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Deficient post-error slowing in children with ADHD is limited to the inattentive subtype

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Abstract

Post-error slowing (i.e., slowing of a response on correct trials following an error) is thought to reflect adaptive behavior that may be impaired in Attention-Deficit/Hyperactivity Disorder (ADHD). The current study examined post-error slowing in children with ADHD and typically developing controls on two cognitive tasks. Fifty-one ADHD-Combined type, 53 ADHD-Inattentive type, and 47 controls completed a Choice Discrimination and Stop Signal Task with incentive and event rate manipulations. Linear mixed models were used to examine reaction times surrounding errors (trial-by-trial). Pre-error speeding and pre- to post-error slowing occurred on both tasks. Impaired post-error slowing was only present on the Choice Discrimination Task for the ADHD-Inattentive type. Post-error slowing is impaired in children with ADHD-Inattentive type, but not ADHD-Combined type, on a simple attention task. These findings highlight the importance of considering task demands and ADHD subtype when examining post-error slowing and also provide a novel approach to quantifying post-error slowing.

Keywords

ADHD; subtype; post-error slowing; adaptive behavior; self-regulation; reaction time

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Self-regulation is a complex process requiring awareness of contextual demands, self-monitoring of one's behavior to evaluate whether it is appropriate for a context, and adjusting behavior when necessary. Impairments in self-regulation may result in developmentally inappropriate inattentive, hyperactive and impulsive behaviors that define Attention-Deficit/Hyperactivity Disorder (ADHD) (Sergeant, 2000). Regulatory deficit models better account for the variability which characterizes individuals with ADHD. However, the nature of the self-regulatory deficit in ADHD remains unclear.

Adaptive behavior is an important component of self-regulation. Within the context of a cognitive task, post-error slowing or slowing of response speed on a trial following a commission error is thought to reflect adaptive behavior at a very basic level (Rabbitt, 1966). When an individual performs an action that is inconsistent with the demands of a situation, an awareness of this inconsistency (e.g., error) and initiation of adaptive control processes to alter behavior may contribute to slowing of a response to increase the likelihood that performance will be improved. Similarly, errors often occur when an individual does not take the time required to ensure an accurate response. Therefore, response slowing on a trial following an error is a form of adaptive behavior. Improving our

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understanding of post-error slowing at the cognitive level may elucidate the components of self-regulation and whether this process is disrupted in ADHD.

The literature examining post-error slowing in children with ADHD has produced somewhat mixed results with some studies reporting diminished post-error slowing in ADHD (e.g., Schachar et al., 2004; Wiersema, van der Meere, & Roeyers, 2005) whereas other studies found comparable post-error slowing for ADHD and control groups (e.g., Groom et al., 2009; O'Connell, Bellgrove, Dockree, & Robertson, 2004; van Meel, Heslenfeld, Oosterlaan, & Sergeant, 2007). This is surprising as deficient adaptive behavior is theoretically implicated in ADHD as a component of impaired self-regulation (Sergeant, 2000). Inconsistent results for post-error slowing in the ADHD literature may be affected by characteristics of the sample (e.g., age range, comorbid conditions, ADHD subtype), characteristics of the task (e.g., cognitive demands, event rate), or the type of error (e.g., inhibition versus discrimination errors).

Another important factor to consider is the way in which post-error slowing is quantified. The majority of studies have compared the mean reaction time (RT) for correct trials following an error versus all other trials. However, if post-error slowing is adaptive following the impulsive response that produced the error, comparing post-error RT with the pre-error RT may provide a more sensitive measure of adaptive behavior. Participants may have slowed their response on the post-error trial compared to the pre-error RT, which tends to be relatively fast. Only one study measured post-error slowing by evaluating the difference between pre-error and post-error RTs and they reported equivalent post-error slowing in ADHD and control children (O'Connell et al., 2004). Further, it may be critical to exclude pre-error RTs from the correct RT mean since these have been shown to be faster than the mean correct RT (Epstein et al., 2010). Thus, excluding pre-error RTs from the correct RT and examining the two separately may be important since not doing so may reduce the correct RT and inflate the post-error slowing difference. In addition, isolating these RT components may provide information about whether ADHD is associated with an impulsive response style (e.g., pre-error speeding), impairments in adaptive behavior (e.g., pre- to post-error slowing) or both.

