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Neurocognitive and Behavioral Predictors of Math Performance in Children with and without ADHD

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Abstract

Objective: This study examined neurocognitive and behavioral predictors of math performance in children with and without attention-deficit/hyperactivity disorder (ADHD).

Method: Neurocognitive and behavioral variables were examined as predictors of 1) standardized mathematics achievement scores, 2) productivity on an analog math task, and 3) accuracy on an analog math task.

Results: Children with ADHD had lower achievement scores but did not significantly differ from controls on math productivity or accuracy. N-back accuracy and parent-rated attention predicted math achievement. N-back accuracy and observed attention predicted math productivity. Alerting scores on the Attentional Network Task predicted math accuracy. Mediation analyses indicated that n-back accuracy significantly mediated the relationship between diagnostic group and math achievement.

Conclusion: Neurocognition, rather than behavior, may account for the deficits in math achievement exhibited by many children with ADHD.

Keywords

ADHD; math achievement; neurocognition; curriculum-based measurement; working memory; behavioral attention

Recent estimates suggest that 8.7% of school-aged children meet diagnostic criteria for Attention-Deficit/Hyperactivity Disorder (ADHD; Froehlich et al., 2007). A common area of functional impairment among children with ADHD is poor academic performance (DuPaul, & Stoner, 2003; Massetti et al., 2008). Specifically, children with ADHD demonstrate poorer rates of homework completion (Langberg et al., 2010), lower grades (Barkley, Fischer, Edelbrock, & Smallish, 1990; DeShazo Barry, Lyman, & Klinger, 2002; Fergusson, Horwood, & Lynskey, 1993), and higher rates of retention (Barkley, Fischer, Edelbrock, & Smallish, 1990; Biederman et al., 1996; Molina et al., 2009) than children without ADHD. Students with ADHD also obtain lower standardized achievement test scores than their grade-equivalent peers (Biederman et al., 1996; DeShazo Barry, Lyman, & Klinger, 2002; Merrell & Tymms, 2001; Molina et al., 2009).

Many students with ADHD have particular difficulty in math (e.g., Nussbaum, Grant, Roman, Poole, & Bigler, 1990). Children with ADHD perform more poorly on standardized math achievement tests (e.g., Biederman et al., 1996; DeShazo Barry, Lyman, & Klinger, 2002; Frick et al., 1991), complete fewer problems (Barkley, Fischer, Edelbrock, &

Smallish, 1990; Benedetto-Nasho & Tannock, 1999), and make more errors on math computation worksheets (Benedetto-Nasho & Tannock, 1999; Zentall et al., 1994) than typically-developing controls. However, the causes and correlates of mathematical difficulties in children with ADHD are not fully understood.

Two likely contributors to poor math performance in children with ADHD are behavioral problems and cognitive deficits (Figure 1). Children with ADHD exhibit more inattention (Zentall, 1983; Zentall, 1985; Zentall, 1986; Zentall, 1990) and evidence more observed off-task behavior and impulsive responding during academic tasks than typically-developing controls (Fischer, Barkley, Edelbrock, & Smallish, 1990; Zentall 1985; Zentall, 1986; Zentall, 1990). The majority of studies (e.g., Faraone et al., 1998; Frick et al., 1991; Paternite et al., 1996) and a recent meta-analysis (Willcutt et al., 2012) suggest that both children with ADHD – Predominantly Inattentive Type (ADHD-I) and those with ADHD-Combined Type (ADHD-C) evidence decreased academic achievement compared to controls. Parent and teacher ratings of inattention, present in both children with ADHD-I and ADHD-C, are negatively correlated with math performance (Diamantopoulou et al., 2007; Thorell, 2007; Rogers et al., 2011).

In addition, children with ADHD show a variety of neurocognitive deficits in comparison with controls, including poorer working memory (WM), inhibitory control, planning, and problem solving, as well as greater reaction time variability (Kopecky, Chang, Klorman, Thatcher, & Borgstedt, 2005; Romine et al., 2004; Vaurio, Simmonds, & Mostofsky, 2009; Weyandt, & Willis, 1994; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Deficits on many neurocognitive constructs, including overall executive function (Biederman et al., 2004; Diamantopoulou, Rydell, Thorell, & Bohlin, 2007), WM (Rogers, Hwang, Toplak, Weiss, & Tannock, 2011), attention switching (Preston, Heaton, McCann, Watson, & Selke, 2009), and sustained attention (Preston, Heaton, McCann, Watson, & Selke, 2009), have been linked to poor math performance.

