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Preliminary Evidence for Reduced Post-Error Reaction Time Slowing in Hyperactive/Inattentive Preschool Children

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Abstract

Background—Attention-Deficit/Hyperactivity Disorder has been associated with deficits in self-regulatory cognitive processes, some of which are thought to lie at the heart of the disorder. Slowing of reaction times (RTs) for correct responses following errors made during decision tasks has been interpreted as an indication of intact self-regulatory functioning and has been shown to be attenuated in school-aged children with ADHD. This study attempted to examine whether ADHD symptoms are associated with an early-emerging deficit in post-error slowing.

Method—A computerized two-choice RT task was administered to an ethnically diverse sample of preschool-aged children classified as either ‘control’ (n = 120) or ‘hyperactive/inattentive’ (HI; n = 148) using parent- and teacher-rated ADHD symptoms. Analyses were conducted to determine whether HI preschoolers exhibit a deficit in this self-regulatory ability.

Results—HI children exhibited reduced post-error slowing relative to controls on the trials selected for analysis. Supplementary analyses indicated that this may have been due to a reduced proportion of trials following errors on which HI children slowed rather than to a reduction in the absolute magnitude of slowing on all trials following errors.

Conclusions—High levels of ADHD symptoms in preschoolers may be associated with a deficit in error processing as indicated by post-error slowing. The results of supplementary analyses suggest that this deficit is perhaps more a result of failures to perceive errors than of difficulties with executive control.

Keywords

ADD/ADHD; cognition; preschool children; reaction time; post-error slowing

Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is an impairing developmental disorder characterized by age-inappropriate levels of hyperactivity/impulsivity and inattention with onset prior to seven years of age. Based mainly on research characterizing multiple cognitive deficiencies in individuals with ADHD who are school-aged and older, recent theories of ADHD etiology have posited that deficits in “core” self-regulatory control

processes underlie the behavioral symptoms of the disorder. Examples of such processes include inhibitory control (Barkley, 1997b), the ability to delay gratification (Sonuga-Barke, 2003), and reinforcement-based learning mechanisms (Sagvolden, Johansen, Aase, & Russell, 2005). Inherent in the idea that these cognitive deficits are causally related to ADHD symptom onset is the requisite assumption that cognitive deficits should predate or parallel symptom development. If deficits in self-regulation are absent when symptoms begin to emerge, it is difficult to argue that they play a role in the development of the disorder. However, while the modal age of symptom onset is during the preschool years (Barkley, 1990; Barkley, Fischer, Edelbrock, & Smallish, 1990), a period characterized by the rapid development of cognitive control processes, there are relatively few studies characterizing cognitive functioning in children at the early stages of the disorder. Thus, determining whether deficits in self-regulatory functions found in older individuals with the disorder are present at symptom onset has important theoretical implications.

Cognitive control processes enable the effortful maintenance of a goal-directed, attentive state, which in turn enables an individual to maintain awareness of his or her actions, the consequences of those actions, and to alter behavioral strategies to optimize functioning within the environment. Error monitoring, detection, correction, and ensuing response strategy adjustments are important processes involved in cognitive control (Yeung, Cohen, & Botvinick, 2004; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Posner & Rothbart, 1998). Together, these processes play key roles in the ability to compensate rapidly for errors and are believed to be responsible for the fact that, after committing an error, both adults and children typically exhibit longer reaction times (RTs) for correct responses on the following trial (Rabbitt, 1969; Sergeant & van der Meere, 1988). A number of studies have investigated error processing, as manifested by post-error slowing, in children with ADHD using computerized RT tasks (van Meel, Heslenfeld, Oosterlaan, & Sergeant, 2007; O'Connell, Bellgrove, Dockree, & Robertson, 2004; Sergeant & van der Meere, 1988; Krusch et al., 1996; Schachar et al., 2004; Wiersema, van der Meere, & Roeyers, 2005). Several of these studies have shown attenuated post-error slowing in school-age children with ADHD (Sergeant & van der Meere, 1988; Krusch et al., 1996; Schachar et al., 2004; Wiersema et al., 2005). While Schachar et al. and Wiersema et al. showed that children with ADHD show a general attenuation of post-error slowing, others showed that this deficiency becomes more pronounced with increasing task difficulty (Krusch et al., 1996; Sergeant & van der Meere, 1988) suggesting that post-error slowing may bear some relation to the ability to exert adequate effort under challenging conditions. One of these studies also suggested that post-error slowing varies with symptom severity, such that children with a diagnosis of ADHD exhibited a more pronounced reduction in post-error slowing than those who exhibited subthreshold levels of symptoms and that the error processing deficit is responsive to treatment with psychostimulant medication (Krusch et al., 1996). However, while methylphenidate administration resulted in increased post-error slowing in children with ADHD, it did not result in levels equivalent to those observed in age-matched control children. Thus, while psychostimulant treatment may address part of the difficulty children with ADHD have modulating effort to meet increasing task demands, it does not normalize performance.