The current study builds on previous work by examining post-error slowing on two cognitive tasks, a Choice Discrimination Task (CDT) and Stop Signal Task (SST), in a large sample of children with ADHD-Combined type (ADHD-C), ADHD-Inattentive type (ADHD-I), and typically developing controls. Furthermore, a novel analytic approach was applied to examine post-error slowing, isolating the contributions of pre-error, post-error, and correct RTs. We hypothesized that pre-error speeding and pre- to post-error slowing would be evident across both tasks and post-error slowing would be diminished in children with ADHD, regardless of subtype.

Method

Participants

Medication naïve children, ages 7–11 years old, including 104 children with ADHD (53 ADHD-I; 51 ADHD-C) and 47 typically developing controls, participated in the study. The sample and procedures used in this study are identical to those presented previously (Epstein, Brinkman, et al., 2011; Epstein, Langberg, et al., 2011). Children with a Full Scale IQ <80 as estimated by the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) and/or standardized achievement scores <80 on the Wechsler Individual Achievement Test, Second Edition (WIAT-II; Wechsler, 2002) Reading or Numerical Operations subtests, or if their medical history suggested organic brain injury, were excluded.

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ADHD participants—Children with ADHD were recruited through community and clinical sources, including schools and local practitioners. Children were considered to have met criteria for a symptom domain (i.e., inattention and/or hyperactivity/impulsivity) if the parent on the Diagnostic Interview Schedule for Children-Parent Report (DISC-P; Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000) and the teacher on the Vanderbilt ADHD Rating Scale (VARS; Wolraich, Feurer, Hannah, Baumgaertel, & Pinnock, 1998) reported 6 non-overlapping symptoms in a symptom domain and both parent and teacher reported at least 4 symptoms in that domain. Children who met these criteria for both inattention *and* hyperactivity/impulsivity were enrolled in the ADHD-C group (i.e., >5 symptoms in both domains), while children who met symptom criteria for inattention but *not* hyperactivity/impulsivity (i.e., >5 inattention symptoms and <6 hyperactivity/impulsivity symptoms) were enrolled in the ADHD-I group. Children in the ADHD-I and ADHD-C groups demonstrated comparable demographic profiles (Table 1).

Typically developing participants—Children in the control group were recruited through schools and community settings. Controls were matched to both ADHD groups according to gender and ethnicity. Controls were only admitted to the study if they demonstrated minimal symptoms of ADHD (≤3 in either symptom domain) and did not meet criteria for any other behavioral disorder.

Measures

Choice discrimination task (CDT)—Participants observed a continuous stream of individually presented circles and squares followed by a presentation of a fixation cross for the duration of the ISI. Participants were asked to push a specific key for circle and another key for square. Following a practice block, participants were presented with 6 blocks of 60 trials. Each block contained an equal proportion of circles and squares presented in random order. During the incentive condition, participants received 1 point for each correct response and lost 1 point for each incorrect response.

Stop-signal task (SST)—A fixation cross was presented in the center of a computer screen for 500ms followed by a 500ms presentation of an airplane facing either left or right (Logan, Cowan, & Davis, 1984). Participants were asked to press the button that corresponded to the airplane direction. An auditory "stop signal" (1000 Hz tone) was presented on 25% of trials within each block, which required participants to inhibit their response to the visual stimulus (stop trials). The delay between presentation of the target stimulus and the tone began at 250ms and varied according to performance. Successful inhibition resulted in increases of 50ms and unsuccessful inhibition resulted in decreases of 50ms. Following three practice blocks, participants completed 6 blocks of 60 trials. During incentive blocks, children earned 1 point for each correct response and lost 4 points for each incorrect response.

Task manipulations—Incentive was manipulated within task such that participants either received incentives on the first half or second half of each task. At the end of each task, the number of points earned was reported to the child and exchanged for prizes (i.e., toys, games, etc.). Three different event rates were used within each task. Stimulus presentation was held constant at 500ms with inter-stimulus intervals of 1s, 3s, or 5s between stimulus presentations. Each task was divided into six continuous "blocks" of trials, with event rate varying across blocks and randomized within task. The task, ER, and incentive condition order was counterbalanced across subjects. Excluding the practice trials, each task took 21 minutes to complete.

