J Abnorm Child Psychol (2007) 35:229–238
DOI 10.1007/s10802-006-9075-2

ORIGINAL PAPER

Restraint and Cancellation: Multiple Inhibition Deficits in Attention Deficit Hyperactivity Disorder

Russell Schachar · Gordon D. Logan · Philippe Robaey · Shirley Chen · Abel Ickowicz · Cathy Barr

Published online: 10 March 2007

Abstract We used variations of the stop signal task to study two components of motor response inhibition—the ability to withhold a strong response tendency (restraint) and the ability to cancel an ongoing action (cancellation)—in children with a diagnosis of attention deficit hyperactivity disorder (ADHD) and in non-ADHD controls of similar age (ages 7–14 years). The goal was to determine if restraint and cancellation were related and if both were deficient in ADHD. The stop signal task involved a choice reaction time task (go task) which required a rapid response. The demand for inhibitory control was invoked through the presentation of a stop signal on a subset of go trials which required that the ongoing response be suspended. The stop signal was presented either concurrently with the go signal (restraint version) or after a variable delay (cancellation version). In Study 1, we compared ADHD and control children on the cancellation version of the stop task; in Study 2, we compared ADHD and controls on the restraint version. In Study 3, a subset of ADHD and control participants completed both tasks so that we could examine convergence of these dimensions of inhibition. Compared to control participants, ADHD participants showed a deficit both in the ability to cancel and to restrain a speeded motor response. Performance on the restraint version was significantly correlated with performance on the cancellation version in controls, but not in ADHD participants. We conclude that ADHD is associated with deficits in both restraint and cancellation subcomponents of inhibition.

R. Schachar (✉) · S. Chen · A. Ickowicz · C. Barr
Psychiatry Research Unit, Department of Psychiatry, Brain and Behavior Programme, Research Institute, The Hospital for Sick Children, University of Toronto,
555 University Avenue, Toronto, M5G 1X8, Canada
e-mail: russell.schachar@sickkids.ca

G. D. Logan
Department of Psychology, Vanderbilt University, Nashville, Tennessee, USA

P. Robaey
Departments of Psychiatry, Ste Justine Hospital, University of Montreal, and Children's Hospital of Eastern Ontario, Ottawa, Canada

C. Barr
Department of Psychiatry, Cellular and Molecular Division, The Toronto Western Research Institute, University Health Network, Toronto, ON, Canada

Keywords ADHD · Inhibition · Stop task

Inhibition is a critical aspect of executive control, the higher-order cognitive mechanisms that regulate subsidiary processes involved in the performance of specific cognitive and motor operations (Band & van Boxtel, 1999; Logan, 1994). Executive control is necessary for flexible interaction with changing environments (Logan, 1985; Mesulam, 1986; Miller & Cohen, 2001). Although the term "inhibition" is applied to a range of psychological and physiological phenomena such as suppression of distraction in selective attention or in working memory (Nigg, 2000), it most commonly refers to situations in which current actions or thoughts must be controlled or stopped. Inhibition in the executive system is akin to brakes in a car. It permits voluntary control over responses in the presence of changing intentions, external cues or performance errors. Inhibitory control plays an important role in normal and abnormal development (e.g., Harnishfeger & Pope, 1996; Nigg, 2000; Radvansky, Zacks, & Hasher, 2005; Williams, Ponesse, Schachar, Logan, & Tannock, 1999) and deficits in inhibition are implicated in the effects of brain pathology (Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003a; Aron & Poldrack, 2005a; Schachar, Levin, Max, Purvis, & Chen, 2004). Deficient inhibition is considered to be one of the central cognitive abnormalities in attention deficit hyperactivity disorder (ADHD) and to be related to its underlying neuropathology (Barkley, 2001; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005).

Just as in driving, however, inhibition in the motor system can act in several ways. Depending on the circumstances, successful inhibition of motor responses could involve *restraining* a strong response tendency pending a signal to stop or it could involve *canceling* an ongoing response when a signal to stop occurs. One could improve the chances of stopping given a red light by altering one's driving e.g., driving more slowly near intersections or by installing disc brakes. The net effect in both cases is better stopping, but the mechanisms appear to differ.

These forms of inhibition are often treated as equivalent on the assumption that they reflect a common process and a common neural substrate. However, there is reason to believe that they may involve different neural networks. Physiological, neuroimaging and lesion-deficit studies strongly implicate the right inferior frontal gyrus and basal ganglia in cancellation of an ongoing response (Aron et al., 2003; Aron & Poldrack, 2005; Aron, Robbins, & Poldrack, 2004; Chambers et al., 2006; Chevrier, Noseworthy, & Schachar, 2004). By contrast, restraint appears to involve more dorsolateral and medial prefrontal areas (Deiber, Honda, Ibanez, Sadato, & Hallett, 1999; Matthews, Simmons, Arce, & Paulus, 2005; Rubia, Smith, Brammer, Toone, & Taylor, 2005; Rubia et al., 2001; Small et al., 2003). Further study is required, but the current preliminary findings suggest that restraint and cancellation inhibition may involve some common and some distinct neural pathways. The relationship between restraint and cancellation subcomponents of inhibition has not been studied in the same individuals. The first goal of the current study, therefore, was to assess the convergence of these forms of inhibition.

