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Behavioral Correlates of Reaction Time Variability in Children With and Without ADHD

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Abstract

Objective—RT variability is often purported to indicate behavioral attention. This study seeks to examine whether RT variability in children with ADHD is associated with observed behavioral indicators of attention.

Methods—One-hundred forty-seven participants with and without ADHD completed five computerized neuropsychological tasks and an analogue math task. Linear mixed models were utilized to examine the relationship between observations of behavioral inattention during the analogue task and measures of RT variability from the neuropsychological tasks.

Results—Significant associations were observed between RT variability and mean duration of on-task behavior on the analogue math task. Secondary analyses indicated that on-task behavior during the math task was also related to accuracy on the neuropsychological tasks.

Conclusions—RT variability, especially the portion of RT variability characterized by long RTs, appears to measure a cognitive phenomenon that relates to successful on-task academic behavior across children with and without ADHD. The relationship between RT variability and on-task behavior is present across multiple neuropsychological tasks and does not appear to be moderated by age, sex, or the presence of anxiety or depression.

Keywords

ADHD; reaction time variability; observed behavior

Attention Deficit Hyperactivity Disorder (ADHD)-related deficits in working memory, attention, and inhibitory control have been well documented on neuropsychological tests (see Hervey et al., 2004 & Willcutt et al., 2005 for meta-analytic reviews). In addition to these cognitive deficits, children with ADHD have higher levels of intra-individual variability in reaction times than typically-developing children (De Zeeuw et al., 2008; Epstein et al., 2011a; Klein, Wendling, Huettner, Ruder, & Peper, 2006; Vaurio, Simmonds, & Mostofsky, 2009). Researchers have proposed that reaction time (RT) variability may be a potential endophenotype for ADHD (Castellanos & Tannock, 2002), particularly since heritability of RT variability is high (Kuntsi & Stevenson, 2001; Andreou et al., 2007).

Most studies have demonstrated increased RT variability using RT standard deviation (RTSD). However, more recent studies have used ex-Gaussian estimates and fast Fourier

transform analyses to demonstrate that children with ADHD are not consistently slower or always more variable than typical children, but that children with ADHD tend to exhibit intermittent long reaction times during task performance (Hervey et al., 2006; Leth-Steensen, Elbaz, & Douglas, 2000; Vaurio et al., 2009). In addition, these instances of long reaction times in children with ADHD may be predictably periodic (Castellanos et al., 2005; Johnson et al., 2007; Vaurio et al., 2009). Although these analyses help to better describe the patterns of RT variability among children with ADHD, it remains unclear what these intermittent periods of long reaction times signify (Tamm et al., 2012). Multiple hypotheses exist postulating what RT variability represents in children with ADHD, including slower cognitive processing, deviant time perception (Kalff et al., 2005) and problems with state regulation (Sergeant, 2005). Several investigators have also posited that periods of long reaction times are indicative of lapses in attention (Leth-Steensen et al., 2000; Hervey et al., 2006), although this remains unsubstantiated.

In an attempt to better understand RT variability, researchers have begun to examine its behavioral correlates. For example, does RT variability relate specifically to inattention? Studies examining differences between children with ADHD-Combined Type and children with ADHD-Predominantly Inattentive Type have shown that both groups have slower mean reaction times and greater RT variability than control groups, but have not indicated substantial differences between the two subtypes (Epstein et al., 2011a; Nigg, Blaskey, Huang-Pollock, & Rappley, 2002; Pasini, Paloscia, Alessandrelli, Porfirio, & Curatolo, 2007; Solanto et al., 2007). Correlational studies examining associations between RT variability and parent- and teacher-reported ADHD symptom domains have found that RT variability is related to composite scores of inattention more so than to hyperactivity/impulsivity (Nigg, 1999; Wahlstedt, 2009). However, a study examining relations between RT variability and individual ADHD symptoms found that RT variability was related to specific symptoms in both ADHD symptom domains (Epstein et al., 2003).