It should be noted that although two studies failed to find evidence for reductions in post-error slowing in children with ADHD (O'Connell et al., 2004; van Meel et al., 2007), these studies may have been limited in their ability to detect ADHD-related differences in post-error slowing. The O'Connell et al. study used a very slow paradigm so that they could collect skin conductance response data in the participants, which may have reduced task difficulty. Van Meel et al. used a response deadline to exert time pressure that may have limited the ability to detect differences in post-error slowing accurately.

There are currently no studies of error processing in preschool children with ADHD. Yet, there is evidence that error-related cognitive processes, including post-error slowing, are intact during the late toddler and early preschool period. Two studies indicated that children develop the ability to detect errors during structured, goal-directed tasks (e.g., assembling nesting cups, building figures from blocks) between 18 and 30 months of age (DeLoache, Sugarman, & Brown, 1985; Bullock & Lutkenhaus, 1988). Another study in children between 36 and 48 months of age indicated that children slow after errors by 39 months of age and that post-error slowing increases considerably by 48 months of age (Jones, Rothbart, & Posner, 2003).

Further, while post-error slowing is typically studied in older children and adults using computerized paradigms, it has only been studied in young children using a non-computerized measure (i.e., Simple Simon game; Jones et al., 2003). Although many would argue that non-computerized measures are more appropriate for preschool children because they can be made to be more engaging and less vulnerable to both fine motor difficulties and off-task behavior characteristic of young children, they are, by nature, more limited than computerized measures in their ability to yield accurate RTs and, thus, to isolate cognitive processes. In addition since the use of computerized measures is ubiquitous in studies of cognition in participants of school-age and older, the ability to use analogous measures in preschool-aged children would provide much needed continuity in the study of cognitive development.

Thus, the objective of this study was to determine whether preschool children with ADHD symptoms exhibit deficits in aspects of error processing as indicated by reduced post-error slowing on a basic computerized RT task. Based on previous findings of attenuated post-error slowing in school-aged children with ADHD (Sergeant & van der Meere, 1988; Krusch et al., 1996; Wiersema et al., 2005; Schachar et al., 2004) and on theories suggesting a role of deficient cognitive self-regulatory processes in ADHD, preschool children exhibiting high levels of ADHD symptoms were expected to exhibit reduced post-error slowing relative to age-matched control participants.

Method

Recruitment and Assessment of Participants

Children 3 through 6 years of age were recruited between 2000 and 2006 from local preschools in Queens, New York or by direct clinical referral from parents, teachers, school psychologists, and school social workers. Exclusion criteria included diagnoses of mental retardation, neurological disorder (e.g., seizure disorder), and pervasive developmental disorder. The study was approved by the Institutional Review Board of Queens College of the City University of New York. Written informed consent was obtained from the parents of all participants, who were compensated for their time and travel expenses.