We used variations of the stop signal task to measure restraint and cancellation (Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984). The stop signal task involves two concurrent tasks, a *go task* and a *stop task*. Participants perform the go task, which is a choice reaction time task, as quickly and as accurately as they can. The demand for inhibitory control is invoked through the random presentation of a stop signal on a subset of go trials. These stop signals instruct the participant that the ongoing response must be stopped. In the *cancellation* condition of the stop task, the stop signal always follows the go signal by some delay. Consequently, the go response is underway before presentation of the stop signal, and stopping involves interruption of the ongoing response. The delay between the onset of the go and the onset of the stop signals is automatically adjusted using a tracking algorithm. The dynamic adjustment of delay ensures that each participant inhibits approximately 50% of their go responses when a stop signal is presented. In the *restraint* condition, the stop and go signals are always presented concurrently; that is, the mean delay is always zero. The signal to stop serves to interrupt the response preparation phase of response execution. In comparison to the cancellation version, the restraint task is amenable to a withholding strategy. In both conditions, the internally generated inhibition process is evident indirectly in whether or not a response is executed or stopped. However, the race model of inhibition affords a method by which the latency of the inhibition process, known as stop signal reaction time (SSRT) can be estimated (Logan, 1994; Logan, Schachar, & Tannock, 1997).

The second objective of this study was to compare ADHD and control participants on measures of restraint and cancellation. A deficit in response inhibition may be central to ADHD and may underlie many of the behavioral, social and academic manifestations of the disorder (Barkley, 1997; Nigg, 2003; Pennington & Ozonoff, 1996; Schachar, Tannock, Marriott, & Logan, 1995b). Yet it is not known whether restraint and cancellation inhibition are both deficient in ADHD. Deficient inhibition in ADHD is inferred from poor performance on a range of tasks that involve various aspects of inhibition especially the ability to inhibit a speeded motor response. The stop signal task is the most frequently studied inhibitory task and generates the strongest evidence of deficit in ADHD (Willcutt et al., 2005). There have been 27 studies comparing ADHD and controls using the stop task, of which 82% have shown a significant difference with an overall effect size of .61. The go no-go task, an inhibition task that involves restraint rather than cancellation, is less sensitive to ADHD once group differences in age are taken into account (McLean et al., 2004; Rhodes, Coghill, & Matthews, 2005; Westerberg, Hirvikoski, Forssberg, & Klingberg, 2004). This could mean that ADHD is associated with deficient cancellation, but not deficient restraint inhibition. However, this conclusion is uncertain because the typical go no-go task confounds selection and inhibition processes. In the typical go no-go task, participants monitor a series of stimuli (e.g., letters) and respond as quickly and accurately as possible to all but one (e.g., do not respond when an X appears). Therefore, the typical go no-go task presents a visual go signal and a visual stop signal and requires the same discrimination process for go and no-go trials. Participants must discriminate between the two go-task stimuli in order to know whether to respond or not. Inhibition that involves selection may be subject to and may invoke refractory effects (Pashler, 1994), which could influence the probability of stopping a response and the latency of the stopping process (Horstmann, 2003). In addition, the stop process and the go process share a common discrimination stage in typical go no-go tasks and are not independent. Independence of the go and the stop process is an important assumption of the race model of response inhibition (Logan & Cowan, 1984; Logan et al., 1984). In the typical stop signal task, by contrast, the go and stop signals are independent because they are presented in different modalities: stop tasks typically use visual go signal and auditory stop signal. And, when the stop signal is presented, the subject has to stop whether the go stimulus is an X or an O—no selection is involved. By using variations of the stop task, the current experiment allowed us to rule out the modality of the stop signal and a common discrimination stage as factors contributing to differences in SSRT between the stop and go no-go tasks (Liefooghe, Vandierendonck, Muyllaert, Verbruggen, & Vanneste, 2005; Schuch & Koch, 2003; Verbruggen, Liefooghe, Notebaert, & Vandierendonck, 2005; Verbruggen, Liefooghe, Szmalec, & Vandierendonck, 2005; Verbruggen, Liefooghe, & Vandierendonck, 2005). Therefore, the current experiment bridges the conceptual gap between go no-go and stop signal inhibition by using two tasks that involve similar stimuli and demands for response selection, but which vary in demand for restraint and cancellation. Consequently, we are able to determine whether ADHD is associated with deficits in one or both inhibition subcomponents.

We conducted three studies in which we compared children with a diagnosis of attention deficit hyperactivity disorder (ADHD) and non-ADHD controls (ages 7–14 years). In Study 1, ADHD and control participants were compared on the restraint version of the stop task, and in Study 2, ADHD and control groups were compared on the cancellation version. Study 3 involved a comparison of a subset of ADHD and control participants who completed both tasks so that we could examine convergence of these dimensions of inhibition. We predicted that it would be easier to stop a response in the restraint than in the cancellation task, that ADHD and control groups would differ in both tasks and that performance in ADHD in the cancellation and restraint tasks would be correlated such that participants with the worst performance in one task would also have the worst performance in the other.

Methods

Participants

A total of 86 children with an established diagnosis of ADHD participated in the studies (Study 1 = 58; Study 2 = 78; Study 3 = 50). Fifty ADHD participants participated in all three studies. Participants were drawn from a clinic for children with attention and behavior problems in an urban general pediatric hospital. The sample was similar in socioeconomic status and ethnicity to that of the community from which it was drawn. We included ADHD participants who had been treated or who were currently being treated with a stimulant medication although participants had to be unmedicated for a minimum of 24 hr before assessment and testing. Participants who were receiving other medications (e.g., SSRI, risperidone) at the time of enrolment (fewer than 5% of the total) were excluded because these medications cannot easily be withdrawn for cognitive testing. The protocol was approved by the Research Ethics Board and written informed consent was obtained.

A total of 87 Controls (Study 1 = 52; Study 2 = 50; Study 3 = 15) were recruited from among visitors to the local provincial science centre (Ontario Science Centre, Toronto). Only 15 controls could perform both restraint and cancellation studies because of time restriction. Similarly, it was not possible to conduct intelligence testing or extensive assessments in controls. Visitors to the Science Centre would likely to be of higher social class and have higher formally tested intelligence than the children in the ADHD group. However, we are confident that any possible differences in intelligence and social class is unlikely to jeopardize the results of the current experiments: Neither intelligence nor social class were correlated with inhibition in ADHD or control samples in previous research (Leblanc et al., 2005; Schachar, Mota, Logan, Tannock, & Klim, 2000; Schachar, Tannock, Marriott, & Logan, 1995a). Moreover, intelligence and social class were not correlated with performance in ADHD participants in the current studies as will be shown below.