Examining behavioral correlates of RT variability using parent- or teacher reports of ADHD behaviors may be limited as behavioral ratings provide general summaries of behavior over an extended period of time (e.g., last week) rather than temporally-specific, moment-by-moment, information about behavioral variability. Observational methods with temporal coding of inattentive behavior may better relate to RT variability than parent or teacher ratings. Indeed, using behavioral observations, children with ADHD exhibit more off-task behavior than controls (see Kofler, Rapport, & Alderson, 2008 for a meta-analytic review). Further, children with ADHD appear to exhibit greater within-subject variability in their off-task behavior than controls (Abikoff, Gittelman-Klein, & Klein, 1977; Lauth, Heubeck, & Mackowiak, 2006; Kofler et al., 2008). Using a continuous coding strategy, Rapport, Kofler, Alderson, Timko, and DuPaul (2009) found that compared with controls, children with ADHD stay on-task for shorter periods of time and exhibit greater variability in visual attention during academic assignment completion in the classroom.

There is a limited literature examining relations between continuously observed ADHD behavior and neuropsychological indicators (Weis & Totten, 2004; Solanto et al., 2001). No study to date has examined neuropsychological-behavioral relations using *RT variability* as a neuropsychological indicator. Given the magnitude of between-group differences on RT variability outcomes (Epstein et al., 2011a) and the supposition that RT variability may be indicative of attentional lapses (Hervey et al., 2006; Leth-Steenson, et al., 2000), an examination of the behavioral correlates of RT variability using continuous behavioral observations provides the opportunity to increase our understanding of RT variability.

The current study sought to build on the results reported by Epstein et al. (2011a). In this study, children with and without ADHD completed five computerized tasks, which tapped

into various aspects of executive functioning. Analyses focused on group differences for a variety of reaction time performance indicators from these five tasks. Results indicated that children with ADHD had greater values of Ex-gaussian tau and the coefficient of variation ($RTSD \div RT \text{ mean}$) than controls across all five tasks. In addition, group differences in accuracy were found on some of the tasks. No group differences were found for mu or sigma on any of the tasks (all $ps > .05$). Along with completing the computerized tasks, participants also completed a math test, during which they were video-recorded.

examined the relationship between indicators of RT variability on five neuropsychological tests and on-task behavior during an analogue math task among children with and without ADHD. We also included additional alternative neuropsychological indicators in order to examine whether the relationship between neuropsychological functioning and observed behavior was specific to RT variability.

Methods

Participants

One-hundred and forty-seven medication naive participants between the ages of seven and eleven (inclusive) participated. One-hundred and two of these participants were diagnosed with ADHD (49 with Combined Type and 53 with Predominantly Inattentive Type) and 45 were classified as control participants. Study participants had no neurological conditions, developmental disabilities, serious medical conditions, or history of brain injury. All participants received a full scale IQ score of least 80 on the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) and scores of at least 80 on the Word Reading and Numerical Operations subtests of the Wechsler Individual Achievement Test-II (WIAT-II; Wechsler, 2001).

ADHD Groups—Participants in the two ADHD groups were recruited through local schools, referrals to our Center for ADHD, local physicians, and mental health professionals. Their diagnostic status was determined using methods similar to those used in the MTA study (MTA Cooperative Group, 1999). Parent report of ADHD symptoms on the Diagnostic Interview Schedule for Children – Parent Version 4.0 (DISC-P; Shaffer, Fisher, Lucas, Dulcan, Schwab-Stone, 2000) could be supplemented with teacher report of ADHD symptoms. Specifically, if a parent reported at least four symptoms in any ADHD symptom domain on the DISC-P, these symptoms could be supplemented with non-overlapping symptoms on the Vanderbilt Teacher Rating Scale (Wolraich, Feurer, Hannah, Baumgaertel, & Pinnock, 1998) in order to meet ADHD symptom criteria. Children had to have six inattention symptoms identified in this manner to meet ADHD diagnostic criteria. If six or more symptoms were present only in the inattentive domain, the child met criteria for ADHD-Predominantly Inattentive Type (ADHD-I). If six or more symptoms were present in both the inattentive and hyperactive-impulsive domains, the child met criteria for ADHD-Combined Type (ADHD-C). In addition to symptom criteria being met using these supplemental rules, children must also have fulfilled DSM-IV criteria B through E (i.e., age of onset, pervasiveness, impairment, and rule out of other causal conditions) based upon parent responses on the DISC-P. Further, children were required to have at least four symptoms of inattention or hyperactivity/impulsivity coded as occurring *often* or *very often* on the Vanderbilt Teacher Rating Scale (Wolraich et al., 1998).

