (no-tone, ignore-tone, standard-tone, ignore-tone-2) mixed-model ANOVA on mean reaction time revealed significant main effects for group, $F(1, 21)=9.37$, $p=0.006$, and MRT condition, $F(3, 63)=11.14$, $p<0.001$. Least Significant Difference post hoc analyses indicate that MRTs were faster in the no-tone, ignore-tone, and ignore-tone-2 conditions relative to the standard-tone condition (all $p<0.01$), and none of the variant conditions were significantly different from each other (all $p>0.05$). These findings, however, must be interpreted in the context of the significant overall group by MRT condition interaction, $F(3, 63)=3.03$, $p=0.04$. Three planned comparison mixed-model ANOVAs were conducted to explicate the interaction effect between group and condition, while only including the standard task and one variant condition (i.e., no-tone, ignore-tone, or ignore-tone-2) in each analysis. The comparison analyses provide additional information about differential group changes in reaction time for each variant condition relative to the standard-tone condition. The main effects for group and condition were significant in all analyses (all $p<0.05$); however, the group by condition interaction was only significant for the ignore-tone-2/standard-tone analysis, F

(1, 21)=6.70, p=0.02. Figure 2a displays the ADHD and TD groups' MRT across conditions. Figures 2b–d show the effect of ignore-tone, no-tone, and ignore-tone-2 condition effects on MRT, relative to the standard-tone condition.

Tier III: Mean Reaction Time Variability

A group (ADHD, TD) by condition (no-tone, ignore-tone, standard-tone, ignore-tone-2) mixed-model ANOVA on mean reaction time variability revealed a significant main effect for group, $F(1, 21)=21.80$, $p<0.001$, but not MRT condition $F(3, 63)=0.605$, $p=0.61$. The group by MRT condition interaction was not significant, $F(3, 63)=2.32$, $p=0.08$. Collectively, this finding indicates that the MRT of children with ADHD was significantly more variable relative to typically developing controls regardless of condition.

Discussion

When go- and stop-processes are activated in close temporal sequence (i.e., go-signal activation followed by stop-signal activation), response inhibition depends on whether the stop process can overtake the go-process according to Logan et al.'s (1984) race model of behavioral inhibition. A slow reaction time to a stop-stimulus (SSRT) decreases the probability that the stop-process will overtake the go-process. Past investigations of the stop-signal task traditionally examine SSRT as the primary measure of behavioral inhibition, and suggest that the occurrence of slower SSRTs in children with ADHD relative to typically developing children provides evidence of motor inhibition deficits. Two recent meta-analytic reviews (Alderson et al. 2007; Lijffijt et al. 2005) reported significantly slower SSRTs in children with ADHD relative to typically developing controls, but attributed the finding to an underlying deficit of attention or cognitive processing, rather than deficient inhibitory control based on non-significant between-group differences in estimated stop-signal delay metrics. The current study directly examined stop-signal delay differences between ADHD-combined type and typically developing controls and found that differences in MRT, rather than stop-signal delay, accounted for SSRT variance. Collectively, these findings