Diagnostic instruments

The *Parent Interview for Child Symptoms (PICS-IV*; (Ickowicz et al., 2006) and the *Teacher Telephone Interview* (TTI-IV; Tannock, Hum, Masellis, Humphries, & Schachar, 2002) were our primary assessment measures of ADHD and other axis I diagnoses. In previous studies, these semi-structured interviews show excellent inter-rater reliable [ADHD ($\kappa = .73$), CD ($\kappa = .73$), and ODD ($\kappa = .80$)] and high convergence with commonly used behavior rating scales. Four Master-level social workers conducted the parent interviews and four master-level psychologists conducted the teacher interviews. Each interviewer was trained to reliability of 90% or better and participated in regular supervision and surveillance through taped interviews.

Intellectual ability (Wechsler Intelligence Scale for Children 3rd Edition; Wechsler, 1991), reading (Woodcock Reading Mastery Test-R Word Identification and Word Attack sub-tests, Woodcock, 1987; Wide Range Achievement Test reading subtest, Wilkinson, 1993), language (Clinical Evaluation of Language Fundamentals 3rd; Semel, Wiig, & Secord, 1995), pure tone hearing, and vision were assessed by a psychologist or speech pathologist. Reading disability diagnosis was based on a score of at least 1.5 Standard Deviations (*SD*) below the mean for age on any one of the 3 reading measures (WRAT-III, Woodcock Reading Mastery Test-R Word Identification or Word Attack subtests) or 1 *SD* below the mean for age on any 2 measures

(Shaywitz, Fletcher, & Shaywitz, 1995). The parent, teacher and child assessments were conducted without knowledge of the results of other portions of the assessment.

Inclusion and exclusion criteria for ADHD

Participants were 7 to 16 years of age and attending a primary or high school in order that teachers could be informants. Participants met DSM-IV criteria for ADHD in one setting and were at least moderately impaired in a second setting. More specifically, participants had at least 6 of 9 inattentive symptoms, 6 of 9 hyperactive-impulsive symptoms, or both according to either parent or teacher interview. In order to meet DSM-IV criterion C for "some impairment from the symptoms is present in two or more setting (e.g., at school [or work] and at home," participants had to exhibit a minimum of 4 symptoms and at least moderate impairment in the second setting (i.e., the setting in which they did not meet full criteria). We have used these criteria for establishing pervasiveness in our previous research. ADHD subtype classification was based on parent and teacher interview results. For example, if a child had six or more inattention symptoms on the parent interview and six or more hyperactive-impulsive symptoms on the teacher interview, they were categorized as combined subtype.

Participants were excluded if they had an IQ below 80 on both verbal and performance scales of the WISC-III, a history of pervasive developmental disorder, psychosis, obsessive compulsive disorder, Tourette syndrome, serious medical problem, substance abuse, or loss of consciousness, concurrent treatment with medication other than a stimulant or treatment with a stimulant within 24 hr of testing, language impairment (CELF overall total language score <85), or a history of abuse. About 10% of cases were excluded.

The parents of control participants at the science centre completed a brief questionnaire about their children's history and behavior. Controls were excluded if they had a history of developmental delay (were slow to walk or talk, ever in special class at school, ever assessed, diagnosed or treated for a mental health problem, or medical illness).

Motor response inhibition tasks

The stop task involved two concurrent tasks—a go and a stop task. The go task involved the presentation of one of two possible letters (an X or an O) on each trial. Participants were required to make a response to the go task stimuli as quickly and as accurately as possible by pressing one key of a hand held response box for an X and the other for an O (go stimuli and go task). The stop task involved an auditory signal which was presented, at random, on 25% of trials. The stop signal instructed participants to withhold their response on that particular trial. In the restraint version, the stop signal was always presented concurrently with the go stimulus (a zero delay between go signal and stop signal). In the cancellation version, the auditory signal was always presented *after* the go stimulus and the delay between the go and the stop signal was adjusted dynamically depending on the participant's performance. Initially, delay in the cancellation task was set at 250 ms. If the participant were able to stop his or her response on a particular stop-signal trial, the delay increased by 50 ms in order to make it more difficult for them to stop on the next stop-signal trial. If the participant were unable to stop on that particular trial, the stop signal was shortened by 50 ms to make it easier for them to cancel their response the next time a stop signal was presented. This dynamic tracking procedure ensured that participants were able to stop their responses on 50% of stop trials on average. The tracking algorithm determined, as well, that slowing go responses as a strategy for increasing probability of inhibition would result in longer stop-signal delay and similar (.5) probability of inhibition thereby ensure that responses would have to be cancelled rather than restrained.

Both tasks involved 128 trials of which 32 involved stop signals and 96 did not. The go task stimulus was presented for 1000 ms immediately following a fixation point of 500 ms. The stop tone was a 1000 Hz tone emitted by the computer and presented by headphones at a comfortable listening level. Dependent measures were accuracy of go task performance, mean go task reaction time (ms), standard deviation of correct go task reaction time (ms), and probability of successful inhibition.