Control Group—Control participants were recruited through local schools, and a database of local families interested in participating in research studies. They met study criteria if their parents endorsed three or fewer ADHD symptoms in either symptom domain and did not meet criteria for any DSM-IV behavioral disorder on the DISC-P (Shaffer et al., 2000).

Participant demographics are summarized in Table 1. Chi square analyses and one-way ANOVAs (three group) were conducted to investigate demographic differences between the three groups. Post hoc tests indicated that both ADHD groups had lower IQ and Numerical Operations scores than the controls. With regard to symptoms, both ADHD groups had a greater number of inattentive symptoms than the controls, and the ADHD-C group had a greater number of hyperactive-impulsive symptoms than the other two groups. Further, rates for oppositional defiant, conduct, and anxiety disorders were significantly higher in the ADHD groups than the control group. These rates are consistent with studies in the ADHD literature showing high rates of comorbid anxiety and disruptive behavior disorders among children with ADHD (MTA Cooperative Group, 1999).

Neuropsychological Assessment Measures

Each participant completed five computerized neuropsychological tasks designed to assess a variety of aspects of neurocognition (working memory, attention, inhibitory control). The five tasks included a choice discrimination task, the Attentional Network Task, a go/no-go task, a stop-signal task, and an n-back task. Test-retest reliability for each of the tasks was good (Epstein et al., 2011b). A full description of these tasks appears elsewhere (Epstein et al., 2011a). A brief overview is presented below.

The choice discrimination task consisted of circles and squares that appeared one at a time in random order and with equal probability for 360 trials. Participants were instructed to indicate which shape was presented by pressing one of two buttons.

The Child Attentional Network Task (ANT; Rueda et al., 2004) consisted of 248 trials. Each trial included a single fish stimulus that appeared on the computer screen either by itself or in the middle of a horizontal row of five fish. Participants were told to indicate which way the middle fish was swimming, by pressing one of two buttons. In trials with a row of five fish, the target (middle) fish could be facing in the same (congruent trials) or opposite (incongruent trials) direction as the other four fish. Neutral trials included just the central fish. Each of these three conditions accounted for 33 percent of the trials. Preceding each target, there was one of four different warning conditions that appeared for 150 milliseconds - a no cue condition, a central cue condition which involved an asterisk in the center of the screen, a double cue which involved two asterisks, or a spatial cue, which involved an asterisk in the location of the target. These four warning conditions each accounted for one quarter of the trials.

The go/no-go (GNG) task consisted of 360 letter stimuli that appeared on the computer screen one at a time. Participants were instructed to press a button on the response pad for every letter except the letter *X*, which occurred on 10% of all trials.

The stop-signal task (SST) consisted of 360 trials with an airplane facing either to the left or right. Participants were instructed to indicate which way the plane was facing with one of two directional response buttons. A 1000 Hz tone was emitted on 25 percent of the trials. On these trials, participants were to inhibit their responses (stop trials). The delay between presentation of an airplane and the tone began at 250 milliseconds from the visual stimulus onset and varied according to the participant's performance. Successful inhibition resulted in increases of 50 milliseconds and unsuccessful inhibition resulted in decreases of 50 milliseconds so that the rate of inhibition on the stop signal trials was approximately 50%.

Finally, the n-back task was a 1-back task that required participants to remember the previous letter within a continuous stream of letters, as they appeared one at a time on the computer screen, over the course of 360 trials. Participants were instructed to indicate

whether each letter was the same or different than the previous letter, using one of two buttons. The same letter was presented on consecutive trials 30 percent of the time.

Tasks were programmed using e-prime 1.2, and were administered on a desktop computer with a 17" monitor and response pad (Cedrus RB-834). Within each task, stimulus presentation was held constant at 500 milliseconds. Although some of the tasks had varying inter-stimulus events (e.g., warning cues during the ANT), the inter-stimulus intervals (ISI) were held constant across tasks so that there was either 1 second, 3 seconds, or 5 seconds between stimulus presentations. Each task was divided into six continuous blocks of trials: two counterbalanced sets of the three ISIs. One of these sets included a reward manipulation, in which participants could earn points based on their performance to trade for prizes. Within the reward and non-reward sets, the order of the three ISIs was randomized and counterbalanced.