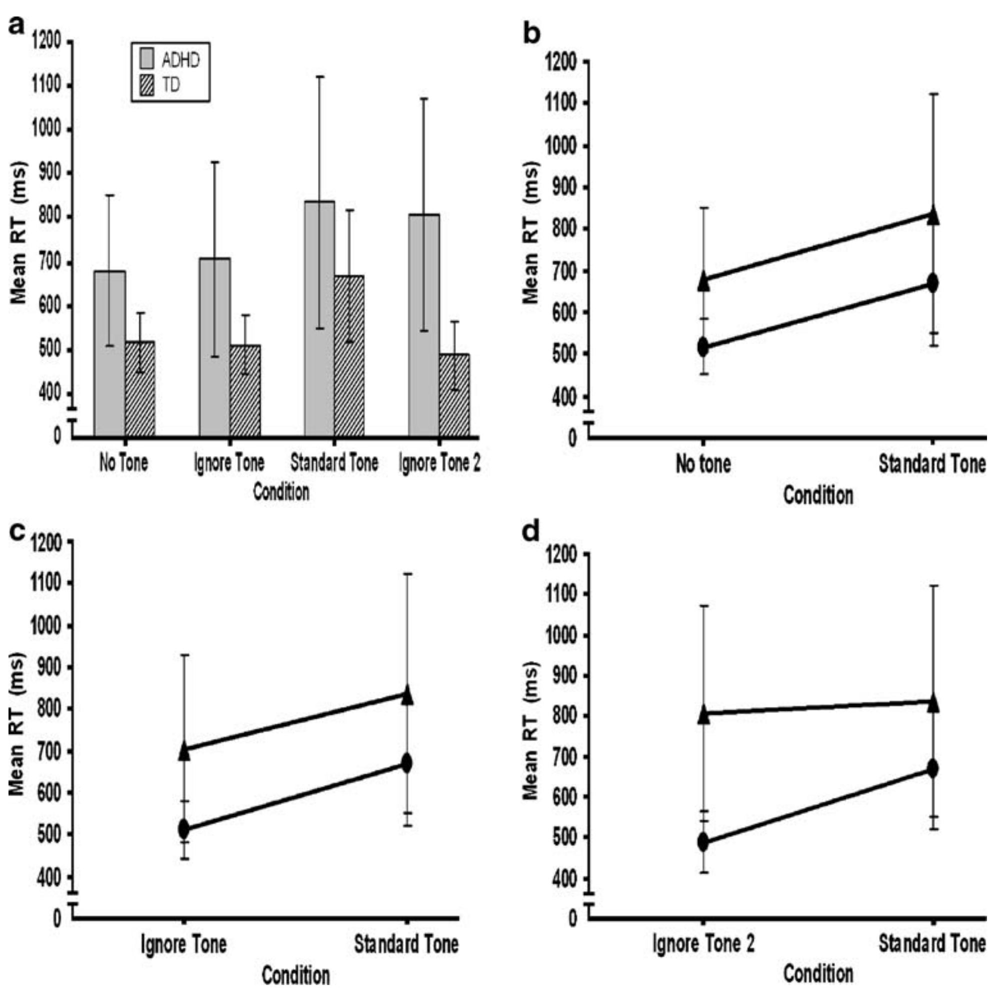

Fig. 2 **a** MRTs of children with ADHD and typically developing children across stop-signal tone conditions. Remaining figures show MRTs of children with ADHD (*triangles*) and typically developing children (*circles*) as a function of **b** no-tone, **c** ignore-tone, and **d** ignore-tone-2 condition contrasts to the standard-tone condition. *Vertical bars* represent standard error

corroborate recent meta-analytic findings and do not support models of ADHD that predict behavioral inhibition deficits in children with ADHD.

The overall finding of slower and more variable responding to the go-stimulus across experimental conditions by children with ADHD is consistent with recent meta-analytic findings (Alderson et al. 2007; Lijffijt et al. 2005) and performance outcomes commonly observed on a wide array of standardized tests, neurocognitive tasks, and experimental paradigms (for a review, see Barkley 2006; Rapport et al. 2001). Factors such as slower cognitive processing (Kalff et al. 2005), slower motor speed (van Meel et al. 2005), deficient cognitive energetic resources (Sergeant et al. 1999), and deficient attentional processes (Lijffijt et al. 2005) have been offered as potential explanations for these differences. The possibility that slower motor speed alone accounts for the between-group differences in MRT can be partially addressed by comparing the between-group differences under the no-tone and standard-tone experimental conditions. The mean reaction time of children with ADHD was consistently slower relative to TD children, even under the no-tone condition, and the magnitude of the between-group differences under the no-tone and standard-tone conditions was nearly identical. This finding indicates that children with ADHD are slower processing and responding to even simple, dual-choice stimuli (i.e., respond to 'X' or 'O') relative to controls regardless of whether or not a tone is present.