Performance in the stop signal task can be modeled as a race between two independent processes—the response execution process initiated by the presentation of the go signal and finishing with the motor response and the stop process initiated by the presentation of the stop signal (Logan et al., 1984; Logan, 1995; Logan & Cowan, 1984). If the stop process finishes before the go process, the response is stopped. If the go process finishes before the stop process, the response is executed just as if no stop signal were presented. The outcome of the race and the probability of stopping a particular response depend on the speed of go responses and the speed of the internally generated stopping process the latency of which is known as stop signal reaction time (SSRT). The outcome of the race also depends on the delay between the onset of the go and the onset of the stop processes. Delay is under experimental control. Go reaction time is evident in the latency of trials that do not involve a stop signal. SSRT can be estimated through an integration procedure in which go reaction times in which no stop signal is presented are rank ordered and the go reaction time that corresponds to the probability of inhibition is determined. For example, if a participant inhibits 60% of their go responses, one finds the 60th slowest go reaction time. All slower go responses would have been stopped; all faster ones would have been executed. SSRT is estimated by subtracting mean delay from the integrated go reaction time. SSRT can be estimated in the restraint version of the task using the integration procedure just as it is estimated in the cancellation version. Consequently, SSRT provides a common metric for assessing inhibitory control in both tasks. Longer SSRT reflects slower or less efficient inhibition.

Design and statistical analyses

The order of task administration was counterbalanced and testing was conducted on the same day, but with another computer task intervening. The intervening task was a measure of working memory. The ADHD and control groups were compared on age and sex using analysis of variance or chi square as appropriate. The association of performance in the two tasks was assessed with Pearson correlation. Regression analysis was used to control the test of association of performance for age, sex, intelligence and comorbid psychopathology. Differences between ADHD and control groups in restraint and cancellation task performance were compared using analysis of variance while taking age and sex into account. Repeated measures ANOVA was used to compare restraint and cancellation task performance in the 50 ADHD and 15 controls that performed both tasks.

Results

Table 1 shows the characteristics of ADHD (86) and control (87) participants in the three studies. ADHD participants were younger than controls (9.5 versus 10.2 yrs) and more likely than controls to be males (79% versus 42%). Comorbidity was common among ADHD participants in both experiments. Among ADHD participants, 32% met criteria for inattentive ADHD subtype, 13% for hyperactive-impulsive subtype, and 55% for combined subtype. No difference in sex, age, IQ, or rate of comorbidity was noted between the ADHD participants who performed both tasks and those who performed only one. However, controls who performed both tasks were significantly older than those who performed one task only ($p = .001$). By definition, controls did not have psychopathology.

ADHD children and controls differed significantly in their performance on the restraint task. Compared with controls, ADHD had significantly lower mean go task accuracy (95% vs. 97.3%), longer mean go task reaction time (729 ms vs. 611.4 ms), greater mean go task reaction time variability (283.3 ms vs. 171 ms), lower mean probability of inhibition (79.2% vs. 84.4%) and longer SSRT (578.6 ms versus 457.1 ms) after controlling for age and sex (Study 1, Table 2).

ADHD children and controls also differed significantly in their performance on the cancellation task. Compared with controls, ADHD had lower mean go task accuracy (93.9% vs. 96.2%), shorter mean delay (293 ms versus 356 ms) and longer SSRT (326 ms versus 255.4 ms) after controlling for age and sex (Study 2, Table 3).

In Study 3, the performance of ADHD children and controls on both tasks were compared (Table 4). As expected from the design of each task, it was easier to stop a response in the restraint (mean probability of inhibition of 81%) than in the cancellation (56%) task [$F(1, 63) = 210.8, p < .001$] condition. Estimated latency of the inhibition process (SSRT) was longer in the restraint (557.4 ms) than in the cancellation (377.3 ms) condition [$F(1, 63) = 37.6$, $p < .001$]. Mean go task accuracy, speed and variability did not differ significantly between the two tasks. Compared with controls, the ADHD group had significantly lower mean go task accuracy, and slower and more variable mean go task reaction time across both tasks. They also had lower mean probability of inhibition in the restraint task, but not in the cancellation task as evident in the interaction between task and group for percent inhibition [$F(1, 63) = 6.2$, $p < .05$]. Most important was the finding of significantly longer SSRT in ADHD

Table 1 Participant characteristics (means, standard deviations or % affected)

Characteristic	ADHD	Controls†	χ^2/F
Number	86	87	
Age (years)	9.5 (1.2)	10.2 (2.7)	4.55*
Sex (% male)	79	42	30.2***
IQ (full scale)	104.5 (12.1)	na	
Comorbidity (%)			
ODD	32.2	na	
CD	25.2	na	
Anxiety	24.3	na	
Reading disability	20	na	
WRAT reading	92.2 (3.9)	na	
WIAT word attach	96.2 (13.4)	na	
WIAT word identification	93.8 (12.4)	na	

Note. †by definition, controls did not have any diagnoses; na, measures were not available for controls; $^{*}p < .05$, $^{**}p < .01$.

Table 2 Restraint task performance for ADHD and control participants (mean, standard deviation)

Variable	ADHD ($n = 58$)	Controls ($n = 52$)	F value†
Go task accuracy	95 (5.2)	97.3 (3.4)	7.25**
Go task reaction time (RT)	729 (165.3)	611.4 (141.1	15.92***
Go task RT variability	283.3 (141.1)	171 (86)	24.70***
% inhibition	79.2 (12.2)	84.4 (12.2)	4.95*
SSRT‡	578.6 (168.3)	457.1 (99.2)	20.66***
Mean delay	0	0	na

Note. ‡SSRT, stop signal reaction time, estimated through integration; $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$; na, not applicable.

Table 3 Cancellation task performance for ADHD and control participants (mean, standard deviation)

Variable	ADHD ($n = 78$)	Controls ($n = 50$)	F value
Go task accuracy (%)	93.9 (5.1)	96.2(5.1)	5.93*
Go task reaction time (RT)	619.9 (109.2)	611.5 (149.5)	.13
Go task RT variability	209.7 (82.1)	182.8 (76.4)	3.45
% Inhibition	50.7 (7.5)	52.6 (5.7)	2.20
SSRT‡	326.0 (163.1)	255.4 (109.0)	7.27**
Mean delay	293.8 (168.6)	356.1 (145.4)	4.62*

Note. ‡SSRT, stop signal reaction time; $^*p < .05$, $^{**}p < .01$.

than in controls across both restraint and cancellation tasks [$F(1, 63) = 16.3, p < .001$].