Five neuropsychological variables were calculated for each neuropsychological task. We chose to use ex-Gaussian indicators of RT distribution since traditional estimators of RT central tendency and variability (i.e., mean and sd) are highly susceptible to outlier data points (e.g., long RTs) and because the ex-Gaussian indicators divide RT variability into normal (sigma) and exponential (tau) components. Tau is particularly relevant because it indicates long RTs, which have been posited to be indicative of attentional lapses (Leth-Steensen et al., 2000). Mu represents the mean of the normal component of the curve. QMPE 2.18 (Cousinau, Brown & Heathcote, 1996) was used to provide ex-Gaussian estimates. We also computed the coefficient of variation (CV; $RTSD \div RT \text{ mean}$) as an additional measure of RT variability. CV was selected instead of RTSD because it provides a normalized measure of within-subject variability by removing the effect of response speed on this estimate of variability. Mean RT can be influenced greatly by long RTs and, therefore, was not utilized. Task accuracy was included as a final neuropsychological variable to provide an alternative, and non-RT related, indicator of task performance. Task accuracy was calculated for each participant by dividing the number of correct responses by the number of total response trials for each block of trials within each task. Only successful response trials were utilized to compute reaction time variables. Only reaction times longer than 100 milliseconds were included in calculating summary statistics, since the non-decision portion of simple RT is approximately 100 milliseconds (Luce, 1986).

Naturalistic Task

Participants completed a naturalistic analogue math task while being videotaped. The task was designed to simulate self-directed classroom work. This task required the participants to work on a set of math worksheets for twenty minutes (or until all of the problems were finished). The difficulty level of math problems for each child was determined by an initial assessment of their skill level using curriculum based measurement methodology (Wright, 2010).

Observational Coding

The mean duration of on-task behavior during the math task was generated from continuous behavioral codings of children's on-task behavior during the math task. On-task behavior was defined as visual attention directed towards the math worksheet and tracked continuously using the Noldus Observer XT® software program (Noldus Information Technology, 2008). Any time a participant's gaze left the worksheet, he/she was considered off-task. However, children often times briefly looked away from the worksheets, during brief periods of thinking, before writing an answer, and sometimes while counting to themselves or counting on their fingers. In order to avoid coding these behaviors as off-task, off-task behavior was defined as visual attention diverted from the worksheet for two or

more seconds, similar to other studies (e.g., Rapport, et al., 2009). Further, children looking away while they counted to themselves or counted their fingers were not coded as off-task. However, if children maintained visual attention during the math task, but were doodling, counting problems, or looking ahead to see how many problems were left, they were considered off-task.

Four coders blinded to diagnostic status coded all of the videos. Coders were trained and calibrated on the coding scheme and Noldus® software using a random set of 20 videos. Further, coders met regularly to code another random subset of videos (20; 7%), in an attempt to decrease coder drift. Of the videos that remained after 40 were chosen for training and group-coding, 35% were double-coded for reliability. Intraclass correlation coefficients (ICCs) were high for the two variables used to derive our summary variables: number of times on-task (.94), total duration of on-task behavior (.89).

In order to capture the oscillating nature of attention, which has been hypothesized as an important differentiating characteristic for children with and without ADHD (Castellanos et al., 2005; Johnson et al., 2007), we calculated the *mean duration* of on-task behavior during the math task by dividing the total duration of time on-task during the math task by the number of times on-task.

Procedure

This study was approved by the Cincinnati Children's Hospital Medical Center Institutional Review Board and all authors complied with the APA ethical standards in the treatment of study participants. Study participation involved three sessions on three separate days, each approximately one week apart. The first session was used to determine whether a participant qualified for an ADHD diagnosis. After written informed consent was obtained, parents completed the DISC-P (Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000), while the child completed the WASI (Wechsler, 1999) and WIAT-II (Wechsler, 2001) screeners, and curriculum based measurement assessment (Wright, 2010) to determine math level proficiency. To ensure the presence of ADHD symptoms across settings needed for an ADHD diagnosis, teachers of participants completed the Teacher Vanderbilt Rating Scale (Wolraich et al., 1998). During sessions two and three, participants completed the five neuropsychological computer tasks and the math task. The order of task completion was identical for each participant. The average time between these two testing sessions for all participants was 6.47 days. The three diagnostic groups did not significantly differ in their time between neuropsychological testing days (see Table 1). Children remained medication naive during all three sessions.