A few studies have directly examined the unique and relative impact of behavioral inattention and neurocognition on math performance in children with ADHD. Using a large sample of kindergartners, Thorell (2007) found that behavioral inattention, as measured by ADHD ratings, and specific aspects of executive functioning (i.e., verbal WM, spatial WM, interference control) were related to math achievement. Further, mediation analyses indicated that both executive functioning and behavioral inattention uniquely influenced math performance in young children. Another study examined whether WM and behavioral inattention, measured by ADHD ratings, were related to academic achievement in adolescents referred for ADHD (Rogers, Hwang, Toplak, Weiss & Tannock, 2011). Again, both inattention and WM contributed unique variance to math achievement.

These studies suggest that neurocognition and behavioral attention predict math achievement. However, we are not aware of any study investigating whether neurocognition and/or behavior mediate the relationship between ADHD and poor math performance (see Figure 1). Further, it is unknown whether neurocognition and behavior predict and/or mediate the relationship between ADHD and other indicators of math performance (i.e., poor productivity). Prior studies have focused on standardized achievement tests, which

emphasize academic knowledge. However, academic proficiency, as evidenced by an inability to complete classwork (Barkley, DuPaul, and McMurray, 1990) or taking a long time to complete homework (Epstein, Pollaway, Foley, and Patton, 1993), is common among children with ADHD and frequently cited as an area of impairment. Thus, exploring neurocognitive and behavioral predictors of other aspects of math performance may shed light on difficulties related to school performance and provide areas for intervention.

The current study investigated math performance deficits in school-age children with ADHD utilizing both achievement scores *as well as* curriculum-based measures of math productivity and accuracy. We predicted that children with ADHD would perform more poorly than controls on all three math outcomes. We then investigated whether specific neurocognitive abilities and indicators of behavioral inattention contributed uniquely to each math performance outcome (i.e., achievement, productivity, and accuracy). Lastly, we examined whether any neurocognitive abilities or aspects of behavioral attention mediated the relationship between ADHD and math performance.

Methods

Participants

Participants (n=147) between the ages of 7 and 11 (inclusive) were recruited from local pediatric clinics and schools. Of these, 102 were diagnosed with ADHD (49 ADHD-C, 53 ADHD-I) and 45 were typically-developing controls. Participants had no neurological or serious medical conditions, developmental disabilities, or history of brain injury. All participants received a full scale IQ score of at least 80 on the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) and standard scores of at least 80 on the Wechsler Individual Achievement Test-II Word Reading and Numerical Operations (WIAT-II NO) subtests (Wechsler, 2001).

Diagnostic status for ADHD participants 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). 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 (Shaffer et al., 2000). 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, Feurer, Hannah, Baumgaertel, & Pinnock, 1998). All study participants were medication naïve.

Typically-developing controls were recruited through local schools and a database of local families interested in research participation. Advertisements indicated that interested families would be participating in "research to study behavioral performance on computer tasks in children with attention problems". Control participants met study criteria if their parents endorsed three or fewer ADHD symptoms in both symptom domains 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. Both ADHD groups had lower IQ scores than controls. Not surprisingly, both ADHD groups had more inattentive symptoms than controls, and the ADHD-C group had more hyperactive-impulsive symptoms than the other two groups. Rates for oppositional defiant, conduct, and anxiety disorders were significantly higher in the ADHD groups than controls.

Tasks/Primary Variables of Interest

Math Achievement—Standardized performance on the WIAT-II NO subtest was utilized as an indicator of math achievement for each participant. This subtest requires children to complete a variety of calculations that increase in difficulty level. Once participants achieve their ceiling, their raw scores are converted to standardized scores based on current grade level.

Analog Math Task—Participants completed one naturalistic analog math task (math worksheets) for twenty minutes while being videotaped. This task was modeled after math tasks assigned in a typical classroom setting (e.g., self-directed classroom work). Children were assigned to complete one of four difficulty levels based on an initial assessment of their skill level using curriculum-based measurement methodology (Wright, 2010; Table 1). Productivity was calculated as the number of math problems a participant completed. Accuracy was calculated as the percentage of problems children answered correctly out of those attempted.

Video recordings of the math task were coded to assess each participant's attention across the task. Four blind coders using Noldus Observer XT® software (Noldus Information Technology, 2008) tracked participants' durations of visual attention towards the task. Off-task behavior was coded whenever a child's visual gaze left the paper for two or more seconds, in line with methods from other studies (e.g., Rapport, Kofler, Alderson, Timko, & DuPaul, 2009). Thirty-five percent of videos were double-coded for reliability. The intraclass correlation coefficient was high for total duration of on-task behavior (.89), which was used as an indicator of behavioral attention.