Procedures

All procedures were approved by the Institutional Review Board at Cincinnati Children's Hospital Medical Center. Participants and their parents completed an initial screening visit, during which parents were administered the DISC-P interview and children were administered the WASI and WIAT-II, and two assessment visits during which they completed the SST and CDT.

Statistical Analyses

For both tasks, if the percentage of omission errors exceeded 50%, data were omitted from all analyses (CDT n=4, SST n=2).[1] Only RTs on correct trials were used for these analyses and all RTs less than 100ms were excluded. Three RT variables were computed: 1) Mean correct RT: correct responses that did not precede or follow an omission or commission error; 2) Pre-error RT: correct RTs that preceded a commission error but did not follow a commission error; and 3) Post-error RT: correct RTs that followed a commission error but did not precede a commission or omission error (Figure 1). The separate response indicators include pre-error speeding (i.e., pre-error RT versus correct RT), pre- to post-error slowing (i.e., pre-error RT versus post-error RT), and post-error versus correct slowing (i.e., post-error RT versus correct RT).[2]

Linear mixed models (i.e., SAS PROC MIXED) were utilized to test for between-subjects effects (Group: ADHD-C, ADHD-I, controls) and within-subjects effects (Trial Type: pre-error, post-error, correct) for RT mean.[3] All interactions were modeled, but only effects involving diagnostic group and trial type were of interest. These models were run separately for each task with an autoregressive within-subject covariance matrix due to the time-series nature of the data and models. For analyses that generated significant effects of trial type, post-hoc Tukey-Kramer tests were conducted to identify differences among the three types of trials and Cohen's d (Cohen, 1988) is reported as a measure of effect size.

Results

Task Effects

There was a main effect of Trial Type on both the CDT, $F(2, 282)=29.53$, $p<.001$, and the SST, $F(2, 276)=75.38$, $p<.0001$. On both tasks, there was evidence of pre-error speeding and pre- to post-error slowing (all ps<.0001, ds=0.65–1.32), but post-error versus correct slowing did not occur (CDT $p>.11$, SST $p>.59$) (Figure 2).

ADHD Subtype Effects

There was an interaction of Group X Trial Type on the CDT, $F(4, 282)=5.45$, $p<.001$. The ADHD-I group exhibited pre-error speeding ($p<.05$, $d=0.62$) but no pre- to post-error slowing or post-error versus correct slowing ($p>.78$). The ADHD-C did not exhibit pre-error speeding ($p>.09$), but did show significant pre- to post-error slowing ($p<.0001$, $d=1.36$) and post-error versus correct slowing ($p<.01$, $d=0.78$). Finally, controls displayed pre-error speeding ($p<.05$, $d=0.74$) and pre- to post-error slowing ($p<.0005$, $d=0.93$), but no post-error versus correct slowing ($p>.90$) (Figure 2). There was no evidence of a Group X Trial Type interaction on the SST, $F(4, 276)=1,3$, $p>.26$.

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[1]Children whose task data was omitted did not differ from children included in the analyses on the following variables: age, sex, race, ODD, conduct disorder, anxiety disorder, mood disorder, or parent- or teacher-rated ADHD symptom scores. Children with omitted data did have lower full-scale WASI scores than children included in the analyses, $t(89) = 2.62$, p<0.05.

[2]Primary performance indicators, including accuracy and reaction time speed and variability have been presented previously (see Epstein, Langberg, et al., 2011)

[3]The task manipulations of event rate and incentive did not differentially impact the trial type effect for ADHD participants in comparison to the control group. For the sake of brevity, these results were not reported.

Discussion

The current study examined whether post-error slowing is impaired in children with ADHD and whether the cognitive demands of the task impacted post-error slowing. Significant pre-error speeding and pre- to post-error slowing was observed on both the CDT and SST, whereas post-error versus correct RTs did not differ. These findings are consistent with the hypothesis that adaptive behavior consists of a slowing of response time following a commission error to correct for response speeding leading up to the error. Impairments in post-error slowing were limited to children with ADHD-I on the CDT whereas all children exhibited significant pre- to post-error slowing on the SST.