Prior to an extensive laboratory assessment, all children were rated by both parents and teachers on the 18 DSM-IV symptoms of ADHD using either the ADHD-RS-IV, Home & School Versions (DuPaul, Power, Anastopoulos, & Reid, 1998; children recruited from 2003 through 2006) or an analogous DSM-IV symptom checklist (children recruited from 2000 through 2003), that, like the ADHD-RS-IV, requires informants to rate each symptom on a 4-point scale. Both scales have been found to have adequate reliability and validity in assessing the presence of ADHD symptoms in young children (Faries, Yalcin, Harder, & Heiligenstein, 2001; DuPaul, 1991; DuPaul et al., 1998). Following a comprehensive clinical evaluation, each participant was also rated by the examiners on a clinical rating scale developed in our laboratory (Behavioral Rating Inventory for Children; BRIC) that includes five-point Likert scale items relevant to five behavioral domains: Attention, Activity Level,

Impulsivity, Affect, and Sociability. Ratings indicating high levels of Attention, Activity Level, and Impulsivity (ratings of 3, 4, or 5) were considered to be indicative of the presence of problematic levels of ADHD symptoms within the laboratory. This scale has been shown to have excellent construct- and criterion-related validity as well as strong test-retest reliability (Gopin, Healey, Castelli, Marks, & Halperin, 2010).

Based on parent and teacher symptom ratings, as well as BRIC ratings, children were classified as either “hyperactive/inattentive” (HI) or control participants. Control children were rated as exhibiting few ADHD symptoms (i.e., fewer than 3 in each domain) on the ADHD-RS-IV or DSM-IV checklist by both parent and teachers. There were two requirements for inclusion in the HI group. First, children included in the HI group were required to exhibit at least 6 symptoms of either hyperactivity/impulsivity or inattention according to one rater (i.e., parent, teacher). Second, to ensure cross-situationality of symptoms, children were required to exhibit at least two symptoms of ADHD according to the other rater (i.e., parent, teacher) or a minimum rating of 3 in any of the symptom-relevant domains on the BRIC. Thus, although not formally clinically diagnosed with ADHD, children in the HI group met the symptom count and cross-situationality, as well as the age-of-onset criteria for a diagnosis of ADHD as outlined in the DSM-IV (American Psychiatric Association, 1994).

Full Scale IQ (FSIQ) was estimated using the Information subtest scaled score from the Wechsler Primary and Preschool Scale of Intelligence (WPPSI). Different versions of this subtest were administered depending on time of entry into the study; participants who entered the project prior to 2004 were administered the WPPSI-R (Wechsler, 1989), while those entering in 2004 or later were administered the WPPSI-III (Wechsler, 2002). Scores on the Information subtest correlate highly with FSIQ in both the WPPSI-R ($r = 0.71$) and WPPSI-III ($r = 0.82$ – 0.83).

Two-choice Reaction Time Task

The task consisted of three blocks of 20 trials. These trial blocks originally served as control conditions for a version of Nassauer & Halperin’s (2003) computerized Perceptual and Motor Conflict Test, which was modified for use with young children (Marks et al., 2005). For two blocks (1 & 3), the stimuli consisted of centrally-located left- and right-pointing arrows (10 of each) that appeared on the computer screen one at a time. During the second block, rectangles appeared one at a time on either the right or the left side of the screen (10 on each side). In all blocks, stimuli appeared in the same random order for all participants and remained on the screen until the child responded. The next stimulus appeared 1 sec after the previous response. For all three blocks children were instructed to make the response that was most compatible with stimulus direction (in the case of arrows) or location (in the case of rectangles), with the corresponding hand, as quickly as possible without making errors. Thus, for blocks 1 and 3, children were instructed to press the mouse button that corresponded to the direction in which the arrow pointed (e.g., to press the left mouse button with the left index finger when a left-pointing arrow appeared). For block 2, children were asked to press the mouse button corresponding to the side of the screen on which the rectangle appeared (e.g., to press the left mouse button with the left index finger when a rectangle appeared on the left side of the screen). Prior to each block, instructions were administered using a demonstration booklet followed by 10 computerized practice trials preceding the actual task. Children received verbal feedback regarding their performance during practice trials to ensure that they understood the instructions and to correct erroneous performance.