Behavioral Attention Ratings—Parent- and teacher-rated inattention scores from the Vanderbilt ADHD Rating Scales (Wolraich, et al., 2003; Wolraich, Feurer, Hannah, Baumgaertel, & Pinnock, 1998) were used as indicators of behavioral attention. On this scale, ADHD symptoms are rated from 0 (never) to 3 (very often); inattention scores range from 0 to 27. Because inattention is consistently related to academic achievement (e.g., Thorell, 2007), only inattention ratings were used in the current study's analyses.

Neuropsychological Tasks—Each participant completed five computerized tasks designed to assess a variety of aspects of neurocognition: choice discrimination task, Attentional Network task (ANT; Rueda et al., 2004; Fan et al., (2002), go/no-go task (Soreni, Crosbie, Ickowicz, & Schachar, 2009), Stop Signal task (Logan, 1994; Soreni, Crosbie, Ickowicz, & Schachar, 2009), and n-back task (1-back). Within each task, stimulus presentation was held constant at 500 milliseconds. Tasks included inter-stimulus intervals (ISI) and reward manipulations (Epstein et al., 2011) which were not the focus of this study. Variables included percent accuracy for the choice discrimination and n-back tasks, percent omission and percent commission errors for the go/no-go task, stop signal reaction time (SSRT) for the stop signal task, and alerting, orienting, and conflict scores for the ANT. For the ANT, higher scores indicated increased benefit from alerting cues, orienting cues, and congruent vs. incongruent cues (conflict score), respectively. See Epstein et al. (2011) for more explanation of these tasks and variables.

Procedure

This study was approved by the Institutional Review Board. Participation involved three sessions on three separate days, each approximately one week apart (average 6.47 days). At the first session eligibility criterion were established (i.e., diagnosis, IQ, and achievement testing). During sessions two and three, participants completed the neuropsychological computer tasks and analog math task.

Analyses

Of the 147 participants who completed the computerized tasks, nine math observations were lost due to technical errors and two were not included due to the children's refusal to follow task directions. Participants with missing math observations had higher teacher-rated inattention than those who had math observations [$t(13.23)=2.27, p=.04$], but did not differ with regard to age, sex, race, IQ, oppositional defiant, conduct, anxiety, or mood disorders, or parent-rated ADHD symptom scores (all $ps >.05$).

To investigate group differences for the math, behavioral attention, and neuropsychological variables, a chi square was conducted to investigate whether problem difficulty levels differed across groups for the math worksheets. General linear models using SAS PROC GLM were then conducted to examine group differences (ADHD-C vs. ADHD-I vs. controls) in math achievement (WIAT-II NO), math productivity (number of problems completed), math accuracy (percentage of problems completed correctly), and behavioral attention (Vanderbilt parent and teacher ratings; percentage of on-task behavior). Math problem difficulty level was included as a covariate in the productivity model, to account for differences in problem length (e.g., one digit addition vs. multiple digit addition). All GLM models were subjected to planned comparisons, to assess significant differences between each pair of groups (Table 2).

Next, analyses were conducted to examine the relationship between the math, behavioral, and neurocognitive variables. After removing the variance attributable to math difficulty level from the math productivity variable, Pearson correlations were calculated (Table 3). Six GLM models were conducted using neurocognitive or behavioral variables as predictors

and math achievement, productivity, and accuracy variables as dependent variables. The predictors selected for inclusion in these models met a cut-off level of $p < .10$ in the correlation table (Table 3; Tabachnick & Fidell, 2001). Math difficulty was included as a covariate in the two math productivity models. Significant ($p < .05$) neurocognitive and behavioral predictors in these six models were then included together as predictors in three math models - one predicting math achievement, one predicting math productivity, and one predicting math accuracy. Again, math difficulty level was included as a covariate in the productivity model and variables meeting a cut-off level of $p < .05$ were considered significant predictors.

Lastly, for math variables that significantly differed between ADHD and controls, we examined whether any of the significant neurocognitive and/or behavioral attention variables above mediated the relationship between diagnostic group and math performance. Mediation models were computed in SAS and all significant neurocognitive and behavioral variables were included as parallel mediators. The 95% confidence intervals for the indirect effects for each mediator were computed using bootstrapping methodology (5,000 samples; Preacher & Hayes, 2008) with the *PROCESS* macro (Hayes, 2012).