Analyses

Primary Analyses—General linear models (SAS PROC GLM) with planned post-hoc comparisons were utilized to examine group differences in the mean duration of on-task behavior for the three groups (ADHD-I, ADHD-C, controls).

Linear mixed models (LMMs; SAS PROC MIXED) were utilized to examine the relationship between RT variability indicators (sigma, tau, and CV) and math on-task behavior for all participants. LMMs allowed us to include neuropsychological indicators from all five tasks in one model, which increased our power to detect significant relationships. All neuropsychological indicators (i.e., mu, sigma, tau, CV, and percent accuracy) were calculated for each block of trials within each task. Because ISI and reward both have effects on neuropsychological performance (see Epstein et al., 2011a), neuropsychological performance outcomes were not averaged or collapsed across the blocks. As a result, each participant had six mu values, six sigma values, six tau values, six

CV values, and six accuracy percentages for each of the five computer tasks, to take into account performance for each of the three ISIs across the two reward conditions. Each model included ISI, task, and reward status to account for variability arising from these factors. Despite group differences, math achievement as measured by the WIAT-II was not included as a covariate since the math task was customized to each individual's achievement level using curriculum based measurement procedures. Further, given arguments for not using IQ as a covariate in neurocognitive studies (e.g., Dennis, Francis, Cirino, Schachar, & Fletcher, 2009), we did not include IQ as a covariate in our statistical models. All models were initially conducted with interactions between reward and task, ISI and task, and mean on-task behavior and task. Only significant interactions were included in the final models, which are presented below. Post-hoc analyses were conducted to investigate the sources of these interactions. A compound symmetry covariance structure was specified for each model. This covariance structure produces the same results that would be produced with a repeated measures general linear model (e.g., SAS PROC GLM). Results at alpha level $p < .05$ were considered significant. Standardized coefficients were computed by multiplying the unstandardized coefficient by the ratio of the standard deviation of predictor variable to the standard deviation of dependent variable.

Next, LMMs were used to examine whether other neuropsychological indicators were related to on-task behavior. Mu and percent accuracy were used as alternate neuropsychological indicators. The modeling process for these analyses was the same as described above. However, since the purpose of these analyses was to determine whether these neuropsychological variables were also related to behavioral attention, we focused our interpretation on the estimates of the relation between the neuropsychological indicator and on-task behavior.

In order to determine whether ADHD status (ADHD, control) moderated any of the observed relationships, the above models were conducted a second time with an ADHD group variable and an ADHD group by on-task behavior interaction term. A significant interaction effect would indicate that the relationship between observed attention and the specific neuropsychological indicator was different across children with and without ADHD. Post-hoc testing was conducted to identify the source and direction of any significant interaction effects.

Secondary Analyses—For any significant relationships between the behavioral and neuropsychological variables, secondary analyses were conducted to investigate potential variables that may moderate this relationship. First, we investigated whether the presence of an anxiety or depressive disorder moderated the relationship between behavioral and neuropsychological variables. This was accomplished by adding anxiety or depression diagnostic status (present or not present) to the model along with the interaction between the disorder status and on-task behavior. Because none of the children in our control group met diagnostic criteria for ODD, we were unable to test whether or not the presence of oppositional defiant disorder moderated the relationship between indicators of reaction time variability and observed behavior. Similarly to our anxiety/depression analyses, we also investigated whether sex and age moderated the relationship between mean on-task behavior and our neuropsychological indicators.

Missing Data—Some participants were missing neuropsychological data. Also, some data was excluded. Specifically, if the percentage of omission errors was greater than or equal to 50% during performance on any of the five neuropsychological tasks, task data were omitted from analyses (Epstein et al., 2011a). The number of participants with missing neuropsychological indicators due to too many omission errors are as follows: GNG task ($n = 1$), SST ($n = 1$), choice discrimination task ($n = 1$), ANT ($n = 3$), and n-back task ($n = 26$).

Those who had one or more tasks dropped due to omission errors had lower IQs [$t(50.98) = -2.57, p = .01$], higher teacher ratings of inattention [$t(45.46) = 2.10, p = .047$], and higher parent ratings of hyperactivity [$t(45.09) = 2.07, p = .048$] than those who did not have any tasks dropped. No significant differences were found between participants with and without dropped data for age, sex, race, ODD, conduct disorder, anxiety disorder, mood disorder, parent ratings of inattention, or teacher ratings of hyperactivity.