The response device was a two-button stationary mouse placed on a table at midline midway between the child and the computer screen. The mouse was large enough to accommodate

the difficulties with fine motor coordination that periodically occur in young children. The buttons on the mouse were clearly separated, with one on each side of the device, so that children could press each of the buttons with a different hand.

To maintain interest and prevent fatigue, each block was administered interspersed between other experimental conditions and cognitive tasks in a preset order that was the same for all participants. The examiner was present for the duration of the task and issued children reminders during off-task behavior and obvious attentional lapses to “keep playing.” To minimize fatigue and maximize effort allocation during task performance, the task battery was administered to children by examiners well-trained in task procedures to ensure smooth transitions between tasks/conditions.

Selection of Trials for Data Analysis

Correct responses following errors (E+1) and those following other correct responses (C+1) were the trials targeted for analysis. Similar to the methods used by Krusch et al. (1996), trials analyzed for each response type condition (i.e., C+1 and E+1) were restricted to control for extraneous variables on correct RTs (e.g., random, unintentional, or impulsive responding; lapses in attention or effort). First, correct RTs were only included if they were between 400 ms (i.e., below which children were empirically determined to perform at chance levels) and 2456 ms (i.e., the RT representing the 90th percentile of all correct responses pooled from all participants). Second, to control for chance responding, since it is unlikely that children would respond correctly by chance three consecutive times, C+1 responses were required to be third in a correct-correct-correct sequence. Finally, because errors that follow other errors may be different from errors that occur in isolation (e.g., may be reflective of longer lapses in attention or error correcting responses rather than erroneous encoding or response selection; Rabbitt & Rodgers, 1977), for E+1 trials, the error preceding the target correct response could not follow another error (errors had to occur in “isolation”). Thus, E+1 responses were the third response in a correct-error-correct sequence. Each participant was required to make a minimum of two eligible C+1 and E+1 responses to be included in the analyses.

Participants

An ethnically diverse sample of 268 children (120 controls, 148 HI) between the ages of 3.0 and 5.4 years [mean (SD) age = 4.4 (0.5) years] met criteria for one of the two groups, with 10.1% being African American; 13.8% Asian; 45.1% Caucasian; 16.0% Hispanic; and 11.6% of mixed ethnicity; an additional 3.4% were of unknown racial/ethnic identity. Not unexpectedly, there was a significantly higher proportion of males in the HI group than in the control group. As shown in Table 1, the mean WPPSI Information subtest scaled score was significantly higher among control children versus HI children.

After all exclusions, 75 controls and 108 HI children were included in the final analyses. Two controls and eight children in the HI group were unable to perform the task. Twenty-six controls and 12 HI children made fewer than two errors. Of those who committed two or more errors, one control and six HI children made fewer than two eligible C+1 responses (i.e., three correct responses in sequence within the acceptable RT limits). Lastly, of those remaining, 16 controls and 14 HI children made fewer than two eligible E+1 responses (i.e., isolated errors).

Table 2 shows the demographic characteristics and estimated IQ for the included sample by symptom group. As designed, the HI and control groups significantly differed from one another on parent and teacher ratings of inattention and hyperactivity and on the BRIC ratings of Attention, Activity Level, and Impulsivity. In addition, the HI group was

comprised of a significantly larger proportion of boys, had a significantly lower average estimated IQ score, and was significantly older than the control group. Due to these differences, these factors were included as factors/covariates in the analysis of group effects on post-error slowing.

Data Analysis

The objectives of the analyses were to examine whether children's correct RTs following errors (E+1 responses) were slower than correct RTs following other correct responses (C+1 responses) and whether children exhibiting high levels of ADHD symptoms showed reduced slowing compared to those with low levels of ADHD symptoms. These questions were addressed by a three-way Trial Type (C+1, E+1) x Group (HI, control) x Sex (male, female) mixed-factorial analysis of covariance, controlling for estimated IQ and age. Since the question of controlling for estimated IQ in studies of cognitive functioning in ADHD is a controversial one (Barkley, 1997a), these analyses were repeated without covarying for IQ to examine the stability of effects as a function of this manipulation. Mean RT, rather than the median, was used as the dependent variable in each analysis to allow for the impact of elongated RTs that, although outlying, may be a result of post-error slowing.