SSRT in the two tasks was significantly correlated in the control group ($r^2 = .59$, $p < .05$), but not in the ADHD group ($r^2 = .01$)—a difference in correlations that was significant ($p < .05$). Percent inhibition in the restraint and percent inhibition in the cancellation task were not significantly correlated in the ADHD ($r^2 = .2$) or in the control ($r^2 = .06$) groups. Percent inhibition in the restraint and SSRT in the cancellation task were not significantly correlated in the ADHD ($r^2 = -.04$) or in the control ($r^2 = -.29$) group, and SSRT in the restraint task and percent inhibition in the cancellation task were not significantly correlated in the ADHD ($r^2 = .03$) or in control ($r^2 = -.22$) group. Controlling age and sex did not substantially alter the magnitude of these correlations for either ADHD or control groups and controlling for intelligence in the ADHD group did not alter these associations (data not shown).

As a check on the effect of possible confounding effects, we examined the association of inhibition with parental education, child age and child sex in the ADHD group. Maternal education and SSRT were not significantly correlated in the restraint ($r = .09$) or in the cancellation tasks ($r = -.01$). Similarly, paternal education and SSRT were not significant correlated for the restraint ($r = .14$) or cancellation tasks ($r = -.05$). Regression analysis showed that age ($\beta = -24.58$; $p < .01$), but not intelligence or sex, was correlated with SSRT in the cancellation task. Age, intelligence and sex were not correlated with percent inhibition and SSRT in the restraint task. We found no association between continuous scores of ODD, CD, anxiety symptoms and reading ability (WRAT reading) and inhibitory control on either task. We observed no differences among the ADHD subtypes in either restraint or cancellation inhibition (data available from authors).

Discussion

The goals of the current study were to evaluate the convergence of two subcomponents of inhibitory control—restraint and cancellation—and to determine whether ADHD is marked by a deficit in one or both of these executive control processes. Groups of ADHD and control participants were compared on each measure and performance across groups and tasks was compared.

We designed the restraint and cancellation versions of the stop task to entail the same stimuli: Only the task demands differed. The restraint version involved a stop signal that always occurred concurrently with the onset of the go stimulus. Previous research indicated that this condition would invoked withholding of a planned response (Lappin & Eriksen, 1966; Logan, 1981; Ollman, 1973). By contrast, the cancellation version involved a stop signal which always followed the go signal by some delay. Consequently, participants will have initiated their responses at the time of the presentation of the stop signal and would have to cancel or withdraw the response during the course of its execution. The cancellation task included a tracking algorithm which minimized or prevented the use of a delaying strategy: If participants imposed a delay following presentation of the go stimulus in order to ‘check’ to see if a stop signal were going to be presented, the tracking algorithm would increase the stop signal delay to ensure that each participant would inhibit about 50% of their responses. The results indicate that the tracking algorithm was successful in achieving the probability of inhibition of approximately .5 across groups. Another innovation in the

Table 4 Performance of ADHD ($N = 50$) and control ($N = 15$) participants who performed both restraint and cancellation tasks (Study 3) (mean, standard deviation)

Variable	Restraint task		Cancellation task		Task	Group	Task × Group
	ADHD	Control	ADHD	Control			
Go task accuracy	94.8 (5.5)	98.5 (1.7)	96.2 (3.9)	98.9 (2)		**	
Go task reaction time (RT)	737.2 (175.8)	609.9 (123.7)	738.9 (119.3)	645.1 (145.3)		**	
Go task reaction time variability (*SD*)	291.7 (148.4)	154.8 (67.9)	262.4 (120.3)	150.8 (62.6)		***	
% Inhibition	78.8 (12.9)	89.8 (8.0)	55.6 (8.6)	56.9 (5.4)	***	***	*
SSRT‡	586.6 (177.7)	460.2 (96.1)	409.1 (157.2)	271.3 (74.1)	***	***	
Mean delay	0	0	329.8 (114.7)	373.8 (145.5)	na	na	na

Note. ‡SSRT, stop signal reaction time estimated through integration; $^*p < .05$, $^{**}p < .01$, $^{***}p < .001$; na = not applicable.

design was the application of the integration method which allowed estimation of the latency of the internally generated inhibition process (SSRT) in both restraint and cancellation tasks (Band, Van Der Molen, & Logan, 2003).

If these tasks assess a common latent inhibition construct, indices of inhibitory control in the two tasks should be strongly correlated. Indeed, there was a significant correlation of inhibition as measured in the restraint and cancellation tasks in the control group. By contrast, in the ADHD group, the correlation between inhibition in the cancellation and restraint tasks was low suggesting that these aspects of inhibition share little in the way of a common inhibitory process.

The observed association of restraint and cancellation inhibition among normally developing children suggests that some common cognitive resources or neural pathways are involved in these two processes. This association supports the argument that there is a unifying mechanism underlying the executive functions of the frontal lobes (e.g., Kane et al., 2004; Kimberg & Farah, 1993) and contradicts those who have reported dissociations of various executive functions among normal adults (Baddeley, Cocchini, Sala, Logie, & Spinnler, 1999; Lowe & Rabbitt, 1998; Miyake et al., 2000; Rabbitt & Lowe, 2000; Robbins et al., 1998; Stuss, Shallice, Alexander, & Picton, 1995).