In addition, the QMPE 2.18 program could not calculate a summary ex-Gaussian value for a block of trials that included many omission errors or excluded reactions times (i.e., for being less than 100 milliseconds). The percentages of data (based on 6 values per person) lost on each task were as follows: GNG task (8%), SST (8%), choice discrimination task (3%), ANT (6%), and n-back task (6%). No significant differences were found between participants with and without missing neuropsychological data for age, sex, race, WASI full scale IQ, ODD, conduct disorder, anxiety disorder, mood disorder, or parent- or teacher-rated ADHD symptom scores.

Lastly, of the 147 participants who completed the computerized tasks, nine math observations were lost due to mechanical errors (e.g., video camera dysfunction). In addition, two behavioral observations were not included in the analyses due to the participants' inability to follow directions. Those who were missing math observations had higher teacher-rated inattention than those who had math observations, $t(13.23) = 2.27, p = .04$. There were no significant differences between participants with and without observational data with regard to age, sex, race, WASI full scale IQ, ODD, conduct disorder, anxiety disorder, mood disorder, or parent- or teacher-rated ADHD symptom scores.

Results

Group Differences

There was a significant main effect of group for on-task duration during the math task, $F(2, 133) = 4.93, p = .008$. Both the ADHD-I ($m = 178.04$ seconds, $sd = 219.72, d = .63$) and ADHD-C ($m = 189.70$ seconds, $sd = 206.94, d = .60$) groups had significantly shorter mean durations of on-task behavior than the control group ($m = 366.04$ seconds, $sd = 357.05$). Mean on-task behavior did not differ between the two ADHD groups.

Relationship between On-task Behavior and RT Variability

There was a significant relationship between tau and on-task behavior [$F(1, 133) = 14.78, p = .0002, \beta = -.29$], such that higher values of tau were associated with lower mean durations of on-task behavior. A similar, significant association between CV and on-task behavior was also found, $F(1, 133) = 19.21, p < .0001, \beta = -.27$. The relationship between sigma and on-task behavior, however, was not significant, $F(1, 133) = 2.22, p = .14, \beta = -.06$.

We assessed whether ADHD diagnostic status moderated the relationship between RT variability and on-task behavior by inserting ADHD diagnostic status and the interaction between ADHD status and on-task behavior into our models. None of the interactions were significant, suggesting that the relationship between RT variability indicators and on-task behavior is consistent across children with and without ADHD.

Interactions between On-task Behavior and Reward, ISI, and Task

As explained above, we also examined whether reward, ISI, or task moderated the relationship between our RT variability variables (i.e., sigma, tau, and CV) and on-task behavior. Reward was not a significant moderator in any of the RT variability models. ISI

significantly moderated the relationship between tau and on-task behavior [$F(2, 3490) = 25.27, p < .0001$] whereby during long ISI trials (i.e., slow trials) the negative relationship between tau and on-task behavior became stronger.

Task also significantly moderated the relationship between tau [$F(4, 3490) = 3.50, p = .007$], CV [$F(4, 3698) = 7.10, p < .0001$] and on-task behavior. Despite these significant interactions, post-hoc analyses indicated that the significant relationships between the two RT variability indicators (i.e., tau and CV) and on-task behavior were evident across all five tasks¹. Please see Supplemental Table 1 for these results and parameter estimates.

Relationship between On-Task Behavior and Alternate Neuropsychological Indicators

Mu [$F(1, 133) = 0.00, p = .99, \beta = .13$] was not significantly related to on-task behavior. There was a significant positive relationship between task accuracy and mean on-task behavior, $F(1, 133) = 15.11, p = .0002, \beta = .17$. Higher percent accuracy values were associated with higher mean durations of on-task behavior. In light of this association, we examined the relationship between tau and on-task behavior with accuracy as a covariate. The relationship between tau and on-task behavior remained significant [$F(1, 133) = 16.08, p = .0001, \beta = -.30$] when controlling for task accuracy.

Secondary Analyses: Additional Potential Moderators

Secondary analyses indicated that anxiety/depression, age and sex also were not significant moderators of the relationship between neuropsychological indicators (i.e., tau, CV, accuracy) and on-task behavior.