Results

Group Differences for Predictor Variables

The ADHD-I ($p < .0001$, $d = 5.17$; $p < .0001$, $d = 3.91$) and ADHD-C ($p < .0001$, $d = 4.72$; $p < .0001$, $d = 4.47$) groups had higher parent- and teacher-rated inattention scores than controls but did not significantly differ from one another (Table 1). Further, the ADHD-I ($p = .008$, $d = .60$) and ADHD-C groups ($p = .045$, $d = .56$) were both on-task less than controls but did not differ from each other (Table 2).

As reported by Epstein et al. (2011), the ADHD-C group differed from controls on the n-back task (less accurate), stop signal task (longer SSRTs), and ANT (higher conflict scores). Both ADHD groups had significantly higher percentages of omission errors than controls (Table 2) on the go/no-go task.

Math Achievement

There were significant group differences for WIAT-II NO scores, $F(2,142) = 16.04$, $p < .0001$. Children in the ADHD-I ($p < .0001$, $d = .93$) and ADHD-C ($p < .0001$, $d = .99$) groups had lower scores than controls (Table 2).

All three inattention variables (parent-rated $r = -.42$, $p < .0001$; teacher-rated $r = -.43$, $p < .0001$; and observed $r = .15$, $p = .07$) were correlated with WIAT-II NO performance at a $p < .10$ level. Only parent-rated inattention remained significant when they were included in a multivariate GLM (Table 4).

Four neurocognitive variables were correlated with WIAT-II NO at $p < .10$ level: go/no-go omission errors ($r = -.25$, $p = .003$), go/no-go commission errors ($r = -.17$, $p = .04$), n-back accuracy ($r = .33$, $p < .0001$) and choice discrimination accuracy ($r = .26$, $p = .002$; Table 3).

Only n-back accuracy remained significant when these four variables were included as predictors of math achievement in a multivariate GLM (Table 4).

Including predictors across both models into a single GLM, parent-rated inattention ($p < .0001$) and n-back accuracy ($p = .005$) significantly predicted math achievement, $F(2, 138) = 19.43$, $p < .0001$, $R^2 = .22$.

Math Productivity

The three groups (ADHD-I vs. ADHD-C vs. controls) did not significantly differ on math productivity (Table 2).

All three inattention variables (parent-rated $r = -.18$, $p = .03$; teacher-rated $r = -.17$, $p = .04$; and observed $r = .48$, $p < .0001$) were correlated with math productivity at a $p < .10$ level (Table 3). Only observed inattention remained significant (Table 4), when all three predictors were included in a multivariate GLM with problem difficulty level as a covariate.

Three neurocognitive variables were correlated with math productivity at a $p < .10$ level: SSRT ($r = -.19$, $p = .02$), go/no-go omission errors ($r = -.21$, $p = .01$), and n-back accuracy ($r = .27$, $p = .001$; Table 3). When these three variables were included as predictors of productivity in a multivariate GLM with problem difficulty level as a covariate, n-back accuracy and SSRT remained significant (Table 4).

Including predictors across both models into a single GLM with problem difficulty level as a covariate, n-back accuracy ($p = .007$) and observed on-task behavior ($p < .0001$) were both significant predictors of math productivity, $F(6, 127) = 20.07$, $p < .0001$, $R^2 = .49$.

Math Accuracy

The three groups (ADHD-I vs. ADHD-C vs. controls) did not significantly differ on math accuracy (Table 2).

None of the attentional variables correlated with math accuracy at a $p < .10$ level (Table 3).

Two neurocognitive variables were correlated with math accuracy at a $p < .10$ level: ANT orienting scores ($r = .16$, $p = .055$) and ANT alerting scores ($r = .35$, $p < .0001$; Table 3). When these two variables were included as predictors of accuracy in a multivariate GLM, only ANT alerting scores remained significant (Table 4).

As the single predictor in the final GLM for accuracy, ANT alerting scores remained significant, $F(1, 141) = 19.87$, $p < .0001$, $R^2 = .12$.

Mediation Analyses

Because there were only group differences between participants with ADHD and controls in math achievement, only math achievement was examined as an outcome variable in our mediation models. In addition, because no ADHD subtype differences in achievement were found, the two ADHD groups were collapsed. Based on the regression analyses, parent-rated attention and n-back accuracy were included as parallel mediators. The indirect effect of

ADHD diagnosis on math achievement through n-back accuracy was significant ($\beta = -2.33$; 95% CI = -4.82 to -.83). The indirect effect of ADHD diagnosis on math achievement through parent-rated inattention was not significant ($\beta = -4.51$; 95% CI = -14.59 to 6.57).