Pre-error speeding and pre- to post-error slowing occurred on both the CDT and SST, suggesting that these processes are robust to the cognitive demands of the task and type of error (i.e., discrimination versus inhibition). However, children with ADHD-I only showed significant pre- to post-error slowing on the SST, whereas this was observed on both the CDT and SST for ADHD-C and control groups. Understanding differences in post-error slowing for the most common ADHD subtypes may elucidate whether distinct neural mechanisms contribute to differences in symptom presentation. One possible explanation is that children with ADHD-I were less aware of their error on the CDT due to primary difficulties with attention. Error awareness may have been heightened on the SST as a result of the auditory stop signal, signaling the need for post-error slowing, whereas error detection on the CDT may require greater attention. No study to date has directly compared post-error slowing in the subtypes of ADHD, but our findings suggest that this deficit may be limited to the ADHD-I subtype and may be task dependent.

The finding that children with ADHD-C exhibit equivalent post-error slowing to typically developing controls is *inconsistent* with some aspects of theoretical models of ADHD (Sergeant, 2000) implicating deficits in error processing and adaptive behavior as contributing to deficient self-regulation (see review by Shiels & Hawk, 2010), yet *consistent* with findings from several studies reporting equivalent post-error slowing between ADHD and controls (Epstein et al., 2010; Groom et al., 2009; O'Connell et al., 2004; van Meel et al., 2007). Self-regulatory models of ADHD postulate that adaptive control is one component of a system influenced by internal and external factors to produce appropriate behavior. It may be that that adaptive control is intact in children with ADHD-C, but the adjustment is insufficient to meet the demands of the task due to cognitive deficits. Alternatively, it may be that children with ADHD-C were more responsive to the incentive context than control participants such that the potential of earning a reward improved adaptive behavior during the task in general rather than specifically during the incentive blocks.

Conclusions

In summary, this study provides the first comprehensive evaluation of post-error slowing in children with the most prevalent subtypes of ADHD on two cognitive tasks using a novel approach to analyzing response speed surrounding errors. Pre- to post-error slowing was only impaired in children with ADHD-I on a simple attention task, suggesting disruption of this process may be limited to children with primary attentional difficulties. These findings highlight the importance of considering quantification of post-error slowing, ADHD subtype, and task demands when examining adaptive behavior.

Limitations and Future Directions

Recognition of the limitations of this study is important for interpreting these results. First, participants were all stimulant naïve suggesting that this may represent a milder ADHD sample. Second, this study was not designed to examine associations among adaptive behavior in different contexts, which limits our ability to extrapolate from these findings to social and academic functioning, an important question to address with future research. Finally, this study focused on behavioral measures of adaptive control, but examination of neural correlates may help elucidate the nature of post-error slowing.

Clinical Implications

There is some support for a distinction between the inattentive and combined subtypes of ADHD based on the absence of post-error slowing in the ADHD-I group during a simple attention task whereas children with ADHD-C may be capable of adapting their behavior after making an error. This may suggest that children with ADHD-I would benefit from learning strategies to either engage in efficient self-monitoring or adapt behavior to meet task demands when an error is detected. Understanding the factors that contribute to producing adaptive behavior and the situations in which it is problematic may inform treatment and preventive interventions.

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Choice Discrimination Task															
Stimulus	○	○	□	○	□	○	□	□	○	□	○	□	□	□	○
Response	Left	Right	Right	Left	Right		Right	Left	Left	Right	Left	Left	Right	Left	Left
Error Type		Com				Omi		Com				Com		Com	
RT	400	380	450	425	480	-	430	390	440	430	400	340	410	400	420
Trial Type (RT components)															
Pre-Error	X						X				X				
Post-Error			X						X						X
Correct				X						X					
Excluded		X			X	X		X				X	X	X	