Children's slower MRTs during the standard-tone task relative to the variant conditions is also consistent with the negative priming literature. Implicit memory of the stop-stimulus is expected to create a response conflict (i.e., to respond or not respond) on subsequent trials, and slow reaction time to the go-stimulus due to additional cognitive processing demands (Logan 1988; Neill and Valdes 1992; Neill et al. 1992). The finding that exposure to intermittent auditory tones resulted in significantly slower MRTs only when the tones were meaningful (i.e., stop-signals) is consistent with a negative priming effect. MRTs estimated in traditional stop-signal paradigms (i.e., mean reaction time of go-responses obtained from go-trials adjacent to intermittent stop-trials) may therefore be downstream from more complex cognitive processing and executive functions that include working memory, self regulation, and internalization of speech. Additional research comparing single- and dual-choice stimuli is needed to disentangle the extent to which simple motor speed and cognitive processing demand deficits contribute to the consistently slowed response time in children with ADHD.

Accurate MRT estimations are critical to assessing behavioral inhibition differences between ADHD and typically developing children, given the role of MRT in the calculation of SSRT (i.e., SSRT=MRT−SSD). Previous stop-signal studies estimated children's MRT by averaging reaction times to the go-stimulus on go-trials presented before and after stop-trials—a methodological approach which assumes MRT is unaffected by potential carryover effects resulting from intermittent exposure to stop-signals. Children's performance on the standard-tone stop-signal task was contrasted with three variant experimental conditions (no-tone, ignore-tone, and ignore-tone-2) to address this possibility. Simply hearing a tone not previously associated with responding, coupled with the instruction to ignore it, had no discernable effect on TD children or those with ADHD given the non-significant differences in each group's MRT between the no-tone and initial ignore-tone conditions. This finding suggests that the mere presence of a non-meaningful auditory signal in the context of a stop-signal paradigm does not exert a singleton distractor effect by momentarily capturing children's attention and slowing their reaction time (Dalton and Lavie 2004).

The question of whether a meaningful auditory tone exerts an overall or differential effect on children's mean reaction time was examined by comparing children's performance under the standard-tone to the variant tone conditions. Both groups of children showed slower MRT under the standard-tone condition relative to the initial two variant conditions, which suggests that the current practice of estimating base differences in MRT by extracting go-trials from meaningful stop-trials is likely to inflate the SSRT estimate for all children (SSRT=MRT−SSD).

A serendipitous finding emerged when comparing between-group MRT differences in the ignore-tone-2 and standard-tone conditions. Typically developing children's MRTs reverted to levels comparable to their MRTs observed under the no-tone and initial ignore-tone conditions. This finding indicates that (a) they were able to successfully ignore or suppress the previous association between hearing a tone and stopping, or (b) the association decayed sufficiently over the 7-day interval between assessment sessions. In contrast, the MRTs of children with ADHD remained slowed and comparable to their mean reaction time under the standard-tone condition. At least two explanations may account for this finding. Children with ADHD may fail to invoke effective metacognitive processes necessary to suppress previously learned associations (e.g., by reminding themselves that the tone no longer has meaning or to simply block out the tone and focus on the X and O stimuli). Some support for this explanation is provided by past studies documenting deficient metacognition in children with ADHD relative to controls (for a review, see Barkley 1997). An alternative explanation is that mechanisms responsible for allowing stimulus-response associations to fade and eventually decay are deficient in children with ADHD over this time interval—a finding consistent with past reports of excessive perseveration in ADHD (Houghton et al. 1999). Collectively, these findings provide fertile ground for investigating whether suppression and/or decay deficiencies contribute to the well-documented executive functioning deficits associated with ADHD (Biederman et al. 2004; Klorman et al. 1999; Willcutt et al. 2005).