The observed dissociation of restraint and cancellation inhibition in ADHD confirms previous reports of dissociations in performance among executive function tasks in children with a diagnosis of ADHD (Schachar, Tannock, & Logan, 1993; Solanto et al., 2001), disruptive behavior disorders (Avila, Cuenca, Felix, Parcet, & Miranda, 2004; Kindlon, Mezzacappa, & Earls, 1995), and in children (Levin et al., 1996) and adults with brain damage (Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Duncan, Burgess, & Emslie, 1995; Avila et al., 2004). The non-significant correlation between SSRT in the restraint and cancellation tasks among ADHD individuals suggests less sharing of cognitive processes, resources or neural substrates in ADHD than in controls (Noppeney, Friston, & Price, 2004).

The integration method of calculating SSRT allowed us to apply a common metric to the restraint and cancellation tasks in order to directly compare latency of inhibition. We found that the latency of the inhibition process was significantly longer in the restraint than in the cancellation task. There are several explanations for this finding. The stop task has features of a dual task which might account for longer SSRT. Dual tasks involve the presentation of two tasks in rapid succession: Both tasks require a response. In dual tasks, response to the second task is typically delayed and the latency of the second response increases as the delay between the presentation of the first and the second stimulus decreases. If inhibition is subject to refractory effects, then one would expect longer SSRT with shorter delays as was found in the restraint task as a result of greater refractory effect arising from processes involved in response to the first stimulus (Pashler, 1994). However, multiple studies have demonstrated that stopping a movement does not appear to be subject to the same refractory effect as do responses to initiate a movement (Brebner, 1968; Logan & Cowan, 1984; Vince & Welford, 1967). It is therefore unlikely that longer SSRT in the restraint task than in the cancellation task is due to greater refractory effect.

The race model upon which SSRT is estimated posits a race between going and stopping processes (Logan et al., 1997; Logan & Cowan, 1984). Circumstances involving such a race are nicely constructed in the cancellation version of the stop task. The restraint version does not construct a simple race. All the stop trials in the restraint task had zero delay, by design. Consequently, the restraint task allowed for a delaying strategy followed by a decision about the presence of a stop signal and subsequent initiation of a go response (wait to see if the go signal also includes a stop signal and if not, initiate a response). The addition of withholding, checking and initiation processes with every stop signal could account for the longer interpolated SSRT that was observed in the restraint than in the cancellation task. Band et al. (2003) conducted computer simulations of stop task performance under a wide range of circumstances and concluded that estimates of SSRT are reliable within the range of 85–15% inhibition. Performance in the restraint task was within this range. It seems reasonable, therefore, to conclude that estimates of SSRT in the restraint version accurately reflect the longer latency of response inhibition.

In the current studies, we found that, on average, ADHD was characterized both by deficient restraint and cancellation inhibition. The ADHD group had longer SSRT in both conditions and lower probability of inhibition in the restraint task. The deficit in cancellation accords with the results of previous research and meta-analyses of stop task performance in ADHD (Willcutt et al., 2005). In addition, we found that ADHD and control groups also differed in restraint inhibition even though many previous studies have not revealed a deficit using a go no-go task (McLean et al., 2004; Rhodes et al., 2005; Westerberg et al., 2004). The major differences between the restraint task in the current study and the go no-go tasks of the studies mentioned above lies in the effect of a common discrimination stage and the role of response withholding. If ADHD individuals have greater difficulty with the discrimination involved in determining whether a response is to be withheld, they may slow down even more than they might in the current restraint task. If they slow their ongoing speed of response, they may actually increase the likelihood of stopping. The sensitivity of the go no-go task will be reduced because the task, as usually analyzed, does not take the speed of responding into account when calculating the primary index of inhibition-probability of successfully withholding responses. Some participants might restrain motor preparation in the go no-go task and thereby minimize the probability of responding given a signal to stop. We overcame this problem in the current study by indexing restraint inhibition with integrated SSRT which takes speed of responding into account in estimating the latency of the inhibition process.

We found that age but not sex affected inhibition in these tasks but that group differences remained after age was taken into account. We found no relationship of intelligence, reading ability, parental education, and ODD, CD and anxiety symptom severity and inhibitory control in ADHD participants. However, we were unable to examine these potentially confounding factors in the control group because we had insufficient time to measure these variables. To increase the generality of the current results, future studies should include larger samples of controls in which social and intellectual factors can be measured and restraint and cancellation can be measured within subject across a wider age range. In addition, we did not find that restraint or cancellation inhibition differed among ADHD subgroups.

In summary, it appears as if restraint and cancellation are related aspects of inhibition in non-ADHD, but not in ADHD individuals. Both cancellation and restraint of a response as measured in the stop task appear to be problems for ADHD individuals. This study does not address the centrality of inhibition deficit to ADHD, nor does it probe aspects of inhibition other than those involved in the control of motor responses. Based on the current results, we predict that there will be significant individual differences among other varieties of inhibition.

Acknowledgement This research was support by the Canadian Institutes of Health Research (NET-54016 to RS and PR and MOP-64277 to RS).

References

Aron, A. R., Fletcher, P. C., Bullmore, E. T., Sahakian, B. J., & Robbins, T. W. (2003). Stop-signal inhibition disrupted by damage to right inferior frontal gyrus in humans. *Nature Neuroscience*, *6,* 115–116.

Aron, A. R., & Poldrack, R. A. (2005). The cognitive neuroscience of response inhibition: Relevance for genetic research in attention-deficit/hyperactivity disorder. *Biological Psychiatry*, *57,* 1285–1292.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, *8,* 170–177.

Avila, C., Cuenca, I., Felix, V., Parcet, M. A., & Miranda, A. (2004). Measuring impulsivity in school-aged boys and examining its relationship with ADHD and ODD ratings. *Journal of Abnormal Child Psychology*, *32,* 295–304.