Discussion

Children with ADHD stayed on-task during the math task for shorter periods of time than the controls. In order to better understand RT variability, the current study examined behavioral correlates of indicators of RT variability (i.e., CV and ex-Gaussian sigma and tau). Both CV and tau were negatively related to mean durations of on-task behavior during a math task, such that higher values of CV and tau on the computerized tasks were associated with shorter durations of on-task behavior during the math task. A relationship between accuracy and attention was also found; lower accuracy scores on the computer tasks were associated with shorter math on-task durations. No significant relationships, however, were found between mu, sigma and on-task behavior.

To date, few studies have examined the relationship between neuropsychological indicators and observed ADHD-related behavior and no studies examining relations between neuropsychological variables and observations of ADHD-related behavior have utilized RT variability as a neuropsychological indicator. Consistent with interpretations in the literature suggesting that RT variability is indicative of lapses in attention (Leth-Steensen et al., 2000), we found significant negative associations between two measures of RT variability (i.e., CV and tau) and observed attention during the math task. However, the relationship between sigma and attention was not significant. Sigma is a measure of the variability in reaction times within the *normal component* of each participant's reaction time distribution. A significant association between tau and task inattention, but not sigma and task inattention, suggests that the long, periodic reaction times exhibited during neuropsychological tasks and measured by the tau indicator are more indicative of behavioral attention.

¹The relationship between on-task behavior and tau on the n-back task was marginally significant ($p = .066$). All other p values testing for the relationship between tau, CV, and on-task behavior on each task were significant at $p < .05$.

Our analyses indicated, however, that RT variability was not the only neuropsychological variable that was related to observed inattention. Indeed, analyses revealed a significant association between task accuracy and behavioral inattention during the math task. Higher accuracy was related to longer durations of on-task behavior. This relationship between task accuracy and observed inattention seems quite logical since individuals can presumably only have high accuracy during neuropsychological tasks if they are visually attending to the tasks. Weis and Totten (2004) also found that error rates on a neuropsychological task were significantly related to ratings of inattentive behavior. Thus, it appears that behavioral inattention is also related to other neuropsychological indicators in addition to RT variability.

Moderators

We conducted additional analyses to examine potential moderators of the relationship between RT variability and academic on-task behavior. Our analyses indicated that the significant relationship between RT variability and observed attention was not moderated by ADHD status. Rather, the relationship between RT variability and on-task behavior existed across both typically-developing children and those with ADHD. While RT variability has increasingly been identified as a sensitive and important neuropsychological measure of ADHD-related neuropsychological deficits, the lack of moderation by ADHD status suggests that RT variability, especially the variability represented by ex-Gaussian tau, is measuring a cognitive phenomenon that relates to successful on-task attention across children with and without ADHD. In addition, since a range of other clinical and demographic variables, including the presence of anxiety and depression, age, and sex, also did not moderate the relationship between RT variability and observed attention, this relationship appears to be fairly robust and independent of these clinical and demographic factors.

We also found that the relationship between on-task behavior and RT variability (tau) was moderated by ISI (i.e., the speed that task stimuli appeared on the computer screen). Specifically, as task stimuli appeared more slowly on the computer screen, children who exhibited more variability in their reaction times (i.e., had higher tau values) stayed on-task for shorter periods of time during their math task. In essence, it appears that the tau indicator is a better indicator of behavioral inattention when the task is slower paced possibly because a slower paced neuropsychological task is similar to performing a math worksheet. As the neuropsychological task becomes slower paced and possibly more similar to completing a boring math worksheet, there is the possibility of distractions and periods of shorter attention and, thus, higher tau values.

Limitations

This study has several limitations. While the math task was designed to mimic classroom situations (i.e., conducting seatwork), it was a laboratory-based analogue task. Thus, participants encountered fewer distractions than would be encountered in a live classroom with other students and may have been better able to pay attention to our math task (i.e., had greater mean on-task values) than if they had been in a live classroom.

Further, even though trial-by-trial data was collected during the neuropsychological tasks and a continuous coding scheme was used for the behavioral data, a more temporal-based analysis (e.g., fractal analysis) was not possible because of the within-task event rate and reward manipulations. Others have used fast Fourier transform (FFT) analyses (Johnson et al., 2007; Castellanos et al., 2005) to describe the oscillating nature (approximately every 13–20 secs) of long RTs among individuals with ADHD. These RT oscillations have been interpreted as the time between on- and off-task states and may correlate with observed on-

task behavior. However, our results indicated much longer periods between on- and off-task states among children with ADHD (178–190 seconds) than have been observed using FFT.