The unique contribution of the current study was its systematic examination of MRT under meaningful and non-meaningful tone conditions, and direct examination of the stop-signal delay metric. Several caveats merit consideration despite these methodological refinements. Generalization of findings from highly controlled laboratory-based experimental investigations to the larger population of children with ADHD is always limited to some extent, and studies with relatively small sample sizes are vulnerable to Type II errors. The results of this study, however, were highly consistent with recent meta-analytic reviews that found significant MRT and SSRT differences, but not significant stop-signal delay differences. It is unlikely that the non-significant stop-signal delay finding is related to low power, given the large SSRT effect size (ES=1.67) between children with ADHD and typically developing children. That is, because SSRT is derived from MRT and stop-signal delay, and between-group differences in SSRT were exceptionally large, increased power would only have allowed for the detection of very small magnitude stop-signal delay differences relative to very large SSRT differences. We were also unable to test a true covariate model (i.e., analysis of covariance) due to the relatively small study sample size. Independent experimental replication with a larger sample and samples that include females, older children, and other ADHD subtypes is recommended.

Several of the children with ADHD met diagnostic criteria for ODD; however, the degree of comorbidity may be viewed as typical of the ADHD population based on recent epidemiological findings (i.e., 59%; Wilens et al. 2002), and a recent meta-analytic review reported that conduct disorder/ODD comorbidity did not significantly moderate ADHD children's mean reaction time, mean reaction time variability, or stop-signal reaction time (Lijffijt et al. 2005).

Finally, although the no-tone and ignore-tone conditions were counterbalanced, the standard-tone and ignore-tone-2 conditions were always presented as the third and fourth experimental condition, respectively, to assure that children were not exposed to stop-signals prior to administration of the no-tone and ignore-tone 2 conditions. Consequently, the possibility of an order effect cannot be entirely eliminated, but is unlikely given the pattern of results relative to the pattern normally expected for order effects involving reaction time data (i.e., order effects are typically associated with faster reaction times in later trials of experimental tasks). Overall, the MRTs in the last condition were not faster than the previous conditions, and were slower for the ADHD group.

The stop-signal paradigm is currently the most commonly used and experimentally sophisticated measure of behavioral inhibition in child psychopathology research. Results of the current study suggest that slower SSRTs in children with ADHD are not due to deficient behavioral inhibition, but rather to (a) slower processing of and responding to visually presented stimuli, and (b) slower processing of a second stimulus (tone). This finding highlights the need for methodological refinement in controlling for initial differences in children's MRTs, and challenges prevailing views concerning the central role of motor behavioral inhibition deficits in ADHD. The inclusion of stop-signal delay metrics in future studies is warranted to ensure that between-group differences in SSRT reflect behavioral inhibition deficits rather than differences in children's MRT. Additionally, the use of separate go-trials in future stop-signal investigations is recommended to provide uncontaminated estimates of MRT. These findings have potentially important clinical implications, and may help explain the inefficacy of cognitive therapies that target symptoms related to impulsivity/behavioral inhibition deficits (Rapport et al. 2001).

References

Achenbach, T. M., & Rescorla, L. A. (2001). *Manual for the ASEBA school-age forms & profiles*. Burlington, VT: University of Vermont Research Center for Children, Youth, & Families.

Alderson, R. M., Rapport, M. D., & Kofler, M. J. (2007). Attention-deficit/hyperactivity disorder and behavioral inhibition: a meta-analytic review of the stop-signal paradigm. *Journal of Abnormal Child Psychology*, *35*, 745–758.

Aman, C. J., Roberts, R. J., & Pennington, B. F. (1998). A neuropsychological examination of the underlying deficit in attention deficit hyperactivity disorder: frontal lobe versus right parietal lobe theories. *Developmental Psychology*, *34*, 956–969.

Barkley, R. A. (1997). *ADHD and the nature of self-control*. New York: Guilford.

Barkley, R. A. (2006). Attention-deficit hyperactivity disorder: a handbook for diagnosis and treatment (3rd ed.). New York: Guilford.

Barkley, R. A., Fischer, M., Smallish, L., & Fletcher, K. (2006). Young adult outcome of hyperactive children: adaptive functioning in major life activities. *Journal of the American Academy of Child and Adolescent Psychiatry*, *45*, 192–202.

Biederman, J., Monuteaux, M. C., Doyle, A. E., Seidman, L. J., Wilens, T. E., Ferrero, F., et al. (2004). Impact of executive function deficits and attention-deficit/hyperactivity disorder (ADHD) on academic outcomes in children. *Journal of Consulting and Clinical Psychology*, *72*, 757–766.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*, 155–159.