Baddeley, A., Cocchini, G., Della Sala, S., Logie, R. H., & Spinnler, H. (1999). Working memory and vigilance: Evidence from normal aging and Alzheimer's disease. *Brain and Cognition*, *41,* 87–108.

Band, G. P., & van Boxtel, G. J. (1999). Inhibitory motor control in stop paradigms: Review and reinterpretation of neural mechanisms. *Acta Psychologica (Amst)*, *101,* 179–211.

Band, G. P., Van Der Molen, M. W., & Logan, G. D. (2003). Horse-race model simulations of the stop-signal procedure. *Acta Psychologica (Amst)*, *112,* 105–142.

Barkley, R. A. (1997). Attention-deficit/hyperactivity disorder, self-regulation, and time: Toward a more comprehensive theory. *Journal of Developmental & Behavioral Pediatrics*, *18,* 271–279.

Barkley, R. A. (2001). The executive functions and self-regulation: An evolutionary neuropsychological perspective. *Neuropsychol Review*, *11,* 1–29.

Brebner, J. (1968). Continuing and reversing the direction of responding movements: Some exceptions to the so-called "psychological refractory period." *Journal of Experiemental Pscyhology*, *78,* 120–127.

Burgess, P. W., Alderman, N., Evans, J., Emslie, H., & Wilson, B. A. (1998). The ecological validity of tests of executive function. *Journal of the International Neuropsychological Society*, *4,* 547–558.

Chambers, C. C., Bellgrove, M. A., Stokes, M. G., Henderson, T. R., Garavan, H., Robertson, I. H., et al. (2006). Executive "brake failure" following deactivation of human frontal lobe. *Journal of Cognitive Neuroscience*, *18,* 444–455.

Chevrier, A., Noseworthy, M. D., & Schachar, R. (2004). Neural activity associated with failed inhibition: An event related fMRI study or performance monitoring. *Brain & Cognition*, *54,* 163–165.

Deiber, M. P., Honda, M., Ibanez, V., Sadato, N., & Hallett, M. (1999). Mesial motor areas in self-initiated versus externally triggered movements examined with fMRI: Effect of movement type and rate. *Journal of Neurophysiology*, *81,* 3065–3077.

Duncan, J., Burgess, P., & Emslie, H. (1995). Fluid intelligence after frontal lobe lesions. *Neuropsychologia*, *33,* 261–268.

Harnishfeger, K. K., & Pope, R. S. (1996). Intending to forget: The development of cognitive inhibition in directed forgetting. *Journal of Experimental Child Psychology*, *62,* 292–315.

Horstmann, G. (2003). The psychological refractory period of stopping. *Journal of Experimental Psychology: Human Perception & Performance*, *29,* 965–981.

Ickowicz, A., Schachar, R., Sugarman, R., Chen, S., Millette, C., & Cook, L. (2006). The parent interview for child symptoms (PICS): A situation-specific clinical research interview for attention deficit hyperactivity and related disorders. *Canadian Journal of Psychiatry*, *50,* 325–328.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133,* 189–217.

Kimberg, D. Y., & Farah, M. J. (1993). A unified account of cognitive impairments following frontal lobe damage: The role of working memory in complex, organized behavior. *Journal of Experimental Psychology: General*, *122,* 411–428.

Kindlon, D., Mezzacappa, E., & Earls, F. (1995). Psychometric properties of impulsivity measures: Temporal stability, validity and factor structure. *Journal of Child Psychology and Psychiatry*, *36,* 645–661.

Lappin, J. S., & Eriksen, C. W. (1966). Use of a delayed signal to stop a visual reaction time response. *Journal of Experimental Psychology*, *72,* 805–811.

Leblanc, N., Chen, S., Swank, P. R., Ewing-Cobbs, L., Barnes, M., Dennis, M., et al. (2005). Response inhibition after traumatic brain injury (TBI) in children: Impairment and recovery. *Developmental Neuropsychology*, *28,* 829–848.

Levin, H. S., Fletcher, J. M., Kusnerik, L., Kufera, J. A., Lilly, M. A., Duffy, F. F., et al. (1996). Semantic memory following pediatric head injury: Relationship to age, severity of injury, and MRI. *Cortex*, *32,* 461–478.

Liefooghe, B., Vandierendonck, A., Muyllaert, I., Verbruggen, F., & Vanneste, W. (2005). The phonological loop in task alternation and task repetition. *Memory*, *13,* 550–560.

Logan, G. (1981). Attention, automaticity, and the ability to stop a speeded choice response. In J. Long & A. D. Baddeley (Eds.), *Attention and performance IX*. Hillsdale, NJ: Erlbaum.

Logan, G., & Cowan, W. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, *91,* 295–327.

Logan, G., Cowan, W., & Davis, K. (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., Schachar, R., & Tannock, R. (1997). Impulsivity and inhibitory control. *Psychological Science*, *8,* 60–64.

Logan, G. D. (1985). Executive control of thought and action. *Acta Psychologica*, *60,* 193–210.

Logan, G. D. (1994). On the ability to inhibit thought and action: A users' guide to the stop signal paradigm. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory processes in attention, memory, and language* (pp. 189–239). San Diego: Academic Press.

Lowe, C., & Rabbitt, P. (1998). Test/re-test reliability of the CANTAB and ISPOCD neuropsychological batteries: Theoretical and practical issues. Cambridge Neuropsychological Test Automated Battery. International Study of Post-Operative Cognitive Dysfunction. *Neuropsychologia*, *36,* 915–923.

Matthews, S. C., Simmons, A. N., Arce, E., & Paulus, M. P. (2005). Dissociation of inhibition from error processing using a parametric inhibitory task during functional magnetic resonance imaging. *Neuroreport*, *16,* 755–760.

McLean, A., Dowson, J., Toone, B., Young, S., Bazanis, E., Robbins, T. W., et al. (2004). Characteristic neurocognitive profile associated with adult attention-deficit/hyperactivity disorder. *Psychological Medicine*, *34,* 681–692.