Results

Table 3 lists overall mean accuracy, number of C+1 and E+1 responses, overall RT, and RT for correct and erroneous responses separately. Controls exhibited significantly higher accuracy rates, significantly more C+1 responses, and significantly fewer E+1 responses than HI participants.

Consistent with previous findings indicating that post-error slowing is reduced in ADHD, the results of the 3-way Trial Type (C+1, E+1) x Group (Control, HI) x Sex (male, female) mixed factorial ANCOVA, covarying for estimated IQ and age, indicated that the HI preschool children slowed less after errors than controls (Trial Type x Group interaction $F = 4.75$; $p < .05$; $\eta_p^2 = .026$; mean [E+1] – [C+1] difference = 222-ms for controls, 169-ms for HI; see Figure 1). Repeating the analysis without covarying for estimated IQ yielded comparable findings, resulting in a slightly smaller, but still marginally significant, Trial Type x Group interaction ($F = 3.85$; $p = .05$; $\eta_p^2 = .021$). Sex did not interact with ADHD symptoms to impact post-error slowing (Trial Type x Group x Sex interaction, $p > .10$), nor were there any other sex-related effects on RT. Follow-up paired-samples *t* tests showed significant levels of slowing in both the control ($t(74) = 6.62$; $p < .001$) and the HI ($t(107) = 6.08$; $p < .001$) groups.

Because a number of confounding factors could account for the reduced post-error slowing observed in the HI children, three subsequent *post hoc* analyses were executed to rule these out. First, because the HI children were less accurate overall, it is possible that the relatively greater post-error slowing observed in the control group is, at least in part, attributable to an increased salience of errors – that is, that controls slowed more because their erroneous responses were more anomalous with respect to their overall performance. Thus, in an attempt to tease out this possible relationship, bivariate correlations between total percent accuracy, the number of E+1 and C+1 responses, and between the RTs for each trial type were examined. These correlations were computed both in the entire sample and within each symptom group (HI and control) separately. The number of C+1 responses and mean C+1 RT was significantly inversely correlated in the full sample ($r = -0.25$; $p < .001$), as well as in each of the symptom groups ($r_{\text{control}} = -0.30$; $p < .01$; $r_{\text{HI}} = -0.24$; $p < .05$), suggesting that the more accurate children were on the task, the *faster* their post-error response was – the opposite of what would be expected if error salience due to infrequency accounted for the finding. In addition, mean E+1 RT was neither significantly related to the frequency of E

+1 responses, nor with overall accuracy, in either group or in the full sample (all $p > .05$). Thus, the magnitude of mean E+1 RT was not related to error frequency.

Second, because the post-error slowing measure was based on a difference score between C+1 and E+1, significant differences across the two groups can be due not only to differences in E+1 latency, but also to differences in the latencies of correct responses *prior to errors*. Thus, a mixed factorial Correct Response Type (Corrects Prior to Errors, All Other Corrects) x Group (HI, Control) ANCOVA, controlling for age and IQ was conducted to assess this. The results indicated that, in both groups, there were no differences between the mean RTs of correct responses prior to errors and those for other correct responses in either group (Correct Response Type x Group interaction $F = 0.04$, $p = 0.84$, partial eta squared = 0.00). Indeed, the mean RTs for both correct response types in both groups were virtually identical.

Finally, because the two groups differed significantly with respect to the time spent on task (Controls = 74 sec; HI = 87 sec; $t(174) = 2.10$, $p = 0.04$), we did a separate analysis including time on task as a covariate in addition to age and IQ to ensure that this did not account for the differences in performance across the two groups. This did not change the findings - the Trial Type x Group interaction was still significant ($F = 4.96$, $p = 0.027$, partial eta-squared = 0.03). Two additional sets of supplementary analyses were conducted in order to better characterize the nature of the reduction in post-error slowing among the HI children; i.e., whether it was due to a reduction in the *absolute magnitude* of slowing on E+1 trials or a reduction in the *proportion of trials* on which individuals exhibited slowing. Each would have a different implication for inferences regarding the cognitive substrates of the post-error slowing deficit in HI children.