Discussion

Consistent with prior research (e.g., Biederman et al., 1996; DeShazo Barry, Lyman, & Klinger, 2002; Frick et al., 1991; Mahone et al., 2002), children with ADHD had lower math achievement scores than controls. In particular, we found that children with ADHD did more poorly on the WIAT-II NO subtest, a test assessing children's ability to solve paper and pencil computations of increasing difficulty. Children's performance on the n-back task and parent-rated inattention both predicted unique variance in math achievement. Further, n-back accuracy mediated ADHD-related deficits in math achievement, suggesting that it is ADHD-related neurocognitive deficits, likely WM and sustained attention (both measured by the n-back task), that are responsible for poorer math achievement among children with ADHD. With regard to math productivity, we did not find performance differences between the diagnostic groups. Math productivity scores were predicted by n-back performance and on-task behavior. Lastly, there were no diagnostic group differences in math accuracy. Math accuracy was predicted by alerting scores on the ANT.

One of the primary goals of this study was to identify specific behavioral and neurocognitive predictors of math performance, particularly those that might account for poorer math achievement in children with ADHD. One variable that predicted math achievement for all participants was parent inattention ratings. Perhaps this relationship is not surprising since in order to perform well on an achievement test, children must sustain their attention over time, avoid distractions, and refrain from making careless mistakes. Prior research has demonstrated that both parent- (DeShazo Barry, Lyman, & Klinger, 2002; Hart, et al., 2010) and teacher- (Barriga et al., 2002; Rogers et al., 2011; Thorell, 2007) ratings of ADHD inattention symptoms are significantly correlated with math achievement. Our study is among the few that have used both parent- and teacher-ratings. While both sets of ratings correlated highly with math achievement in our study, parent-ratings accounted for the majority of the variance in math achievement. Recently, Bauermeister, Barkley, Bauermeister, Martinez, and McBurnett (2012) also demonstrated that maternal ratings of ADHD symptoms accounted for greater variance in academic achievement (i.e., reading and math) than teacher ratings. Perhaps the opportunity for parents to view the child across a range of activities and settings allows them to more accurately or reliably rate inattention. Or possibly since the parent's academic observations of the child are based primarily on homework time (i.e., one-on-one learning) which more closely approximates the achievement testing situation, parent ratings are more likely to correlate with achievement results than teacher ratings.

N-back accuracy also predicted math achievement. The n-back task is usually interpreted as a WM task (Owen, McMillan, Laird, & Bullmore, 2005; Strand et al., 2012). However, some have argued that it is better characterized as a sustained attention task, due to its low correlations with other traditional measures of WM (Kane, Conway, Miura, & Colflesh, 2007), and the fact that the 1-back reduces the requirement to hold and manipulate

information in memory. However, the n-back task does require individuals to update information over time, thought to be a component of WM (e.g., Morris & Jones, 1990; Miyake et al., 2000). Given that performance on the n-back predicted math achievement above and beyond other measures of attention which included a sustained attention component (i.e., choice discrimination accuracy, go/no-go omissions, and ANT), it appears that the n-back task assessed more than sustained attention, and quite possibly provides a measure of WM ability.

If the n-back task does indicate WM ability, our findings are consistent with several other studies with typically-developing children (e.g., Bull & Scerif; Raghubar, Barnes, & Hecht, 2010; Maybery & Do, 2003; St. Clair-Thompson & Gathercole; 2006, Thorell, 2007), children with math learning disabilities (Raghubar, Barnes, & Hecht, 2010), and adolescents with attentional difficulties (Rogers et al., 2011), which have shown that WM predicts math achievement. WM appears to be a critical cognitive skill necessary for successful math performance, particularly as assessed on achievement tests (e.g., arithmetic computation, problem solving, etc.; Männamaa, Kikas, Peets & Palu, 2012; Maybery & Do, 2003; Swanson, 2004). Poor WM can lead to counting errors (Swanson, 2004), procedural errors due to problems with monitoring and updating information (e.g., adding instead of subtracting, not borrowing or carrying correctly), and difficulties with multi-step problems (Geary, 2004). The rapid responding that results from difficulties with holding and updating information may lead to increased careless mistakes and decreased problem solving efforts (Zentall, 2007). All of these difficulties may contribute to lower math achievement scores.