Mesulam, M. M. (1986). Frontal cortex and behavior. *Annals of Neurology*, *19,* 320–325.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24,* 167–202.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41,* 49–100.

Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, *126,* 220–246.

Nigg, J. T. (2003). Response inhibition and disruptive behaviors: Toward a multiprocess conception of etiological heterogeneity for ADHD combined type and conduct disorder early-onset type. *Annals of the New York Academy of Science*, *1008,* 170–182.

Noppeney, U., Friston, K. J., et al. (2004). Degenerate neuronal systems sustaining cognitive functions. *Journal of Anatomy*, *205,* 433–442.

Ollman, R. T. (1973). Simple reactions with random countermanding of the "go" signal. In S. Kornblum (Ed.), *Attention and performance* (Vol. IV, pp. 571–581). New York: Academic Press.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, *116,* 220–244.

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, *37,* 51–87.

Rabbitt, P., & Lowe, C. (2000). Patterns of cognitive ageing. *Psychological Research*, *63,* 308–316.

Radvansky, G. A., Zacks, R. T., & Hasher, L. (2005). Age and inhibition: The retrieval of situation models. *Journals of Gerontology Series B-Psychological Sciences & Social Sciences*, *60,* 276–278.

Rhodes, S. M., Coghill, D. R., & Matthews, K. (2005). Neuropsychological functioning in stimulant-naive boys with hyperkinetic disorder. *Psychological Medicine*, *35,* 1109–1120.

Robbins, T. W., James, M., Owen, A. M., Sahakian, B. J., Lawrence, A. D., McInnes, L., et al. (1998). A study of performance on tests from the CANTAB battery sensitive to frontal lobe dysfunction in a large sample of normal volunteers: Implications for theories of executive functioning and cognitive aging. Cambridge Neuropsychological Test Automated Battery. *Journal of the International Neuropsychological Society*, *4,* 474–490.

Rubia, K., Russell, T., Overmeyer, S., Brammer, M. J., Bullmore, E. T., Sharma, T., et al. (2001). Mapping motor inhibition: Conjunctive brain activations across different versions of go/no-go and stop tasks. *Neuroimage*, *13,* 250–261.

Rubia, K., Smith, A. B., Brammer, M. J., Toone, B., & Taylor, E. (2005). Abnormal brain activation during inhibition and error detection in medication-naive adolescents with ADHD. *American Journal of Psychiatry*, *162,* 1067–1075.

Schachar, R., Levin, H. S., Max, J. E., Purvis, K., & Chen, S. (2004). Attention deficit hyperactivity disorder symptoms and response inhibition after closed head injury in children: Do preinjury behavior and injury severity predict outcome? *Developmental Neuropsychology*, *25,* 179–198.

Schachar, R., Mota, V. L., Logan, G. D., 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., & Logan, G. (1993). Inhibitory control, impulsiveness, and attention deficit hyperactivity disorder. *Clinical Psychology Review*, *13,* 721–739.

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

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

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception & Performance*, *29,* 92–105.

Semel, E., Wiig, E. I., & Secord, W. A. (1995). *CELF 3 Clinical evaluation of language fundamentals* (3rd Ed.). San Antonio: The Psychological Corporation.

Shaywitz, B. A., Fletcher, J. M., & Shaywitz, S. E. (1995). Defining and classifying learning disabilities and attention-deficit/hyperactivity disorder. *Journal of Child Neurology*, *10*(Suppl. 1), S50–S57.

Small, D. M., Gitelman, D. R., Gregory, M. D., Nobre, A. C., Parrish, T. B., & Mesulam, M. M. (2003). The posterior cingulate and medial prefrontal cortex mediate the anticipatory allocation of spatial attention. *Neuroimage*, *18,* 633–641.

Stuss, D. T., Shallice, T., Alexander, M. P., & Picton, T. W. (1995). A multidisciplinary approach to anterior attentional functions. *Annals of the New York Academy of Science*, *769,* 191–211.

Tannock, R., Hum, M., Masellis, M., Humphries, T., & Schachar, R. (2002). Teacher telephone interview for children's academic performance, attention, behavior, and learning: DSM-IV Version (TTI-IV). Toronto, Canada: The Hospital for Sick Children. Unpublished document.

Verbruggen, F., Liefooghe, B., Notebaert, W., & Vandierendonck, A. (2005). Effects of stimulus-stimulus compatibility and stimulus-response compatibility on response inhibition. *Acta Psychologica*, *120,* 307–326.

Verbruggen, F., Liefooghe, B., Szmalec, A., & Vandierendonck, A. (2005). Inhibiting responses when switching: Does it matter? *Experimental Psychology*, *52,* 125–130.

Verbruggen, F., Liefooghe, B., & Vandierendonck, A. (2005). On the difference between response inhibition and negative priming: Evidence from simple and selective stopping. *Psychological Research*, *69,* 262–271.

Vince, M. A., & Welford, A. T. (1967). Time taken to change the speed of a respnse. *Nature*, *213,* 532–533.

Wechsler, D. (1991). *Wechsler intelligence scale for children* (3rd Ed.). San Antonio, TX: Harcourt Brace & Co.

Westerberg, H., Hirvikoski, T., Forssberg, H., & Klingberg, T. (2004). Visuo-spatial working memory span: A sensitive measure of cognitive deficits in children with ADHD. *Child Neuropsychology*, *10,* 155–161.

Wilkinson, G. S. (1993). *Wide Range Achievement Test—Revision 3*. Wilmington, DE: Jastak Associates.

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.

Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology*, *35,* 205–213.

Woodcock, R. W. (1987). *Woodcock reading mastery test—Revised*. Circle Pines, MN: American Guidance Service, Inc.