Dalton, P., & Lavie, N. (2004). Auditory attentional capture: effects of singleton distractor sounds. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 180–193.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175–191.

Fox, E. (1995). Negative priming from ignored distractors in visual selection: a review. *Psychonomic Bulletin and Review*, *2*, 145–173.

Gadow, K. D., Sprafkin, J., & Salisbury, H. (2004). Further validity evidence for the teacher version of the child symptom inventory-4. *School Psychology Quarterly*, *19*, 50–71.

Hollingshead, A. B. (1985). Four-factor index of social status. New Haven, CT: Author.

Houghton, S., Douglas, G., West, J., Whiting, K., Wall, M., Langsford, S., et al. (1999). Differential patterns of executive function in children with attention-deficit hyperactivity disorder according to gender and subtype. *Journal of Child Neurology*, *14*, 801–805.

Iaboni, F., Douglas, V. I., & Baker, A. G. (1995). Effects of reward and response costs on inhibition in ADHD children. *Journal of Abnormal Psychology*, *104*, 232–240.

Kalff, A. C., De Sonneville, L. M. J., Hurks, P. P. M., Hendriksen, J. G. M., Kroes, M., Feron, F. J. M., et al. (2005). Speed, speed variability, and accuracy of information processing in 5 to 6-year-old children at risk of ADHD. *Journal of the International Neuropsychological Society*, *11*, 173–183.

Kaufman, J., Birmaher, B., Brent, D., Rao, U., Flynn, C., Moreci, P., et al. (1997). Schedule for affective disorders and schizophrenia for school-age children-present and lifetime version (K-SADS-PL): Initial reliability and validity data. *Journal of the American Academy of Child & Adolescent Psychiatry*, *36*, 980–988.

Klorman, R., Hazel-Fernandez, L. A., Shaywitz, S. E., Fletcher, J. M., Marchione, K. E., Holahan, et al. (1999). Executive functioning deficits in attention-deficit/ hyperactivity disorder are independent of oppositional defiant or reading disorder. *Journal of the American Academy of Child and Adolescent Psychiatry*, *38*, 1148–1155.

Lijffijt, M., Kenemans, L., Verbaten, M. N., & van Engeland, H. (2005). A meta-analytic review of stopping performance in attention-deficit/hyperactivity disorder: deficient inhibitory motor control? *Journal of Abnormal Psychology*, *114*, 216–222.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*, 492–527.

Logan, G. D., Cowan, W. B., & Davis, K. A. (1984). On the ability to inhibit simple and choice reaction time responses: a model and a method. *Journal of Experimental Psychology*, *10*, 276–291.

Logan, G. D., Schachar, R. J., & Tannock, R. (1997). Impulsivity and inhibitory control. *Psychological Science*, *8*, 60–64.

Mannuzza, S., Klein, R. G., Bessler, A., Malloy, P., & LaPadula, M. (1993). Adult outcome of hyperactive boys: educational achievement, occupational rank, and psychiatric status. *Archives of General Psychiatry*, *50*, 565–576.

Mason, D. J., Humphreys, G. W., & Kent, L. (2004). Visual search, singleton capture, and the control of attentional set in ADHD. *Cognitive Neuropsychology*, *21*, 661–687.

Mason, D. J., Humphreys, G. W., & Kent, L. (2005). Insights into the control of attentional set in ADHD using the attentional blink paradigm. *Journal of Child Psychology and Psychiatry*, *46*, 1345–1353.

May, C. P., Kane, M. J., & Hasher, L. (1995). Determinants of negative priming. *Psychological Bulletin*, *118*, 35–54.

Neill, W. T., & Valdes, L. A. (1992). Persistence of negative priming: Steady-state or decay. *Journal of Experimental Psychology: Learning Memory and Cognition*, *18*, 565–576.

Neill, W. T., Valdes, L. A., Terry, K. M., & Gorfein, D. S. (1992). Persistence of negative priming. 2. Evidence for episodic trace retrieval. *Journal of Experimental Psychology: Learning Memory and Cognition*, *18*, 993–1000.