Stop Signal Task															
Stimulus	Go	Stop	Go	Go	Go	Go	Go	Stop	Go	Stop	Go	Go	Go	Stop	Go
Response	Right	Left	Left	Right	Left		Right	Left	Left	Left	Right	Left	Left	Left	Right
Error Type		Com				Omi		Com				Com		Com	
RT	400	380	450	425	480	-	430	390	440	435	400	340	410	400	420
Trial Type (RT components)															
Pre-Error	X						X				X				
Post-Error			X						X						X
Correct				X						X					
Excluded		X			X	X		X				X	X	X	

Figure 1.
Categorization of pre-error, post-error and correct trial types used to compute reaction time components. Stimulus = stimulus presented on a single trial; Response = response made by a hypothetical participant; Error Type = omission (Omi) or commission (Com) error depending on participant's response; RT = reaction time; Pre-Error = correct response that preceded a commission error; Post-Error = Correct response that followed a commission error; Correct = correct response that did not precede or follow an error; Excluded = Trials not included in the RT calculation (i.e., error trials, pre-omission trials, and trials that are both pre-error and post-error trials).

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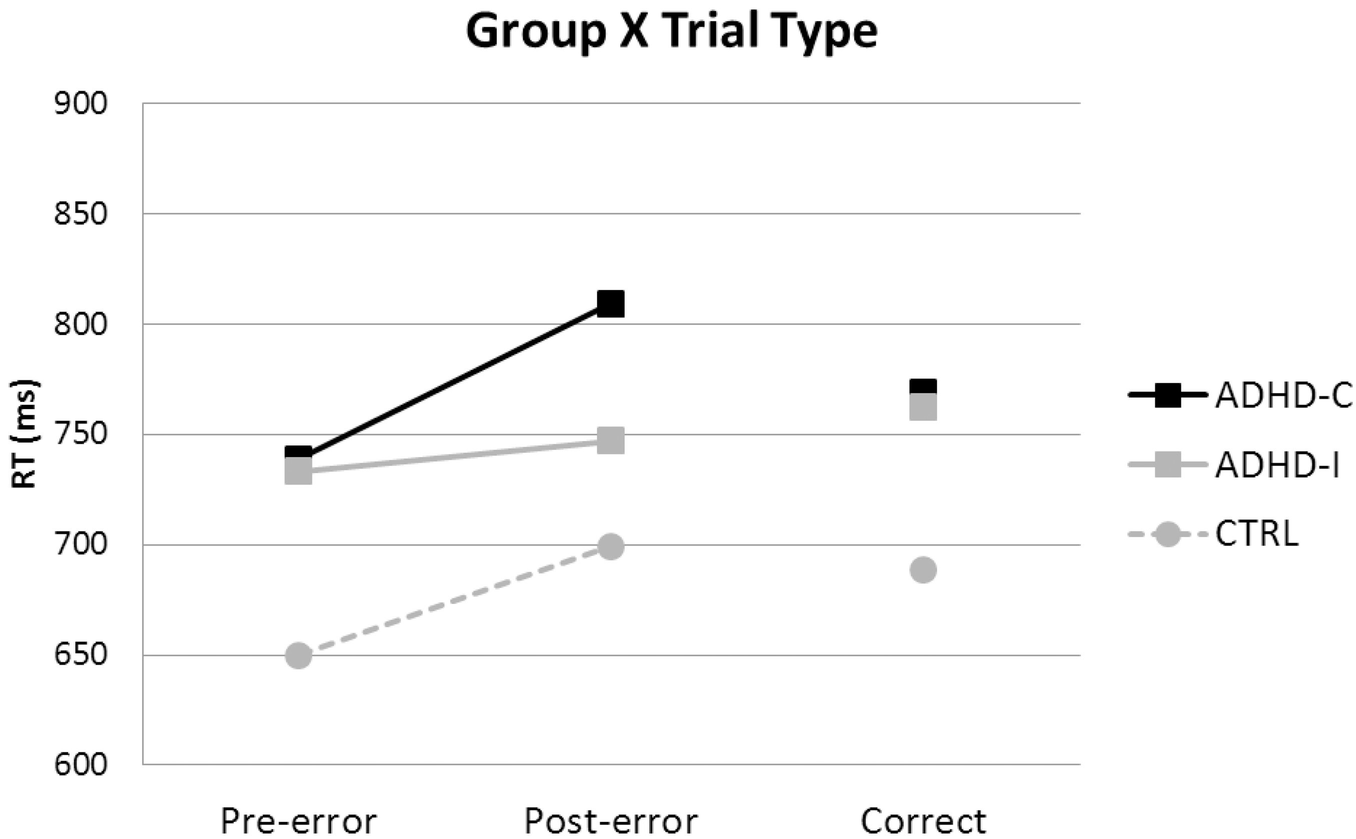