A final limitation concerns the medication status of our participants. Individuals who had a history of taking any psychiatric medications, including ADHD medications, were excluded from participation to methodologically control for any possible effects of stimulants on neuropsychological performance or behavior (Evans et al., 2001; Spencer et al., 2009; Tannock et al., 1995). Excluding child with prior medication use may have excluded participants with more severe ADHD symptomatology who may have received treatment earlier.

Conclusion

In conclusion, it appears that there is a relationship between observed attention and RT variability. This appears to be a robust relationship as evidenced by the observed associations across five different neuropsychological tasks. Moreover, this relationship does not appear to be moderated by age, sex, or the presence of anxiety or depression. Nor is it specific to only children with ADHD. Given that this is the first study to examine the relationship between RT variability and observed attention, continued investigation is needed to further determine the magnitude and specificity of the relationships between these two variables. Future studies should consider assessing ADHD-related behaviors outside of a laboratory setting. In addition, future research should consider corroborating behavioral coding of off-task behavior with psychophysiological indicators of attention (e.g., EEG) during to better approximate attentional allocation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations

RT reaction time

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Table 1
Demographic and Clinical Characteristics of the ADHD-C, ADHD-I and Control Samples

	ADHD-C (n = 49)		ADHD-I (n = 53)	Control (n = 45)	Group Comparisons
Mean (SD) age in years	7.96 (1.12)		8.36 (1.30)	8.28 (1.34)	ns
Number male	39		35	32	ns
Number of each ethnicity (percentage)					(comparing proportion of Caucasians to minorities) ADHD-C > ADHD-I*
Caucasian	32		42	37	
African American	15		2	7	
Hispanic (non-Black)	0		2	1	
Asian	0		2	0	
Mixed	0		0	0	
American Indian	1		1	0	
WASI full scale IQ (SD)	105.55 (11.53)		105.51 (13.34)	116.40 (14.34)	ADHD-C < C** ADHD-I < C**
WIAT Numerical Operations SS (SD)	96.61 (13.19)		97.89 (13.79)	112.84 (18.17)	ADHD-C < C** ADHD-I < C**
Parent Vanderbilt Scores (SD)					
Inattention Symptom Score	7.51 (2.04)		7.57 (1.82)	0.07 (.25)	ADHD-C > C** ADHD-I > C**
Hyperactivity/Impulsivity Symptom Score	7.04 (2.25)		4.23 (2.76)	0.02 (.15)	ADHD-C > C** ADHD-I > C** ADHD-C > ADHD-I**
Total Symptom Score	14.55 (3.90)		11.79 (3.83)	0.09 (.29)	ADHD-C > C** ADHD-I > C** ADHD-C > ADHD-I**
Teacher Vanderbilt Scores (SD)					
Inattention Symptom Score	7.43 (1.98)		7.04 (1.98)	0.20 (.59)	ADHD-C > C** ADHD-I > C**
Hyperactivity/Impulsivity Symptom Score	7.16 (1.75)		2.28 (2.14)	0.29 (.79)	ADHD-C > C** ADHD-I > C** ADHD-C > ADHD-I**
Total Symptom Score	14.59 (2.96)		9.32 (3.07)	0.49 (1.27)	ADHD-C > C**

	ADHD-C (n = 49)	ADHD-I (n = 53)	Control (n = 45)	Group Comparisons
Number with specified comorbid psychological disorder from DISC-P				ADHD-I > C ** ADHD-C > ADHD-I **
Oppositional Defiant Disorder	22	16	0	ADHD-C > C ** ADHD-I > C *
Conduct Disorder	4	0	0	ADHD-C > C * ADHD-I > C *
Any Anxiety Disorder	16	20	2	ADHD-C > ADHD-I *
Any Mood Disorder	1	1	0	ns
Number of Days Between Testing Days	5.98 (5.35)	6.81 (9.14)	6.58 (8.23)	ns

Note:

* $p < .05$;

** $p < .01$;

ns = non-significant. ADHD-C = ADHD-Combined Type. ADHD-I = ADHD-Predominantly Inattentive Type. All three comparisons were run for all variables. Only significant differences are presented.