While both higher ratings of parent-rated inattention and poorer n-back performance contributed to poorer math achievement, our mediation analyses found that it was n-back performance that mediated ADHD-related deficits in math achievement. That is, results suggest that WM deficits in children with ADHD partially account for ADHD-related deficits in math achievement. Given this relationship and the consistency, magnitude, and breadth of WM deficits in children with ADHD (for a review, see Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005), ADHD-related deficits in math achievement are not surprising. In fact, the types of aforementioned mathematical errors that are related to WM impairment seem consistent with several of the symptoms that define ADHD (e.g., careless mistakes, inability to follow through on instructions). This set of findings suggests that interventions targeting math achievement in children with ADHD should focus on providing them with adequate time to complete tests and assignments, encouraging them to be deliberate in their computations, and promoting double-checking of their work.

In contrast with mathematical achievement, we did not find any ADHD-related deficits in math productivity. Our math analog math task was designed to simulate classroom seatwork. Using similar tasks, children with ADHD have been shown to be less productive than children without ADHD (e.g., Barkley et al., 1990; Benedetto-Nasho & Tannock, 1999). One major difference between our math task and those used in other studies is that we customized our task to each participant's level of achievement, selecting a level for each child in which the child demonstrated proficiency but not mastery. Prior research examining math productivity deficits in children with ADHD has utilized the same math problems for all participants (e.g., Barkley, Fischer, Edelbrock, & Smallish, 1990). Our lack of between-

group differences may suggest a clinically relevant phenomenon. That is, children with ADHD may be as productive as children without ADHD when problem difficulty is controlled, but when they are forced to do comparable work to their peers, possibly beyond their proficiency level, that math productivity deficits emerge. This suggests that the ADHD-related deficits in productivity shown in prior research, and which are often observed in the classroom and during homework, may be a reflection of ADHD-related deficits in math achievement.

Similar to our analyses predicting math achievement, we found that inattention also predicted math productivity. However, unlike math achievement, it was observed on-task behavior during the math task that best predicted math productivity and not ratings of inattention symptoms. Math productivity, in effect, depended on the child's ability to attend to the math task over time and overcome boredom and distractions. On-task behavior during the math task predicted math productivity better than ratings likely because parent and teacher ratings reflect overall behavior patterns, whereas the observational codings more accurately capture behavior during performance of the task at hand.

Just as it did for math achievement, n-back accuracy also predicted math productivity. The purported mathematical errors engendered by WM deficits (e.g., counting errors, procedural errors, multistep errors; e.g., Geary, 2004; Männamaa, Kikas, Peets & Palu, 2012; Maybery & Do, 2003; Swanson, 2004; Zentall, 2007) not only impair math achievement abilities but quite obviously impair a child's ability to complete mathematical computations in an efficient manner. In summary, WM appears to be a critical skill for successful math performance as measured by achievement scores or measures of math productivity. The ability to effectively monitor, update, and hold numerical information in mind during computation directly affects math performance.

Finally, turning to math accuracy, there were no differences in math accuracy between children with and without ADHD. Additionally, none of the behavioral variables were significantly related to accuracy. Similarly to productivity, this lack of findings may be due to the way in which we assigned math tasks to each child (i.e., using a pre-test to determine their own ability level). This methodology likely created ceiling effects and low variances within groups, thus limiting our ability to detect group differences in or behavioral predictors of math accuracy.

Interestingly, alerting scores on the Attention Network Task (Rueda et al., 2004) significantly predicted math accuracy, suggesting that vigilance is required in order to respond accurately on an independent math task. However, given that this study seems to be the first to report such a relation, this finding requires replication.

Our study results must be considered in light of several limitations. First, children with poor math achievement were excluded from the study and, thus, the pattern of study findings may not generalize to those children with learning disabilities. In addition, our results may not fully generalize to real world settings because our math task was completed in a laboratory setting rather than a classroom where there may be different attentional demands on a child. Furthermore, we did not include tests assessing other aspects of WM (e.g., visuospatial) or

other neurocognitive abilities (e.g., divided attention) which may predict and/or mediate math performance deficits. Lastly, this study only included participants who were medication naive. Excluding participants with prior medication use may have excluded those with more severe ADHD symptomatology who may have received treatment at an earlier age.