Figure 2.
Group X Trial Type on the choice discrimination task.

Table 1

Demographic and Clinical Characteristics of the ADHD-C, ADHD-I and Typically Developing Controls

	ADHD-C (n=51)	ADHD-I (n=53)	Control (n=47)	Group Comparison	Post-Hoc Comparisons
Mean (SD) age in years	7.90 (1.11)	8.35 (1.31)	8.33 (1.35)	$F(2, 150) = 1.9, p = .15$	ns
Number male	41	34	31	$F(2, 150) = 1.5, p = .22$	ns
Ethnicity (%)				$F(2, 145) = 3.4, p < .05$	ADHD-C > ADHD-I*
Caucasian	65	79	83	(comparing proportion of	
African American	31	4	15	Caucasians to minorities)	
Hispanic (non-Black)	0	4	2		
Asian	0	4	0		
American Indian	2	2	0		
IQ Score	104.88 (11.79)	105.51 (13.34)	116.11 (14.14)	$F(2, 150) = 11.2, p < .001$	ADHD-C < NC** ADHD-I < NC**
WIAT Scores					
Word Reading	100.33 (12.06)	101.41 (11.41)	109.47 (10.55)	$F(2, 149) = 13.3, p < .001$	ADHD-C < NC** ADHD-I < NC**
Numerical Operations	96.59 (12.77)	98.39 (13.67)	111.55 (18.60)	$F(2, 149) = 17.0, p < .001$	ADHD-C < NC** ADHD-I < NC**
Spelling	97.71 (12.25)	100.67 (12.73)	109.10 (12.73)	$F(2, 149) = 13.6, p < .001$	ADHD-C < NC** ADHD-I < NC**
Parent Vanderbilt Scores					
Inattention Symptom Score	20.62 (5.04)	20.79 (4.57)	2.46 (2.06)	$F(2, 148) = 306.4, p < .001$	ADHD-C > NC** ADHD-I > NC**
Hyperactivity/Impulsivity Symptom Score	19.96 (5.04)	13.17 (5.65)	1.24 (1.28)	$F(2, 145) = 203.0, p < .001$	ADHD-C > NC** ADHD-I > NC** ADHD-C > ADHD-I**
Total Symptom Score	40.73 (9.19)	33.96 (8.49)	3.77 (2.83)	$F(2, 144) = 311.6, p < .001$	ADHD-C > NC** ADHD-I > NC** ADHD-C > ADHD-I**
Teacher Vanderbilt Scores					
Inattention Symptom Score	21.16 (4.81)	19.81 (5.19)	3.17 (3.04)	$F(2, 147) = 240.2, p < .001$	ADHD-C > NC**

	ADHD-C (n=51)	ADHD-I (n=53)	Control (n=47)	Group Comparison	Post-Hoc Comparisons
					ADHD-I > NC**
Hyperactivity/Impulsivity Symptom Score	20.0 (4.31)	8.47 (5.73)	1.98 (3.2)	$F(2, 148) = 191.3$, $p < .001$	ADHD-C > NC** ADHD-I > NC** ADHD-C > ADHD-I**
Total Symptom Score	41.0 (7.18)	27.98 (8.09)	5.15 (6.01)	$F(2, 146) = 303.5$, $p < .001$	ADHD-C > NC** ADHD-I > NC** ADHD-C > ADHD-I**

Note: ADHD-C = ADHD Combined type; ADHD-I = ADHD Predominantly Inattentive type.

* $p<.05$;

** $p<.01$;

ns = not significant; all three comparisons were run for all variables. Only significant differences are presented.