First, to determine whether the proportion of slowing trials was different in HI versus typically-developing children, E+1 trials were characterized as either positive or negative slowing trials. Positive-slowing trials were those with an RT longer than each child's mean C+1 RT and negative-slowing trials were those with an RT faster or equal to the child's mean C+1 RT. Pooling all trials across participants, we found that while, as a group, typically-developing preschoolers slowed on 67% of E+1 trials, HI children slowed on only 60%. This difference, while small, was marginally significant ($\chi^2 = 3.74$; $p = .05$).

Second, to determine whether there were any differences between the groups in the magnitude of slowing on *positive-slowing E+1 trials*, for each subject, the mean difference between each E+1 trial and the mean C+1 RT was computed for only those trials where E+1 RT was longer than the mean C+1 RT for a given participant. These subject means were then averaged for each group. An independent-samples t test indicated that both the HI [Mean (SD) = 496 ms (278 ms)] and typically-developing children [Mean (SD) = 436 ms (257 ms)] showed equivalent levels of post-error slowing when only positive-slowing trials were considered ($p > .10$).

Discussion

The primary objective of this study was to determine whether preschool children exhibiting high levels of ADHD symptoms exhibit deficits in error processing as indicated by post-error slowing. Consistent with findings in school age children with ADHD (Sergeant & van der Meere, 1988; Krusch et al., 1996; Schachar et al., 2004; Wiersema et al., 2005), hyperactive/inattentive children exhibited a relative deficit in post-error slowing even at this early stage of the disorder. This relative deficit could not be attributed to differences between the groups in error salience due to higher accuracy in the control group because there were no significant correlations between accuracy and the post-error slowing magnitude in either group. Since the reduction in the mean magnitude of post-error slowing

in the HI children could have emerged from one of two sources (i.e., from a reduction in the *absolute magnitude* of slowing on E+1 trials or from a reduction in the *proportion of trials* on which individuals exhibited slowing) and each has a different implication for determining the cognitive substrates of the post-error slowing deficit in HI children, an additional set of supplemental analyses was done in an attempt to better understand the nature of the reduction in post-error slowing among HI children. These analyses indicated that HI children exhibited equivalent levels of post-error slowing on the trials where slowing occurred; however, as a group, HI children slowed on a smaller proportion of the errors they committed.

While the results of the supplementary analyses must be interpreted with caution, these analyses were of import since the source of the group differences has implications for inferences regarding the cognitive substrates involved. Post-error slowing *magnitude* on slowed E+1 trials can be regarded as an indication of the time it takes for the underlying error-related cognitive processes to occur. These processes might include preconscious detection of the error (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Kerns et al., 2004; West & Travers, 2007; Gehring & Knight, 2000; Gehring, Goss, Coles, Meyer, & Donchin, 1993; Gehring, Coles, Meyer, & Donchin, 1990; Debener et al., 2005), response conflict generated by the suppression of involuntary corrective responses on E+1 trials in order to respond correctly to the E+1 signal (Rabbitt & Rodgers, 1977) and/or increased prefrontal cortical activity mediating the conscious, executive, self-regulatory processes leading to more careful responding following errors (Rabbitt, 1969; Falkenstein et al., 2000). However, it was not the case that children in the HI group exhibited a reduction in the *magnitude* of post-error slowing on positive-slowness E+1 trials. Rather, there was a reduced *proportion* of positive-slowness E+1 trials in this group. This finding implicates two possible causes of the differences in post-error slowing in HI children: differences in awareness of errors (i.e., error detection) versus differences in the operating components of post-error adjustment.

Post-error slowing may be reduced in HI children if they tend to make more fast “error-correcting responses” on E+1 trials than the control group (Rabbitt & Rodgers, 1977). In self-paced, 2-stimulus tasks such as this, stimulus repetitions are frequent and a child’s attempt to self-correct an erroneous response can be coded as a fast correct response following an error. If this happened more frequently in the HI group than in the TD group, it may have caused differences in E+1 RT. Unfortunately, because there were so few errors committed by the participants in this study, we did not have the power to analyze E+1 stimulus repetitions and alternations separately. However, there was probably no need to do this since abnormally fast RTs were excluded and thus, more often than not, error-correcting responses would likely have been categorized as anticipatory responses.