In conclusion, this study is one of the most comprehensive studies to date examining the relationship between attention, neurocognition, and math performance in children. We largely replicate previous research demonstrating that inattention and WM predict math achievement in kindergarteners (Thorell, 2007) and adolescents (Rogers et al., 2011). Our results extend these relationships to elementary-aged children with ADHD. Also, by including multiple measures of behavioral attention, neurocognition, and math performance, we are able to conclude that neurocognitive abilities, particularly those assessed on the n-back task (e.g., WM and sustained attention) are strong predictors of both math achievement and math productivity and appear to directly mediate the ADHD-related deficits in math achievement.

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Figure 1.

Theoretical model. This figure shows how behavior and neurocognitive abilities may mediate the relationship between ADHD diagnosis and math performance.

Table 1

Demographic and Clinical Characteristics of the ADHD-Combined Type, ADI-iD-Predominantly inattentive Type, and Control Groups

	ADHD-C (n = 49)	ADHD-I (n = 53)	Control (n = 45)	Group Comparisons
Mean (SD) Age in Years	7.92(1.11)	8.36(1.30)	8.29(1.34)	ns
Number Male (%)	39(80)	35(66)	32(71)	ns
Number of Each Ethnicity (%)				
Caucasian	31(63)	42(79)	37(82)	ADHD-C < ADHD-I*
Non-Caucasian	17(35)	7(13)	8(18)	(proportion of Caucasians)
Not Reported	1(2)	4(8)	0(0)	
WASI Full Scale IQ (SD)	105.12(11.71)	105.51(13.34)	116.40(14.34)	ADHD-C < C**, ADHD-I < C**
Parent Vanderbilt Total Inattentive Score (SD)	20.75(5.02)	20.79(4.57)	2.54(2.06)	ADHD-C > C**, ADHD-I > C**
Teacher Vanderbilt Total Inattentive Score (SD)	21.11(4.81)	19.81(5.19)	3.27(3.08)	ADHD-C > C**, ADHD-I > C**
Parent Vanderbilt Total Hyperactive/Impulsive Score (SD)	20.07(5.12)	13.17(5.65)	1.30(1.28)	ADHD-C > ADHD-I**, ADHD-C > C; ADHD-I > C**
Teacher Vanderbilt Total Hyperactive/Impulsive Score (SD)	20.15(4.33)	8.47(5.73)	2.04(3.25)	ADHD-C > ADHD-I**, ADHD-C > C; ADHD-I > C**
Number with a Comorbid Psychological Disorder				
Oppositional Defiant Disorder	22	16	0	ADHD-C > C**, ADHD-I > C*
Conduct Disorder	4	0	0	ADHD-C > C*, ADHD-I > C*, ADHD-C > ADHD-I*
Any Anxiety Disorder	16	20	2	ADHD-C > C**, ADHD-I > C**
Any Mood Disorder	1	1	0	ns
Number Completing Each Math Problem Difficulty Level				
Single Digit Addition	23	29	13	ns
Multiple Digit Addition	16	10	14	
Single Digit Multiplication	6	10	10	
Multiple Digit Multiplication	6	4	8	

Note. ns= not significant;

ADHD-C = ADHD-Combined Type; ADHD - I = ADHD-Predominantly Inattentive Type; C=control group.

**
p <.01.

*
p <.05;

Table 2

Means and Group Differences for Math, Behavioral and Neurocognitive Variables

	Control Group	ADHD-I Group	ADHD-C Group		
	Mean(SD)	Mean(SD)	Mean(SD)	<i>F</i>	<i>P</i>
WIAT-II Numerical Operations Standard Score	112.84 (18.17)	97.89 (13.79)	97.06 (13.19)	16.04	< .0001
** Number of Math Problems Attempted	156.33 (88.77)	153.42 (88.42)	139.24 (58.94)	.84	.43
Percentage of Math Problems Answered Correctly	94.07(13.92)	91.85(15.51)	95.19(7.71)	.86	.43
Proportion of Time On-Task	.96 (.06)	.88 (.18)	.90 (.14)	3.96	.02
* Choice Discrimination Task Accuracy	88.48(1.83)	82.83(1.83)	84.29(1.79)	2.70	.15
* N-back Task Accuracy	81.90(2.25)	72.07(2.05)	68.40(2.44)	9.22	.0009
* Stop Signal Task SSRT	333.95(21.82)	368.66(20.25)	413.30(21.53)	3.37	.04
Go/No-Go Omission Errors (percentage)	.01 (.02)	.07 (.10)	.08 (.12)	6.86	.001
Go/No-Go Commission Errors (percentage)	.41 (.23)	.46 (.21)	.45 (.19)	1.31	.27
*Flanker Task Alerting Score	80.64(11.57)	80.57(10.66)	89.34(11.44)	0.20	.82
*Flanker Task Orienting Score	24.17(6.91)	28.62(6.38)	20.29(6.84)	0.40	.67
*Flanker Task Conflict Score	53.07(10.35)	54.95(9.61)	88.14(10.23)	3.77	.03