Overtoom, C. C. E., Kenemans, J. L., Verbaten, M. N., Kemner, C., van der Molen, M. W., van Engeland, H., et al. (2002). Inhibition in children with attention-deficit/hyperactivity disorder: A psychophysiological study of the stop task. *Biological Psychiatry*, *51*, 668–676.

Rapport, M. D., Chung, K., Shore, G., & Isaacs, P. (2001). A conceptual model of child psychopathology: implications for understanding attention deficit hyperactivity disorder and treatment efficacy. *Journal of Clinical Child Psychology*, *30*, 48–58.

Rapport, M. D., Kofler, M. J., Alderson, R. M., & Raiker, J. (2008). Attention-deficit/hyperactivity disorder. In M. Hersen, & D. Reitman (Eds.) Handbook of psychological assessment, case conceptualization and treatment, volume 2: children and adolescents (pp. 349–404). NJ: Wiley.

Rieger, M., Gauggel, S., & Burmeister, K. (2003). Inhibition of ongoing responses following frontal, nonfrontal, and basal ganglia lesions. *Neuropsychology*, *17*, 272–282.

Rommelse, N. N. J., Altink, M. E., de Sonneville, L. M. J., Buschgens, C. J. M., Buitelaar, J., Oosterlaan, J., et al. (2007). Are motor inhibition and cognitive flexibility dead ends in ADHD? *Journal of Abnormal Child Psychology*, *35*, 957–967.

Schachar, R. J., Chen, S., Logan, G. D., Ornstein, T. J., Crosbie, J., Ickowicz, A., et al. (2004). Evidence for an error monitoring deficit in attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology*, *32*, 285–293.

Schachar, R., Mota, V., Logan, G., Tannock, R., & Klim, P. (2000). Confirmation of an inhibitory control deficit in attention-deficit/hyperactivity disorder. *Journal of Abnormal Child Psychology*, *28*, 227–235.

Schachar, R., Tannock, R., Marriott, M., & Logan, G. (1995). Deficient inhibitory control in attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology*, *23*, 411–437.

Sergeant, J. A., Oosterlaan, J., & van der Meere, J. (1999). Information processing and energetic factors in attention-deficit/hyperactivity disorder. In H. C. Quay, & A. E. Hogan (Eds.) *Handbook of Disruptive Behavior Disorders* (pp. 75–104). Dordrecht, Netherlands: Kluwer Academic Publishers.

Sonuga-Barke, E. J. S. (2002). Psychological heterogeneity in AD/HD—A dual pathway model of behaviour and cognition. *Behavioural Brain Research*, *130*, 29–36.

Szatmari, P. (1992). The epidemiology of attention-deficit hyperactivity disorders. In G. Weiss (Ed.) Child and adolescent psychiatry clinics of North America: attention deficit disorder (pp. 361–372). Philadelphia: Saunders.

van Meel, C. S., Oosterlaan, J., & Heslenfeld, D. J. (2005). Motivational effects on motor timing in attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry*, *44*, 451–460.

Walcott, C. M., & Landau, S. (2004). The relation between disinhibition and emotion regulation in boys with attention deficit hyperactivity disorder. *Journal of Clinical Child and Adolescent Psychology*, *33*, 772–782.

Wechsler, D. (1991). *Wechsler Intelligence Scale for Children* (3rd ed.). San Antonio, TX: Psychological Corporation.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children* (4th ed.). San Antonio, TX: Psychological Corporation.

Wilens, T. E., Biederman, J., Brown, S., Tanguay, S., Monuteaux, M. C., Blake, C., et al. (2002). Psychiatric comorbidity and functioning in clinically referred preschool children and school-age youths with ADHD. *Journal of the American Academy of Child & Adolescent Psychiatry*, *41*, 262–268.

Willcutt, E. G., Doyle, A. E., Nigg, J. T., Faraone, S. V., & Pennington, B. F. (2005). Validity of the executive function theory of attention-deficit/hyperactivity disorder: a meta-analytic review. *Biological Psychiatry*, *57*, 1336–1346.