The other, and more likely, possibility is that HI children failed to perceive a greater proportion of their errors than typically-developing children. Several recent studies have shown that the magnitude of post-error slowing is markedly reduced, even absent, after errors individuals fail to perceive (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Klein et al., 2007; Hester, Foxe, Molholm, Shpaner, & Garavan, 2005). These findings are consistent with a well-established literature indicating attentional lapses among children with ADHD resulting in more variable performance on reaction time tasks (Leth-Steensen, Elbaz, & Douglas, 2000; Hervey et al., 2006; Castellanos et al., 2005). Children with high levels of ADHD symptoms may be less frequently aware of the responses they are making, and this lack of awareness may lie at the root of *both* reduced post-error slowing – which is an indication of conscious error detection and subsequent efforts to modulate their response strategies to optimize performance – and the increased response variability that is consistently shown in the literature – which has been attributed to longer response times that

result from lapses in sustained attention (Leth-Steensen et al., 2000; Hervey et al., 2006; O'Connell et al., 2009; Yordanova et al., 2011b; Yordanova et al., 2011a; Vaurio, Simmonds, & Mostofsky, 2009). Thus, although the supplementary analyses were exploratory and need to be interpreted with caution, and despite the fact that HI children did not differ from controls in the amount of variability of responding, possibly because of the exclusion of very long reaction times (> 2456 ms), the fact that HI children failed to exhibit post-error slowing on a greater proportion of trials is consistent with the hypothesis that lapses in sustained attention may have been, in large part, responsible for the reduced post-error slowing among HI children in this study.

It would be interesting to examine the contribution of lapses in sustained attention that may occur at some regular frequency (Sonuga-Barke and Castellanos, 2007; Vaurio et al., 2009) to post-error slowing in children with ADHD. For example, if it is the case that children fail to slow after errors with greater frequency during these attentional lapses, then clinical interventions aimed at reducing these lapses might increase the speed and efficiency of error-related cognitive processes and thus, positively impact on learning. Alternatively, if failures of post-error slowing are more evenly distributed throughout the time spent on task, this might indicate that the nature of the deficit is more executive and interventions aimed at increasing the salience of errors so that children are more aware of them may help to increase the efficiency of learning and implementing strategies for optimal responding.

Due to several limitations inherent in this study (i.e., low numbers of error trials, lack of a formally diagnosed ADHD group, post hoc supplementary analyses), these results should be considered preliminary and interpreted with caution. Future studies in children of this age are needed to better elucidate the cognitive processes underpinning often attenuated post-error slowing in children with ADHD. Of import, due to the difficulties inherent in trying to keep young children engaged in longer computerized tasks, to ensure that results are generalizable and to reduce the likelihood of Type I error due to unstable RT means based on such few trials, it may be helpful for future studies to individually calibrate both the length and difficulty level of tasks to produce an optimal number of errors (e.g., minimum of 10; 15 – 25% error rate) for each child in the study.

However, while the results of this study are equivocal, the fact that post-error slowing deficits appear to be present before deficits in other executive functions, such as inhibitory control (Berwid et al., 2005; Marks et al., 2005), may suggest that post-error slowing deficits lie at the heart of the disorder and that there are deficiencies or delays in the development of brain systems that are ontogenetically older, like ACC, or dopaminergic and/or noradrenergic innervation of frontal cortex (Holroyd & Coles, 2002). Future studies should thus explore the relative contributions of deficient error monitoring, prefrontally mediated self-regulation, affect/motivation, and/or attention to post-error slowing reductions in young hyperactive/inattentive children. In addition, the inclusion of strategies aimed at increasing the awareness and/or salience of errors may be an interesting aspect to include in psychosocial interventions for ADHD.