Note. SSRT = Stop Signal Reaction Time; WIAT-II = Wechsler Individual Achievement Tests-2nd Edition Statistics marked with asterisks were originally presented by Epstein et al. (2011). (REMOVED FOR BLIND REVIEW) and take into account event rate and reward conditions. Models with ** included problem difficulty level as a covariate.

Table 3
Pearson Correlations for all Math, Behavioral, and Neurocognitive Variables for All Participants

	1	2*	3	4	5	6	7	8	9	10	11	12	13	14
1) WIAT-II Numerical Operations	1													
2) Productivity *	.01	1												
3) Accuracy	.02	.03	1											
4) Parent-rated Inattention	-.42 ^e	-.18 ^b	-.04	1										
5) Teacher-rated Inattention	-.43 ^e	-.17 ^b	-.03	.80 ^e	1									
6) Observed Inattention	.15 ^a	.48 ^e	-.003	-.29 ^d	-.27 ^c	1								
7) SSRT	-.01	-.19 ^b	-.03	.16 ^a	.26 ^c	-.12	1							
8) Go/No-Go Omission Errors	-.25 ^c	-.21 ^c	-.05	.29 ^d	.27 ^c	-.20 ^b	.04	1						
9) Go/No-Go Commission Errors	-.17 ^b	-.14	.06	.15 ^a	.22 ^b	-.06	.06	.11	1					
10) ANT Alert	-.08	-.10	.35 ^e	.03	.02	-.10	-.07	.26	-.06	1				
11) ANT Orienting	-.02	.05	.16 ^a	.09	.11	.09	.07	.10	-.04	.36 ^e	1			
12) ANT Conflict	.00	-.10	.04	.02	.05	-.06	.02	-.02	-.10	.15 ^a	.08	1		
13) N-back Accuracy	.33 ^e	.27 ^c	.008	-.32 ^e	-.33 ^e	.06	-.24 ^c	-.35 ^e	-.16 ^a	-.07	-.04	.13	1	
14) Choice Discrimination Accuracy	.26 ^c	.14	-.03	-.21 ^b	-.18 ^b	.12	-.21 ^b	-.41 ^e	-.34 ^e	0	-.09	.11	.31 ^d	1

Note. SSRT = Stop Signal Reaction Time. ANT = Attention Network Task. WIAT-II = Wechsler Individual Achievement Tests-2nd Edition.

^a $p < .10$,

^b $p < .05$,

^c $p < .01$,

^d $p < .001$,

^e $p < .0001$;

* Correlations between productivity and other variables controlled for problem difficulty level participants were assigned to for their math worksheets.

Table 4

Behavioral and Neurocognitive Predictors of Math Achievement and Productivity

	WIAT-II Numerical Operations		Problems Attempted		Problem Accuracy	
Behavioral Variable	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
Parent Vanderbilt Inattention Score	4.89	.03	0.10	.75	-	-
Teacher Vanderbilt Inattention Score	2.02	.16	0.05	.82	-	-
Percentage of Time Coded On-Task	0.16	.69	32.30	< .0001	-	-
Math Problem Difficulty Level	-	-	21.55	< .0001	-	-
Neurocognitive Variable ^e						
N-back Accuracy	8.32	.005	4.94	.03	-	-
Choice Accuracy	1.49	.22	-	-	-	-
Go/No-Go Omission Errors	1.39	.24	3.46	.07	-	-
Go/No-Go Commission Errors	1.00	.32	-	-	-	-
Stop Signal SSRT			4.00	.047	-	-
Flanker Orienting Score	-	-	-	-	0.21	.64
Flanker Alerting Score	-	-	-	-	15.84	.0001
Flanker Conflict Score	-	-	-	-	-	-
Math Problem Difficulty Level	-	-	15.19	< .0001	-	-

Note. SSRT = Stop Signal Reaction Time. WIAT-II = Wechsler Individual Achievement Tests-2nd Edition. Results in this table report main effects within each model rather than the overall significance of each model. The Problems Attempted models included problem difficulty level as covariate.