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Abbreviations

ADHD-RS-IV	ADHD Rating Scale, Fourth Edition
BRIC	Behavioral Rating Inventory for Children
C+1	first correct response following a correct response
E+1	first correct response following an error
HI	hyperactive/inattentive

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Figure 1.

Effect of ADHD symptoms on post-error RT slowing in preschool children. Data points indicate means corrected for WPPSI Information subtest scaled score and age. Error bars indicate standard error of the mean.

Table 1

Preschool Sample Characteristics: Full Sample

Characteristic	Control (n=120)		HI (n=148)		<i>t</i> / χ^2	<i>p</i>
	Mean	SD	Mean	SD		
% Boys	60.0%		76.4%		8.29	.004
Age	4.31	.58	4.41	.48	1.56	.12
WPPSI Information	11.33	3.05	10.07	2.93	3.42	.001
Parent DSM-IV Ratings*						
Inattention	4.25	2.96	11.96	5.70	14.26	<.001
Hyperactivity/Impulsivity	4.58	2.68	15.41	6.23	19.12	<.001
Teacher DSM-IV Ratings*						
Inattention	2.27	2.59	14.55	7.20	19.28	<.001
Hyperactivity/Impulsivity	2.21	2.63	16.40	8.04	20.19	<.001
Clinician BRIC Ratings [§]						
Activity	2.44	1.20	3.64	1.20	8.07	<.001
Impulsivity	2.02	1.03	3.32	1.39	8.68	<.001
Attention	2.10	1.15	3.53	1.21	9.71	<.001

* Based on sums of 9 rating items

[§] Control n = 116; HI n = 146

Table 2

Preschool Sample Characteristics: Included Sample[^]

Characteristic	Control (n=75)		HI (n=108)		<i>t</i> / χ^2	<i>p</i>
	Mean	SD	Mean	SD		
% Boys	58.7%		75.0%		5.45	.02
Age	4.26	.54	4.44	.46	2.49	.01
WPPSI Information	11.61	2.81	10.25 ^a	2.91	3.15	.002
Parent DSM-IV Ratings [*]						
Inattention	4.24	2.92	12.28	5.84	12.27	<.001
Hyperactivity/Impulsivity	4.71	2.77	15.56	6.53	15.39	<.001
Teacher DSM-IV Ratings [*]						
Inattention	2.39	2.57	14.44	7.23	15.92	<.001
Hyperactivity/Impulsivity	2.52	2.81	16.43	8.05	16.56	<.001
Clinician BRIC Ratings [§]						
Activity	2.63 ^b	1.20	3.56 ^a	1.19	5.13	<.001
Impulsivity	2.07 ^b	1.07	3.21 ^a	1.39	6.19	<.001
Attention	2.22 ^b	1.17	3.43 ^a	1.20	6.68	<.001

[^] Participants with fewer than 2 eligible C+I or E+I responses excluded^{*} Based on sums of 9 rating items[§] Control n = 72; HI n = 107

Table 3

Performance Statistics for the Preschool Sample: Included Sample*

Statistic	Control (n=75)		HH (n=108)		t	p
	Mean	SD	Mean	SD		
% Correct	87.47	9.64	80.06	12.41	4.54	<.001
# C+1 ^a	34.61	10.46	27.08	12.15	4.48	<.001
# E+1 ^b	3.40	1.25	3.85	1.70	2.07	.04
RT _{correct} ^c	1059	204	1055	199	.14	.89
RTSD _{correct} ^{c^}	376	99	402	103	.33	.75
RT _{error}	1107	758	1378	1556	1.39	.17
RT _{C+1} ^c	1014	207	1018	221	.13	.90
RTSD _{C+1} ^{c^}	358	115	363	108	1.74	.08
RT _{E+1} ^c	1236	357	1187	342	.94	.35

* Participants with fewer than 2 eligible C+1 or E+1 responses excluded

^a C+1 = number of correct responses made following 2 consecutive correct responses

^b E+1 = correct responses made following isolated errors

^c RTs under 400 ms and over 2456 ms excluded

[^] RTSD = mean within-subject RT standard deviation