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Which Neuropsychological Functions Predict Various Processing Speed Components in Children with and without Attention-Deficit/Hyperactivity Disorder?

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Abstract

We identified statistical predictors of four processing speed (PS) components in a sample of 151 children with and without ADHD. Performance on perceptual speed was predicted by visual attention/short-term memory, whereas incidental learning/psychomotor speed was predicted by verbal working memory. Rapid naming was predictive of each PS component assessed, and inhibition predicted all but one task, suggesting a shared need to identify/retrive stimuli rapidly and inhibit incorrect responding across PS components. Hence, we found both shared and unique predictors of perceptual, cognitive, and output speed, suggesting more specific terminology should be used in future research on processing speed in ADHD.

Key words: processing speed, ADHD, working memory, rapid naming, inhibition

Introduction

Processing speed (PS) is commonly affected in Attention-Deficit/Hyperactivity Disorder (ADHD; e.g., Calhoun & Mayes, 2005; Jacobson et al., 2011; Nikolas & Nigg, 2013; Shanahan et al., 2006; Weiler, Bernstein, Bellinger, &Waber, 2000; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Nevertheless, limited research has been conducted on the predictors of processing speed deficits to determine potential neuropsychological correlates of them. To help bridge the gap in our understanding between the different components of processing speed and the cognitions corresponding with them, our study determined unique versus shared statistical predictors for perceptual, cognitive, and output processing speed components in children with and without ADHD. While this study is correlational in nature, it is among the few to examine neuropsychological correlates that may be contributors to, or ramifications of, the various PS deficits in ADHD.

Although processing speed is commonly studied in various disorders, there is no consensus across authors as to what PS is or how it should be measured. To address this issue, Salthouse (2000) recorded the most prominent definitions used to measure PS in the literature. These operational definitions map onto multiple constructs including psychophysical speed, perceptual speed, decision speed, reaction time, and psychomotor speed. While each may measure a somewhat distinct ability, it is likely that every one contributes to PS in its entirety. Shanahan defined PS as the "underlying cognitive efficiency at understanding and acting upon external stimuli, which includes integrating low level perceptual, higher level cognitive, and output speed" (Shanahan et al., 2006, p. 586). This appears to be a suitable definition of PS as it incorporates the various constructs operationalized by Salthouse into components that are more readily assessed with clinical measures.

In a recent study using this sample (manuscript submitted for publication), we found children with ADHD-Predominantly Inattentive Type (ADHD-PI) and ADHD-Combined Type displayed worse perceptual (WISC Symbol Search) and incidental learning/psychomotor (WISC Coding) speed than controls, and children with ADHD-PI had slower decision speed (WJ Decision Speed) than controls, consistent with prior literature on processing speed in ADHD (Calhoun & Mayes, 2005; Walg, Hapfelmeier, El-Wahsch & Prior, 2017; Willcutt et al., 2005). All three groups were comparable in simple reaction time. The two subtypes did not differ on any processing speed measure, and ADHD performed worse than controls on psychomotor speed (WISC Coding Copy). Thus, perceptual, cognitive, and more complex output speed were affected similarly across ADHD-PI and ADHD-C subtypes. The sample did not include ADHD-Hyperactive/Impulsive Type. We also found perceptual and psychomotor speed to be associated with the inattention dimension. Coding was slightly associated with both dimensions of ADHD, inattention and hyperactivity, although only hyperactivity was significant. Decision Speed variance was not captured by either dimension. Given this variability, each aspect of PS is assessed separately to determine how neuropsychological predictors may vary. Further, ADHD is assessed as a group when examining predictors of PS as the two subtypes performed similarly on the PS measures used in this study.

While extensive literature has demonstrated PS deficits in ADHD (e.g., Calhoun & Mayes, 2005; Jacobson et al., 2011; Nickolas & Nigg, 2013; Nigg, Blaskey, Huang-Pollock, & Rappley, 2002; Shanahan et al., 2006; Weiler et al., 2000; Willcutt et al., 2005), limited research has been conducted on the neuropsychological correlates of PS deficits. Only two articles were found in this area: one by Jacobson and colleagues (2011) and one by Crowe and colleagues (1999). To determine the statistical predictors of Coding performance, Jacobson and colleagues

(2011) combined their ADHD and control samples into one group and entered verbal focused attention/short-term memory, verbal working memory, spatial working memory, mean reaction time, naming automaticity, intra-subject reaction time variability, and inhibition as predictor variables into a regression model. The significant predictors were focused auditory attention/verbal short-term memory, verbal working memory, and spatial working memory, suggesting the importance of short-term/working memory in this task. Similarly, Crowe and colleagues (1999) utilized verbal working memory, median reaction time, visual-spatial focused attention/short-term memory, graphomotor speed, incidental learning, and executive functioning as statistical predictors, and found graphomotor speed and incidental learning were significant predictors of Symbol Search, and graphomotor speed and executive functioning were significant predictors of Digit Symbol-Coding in a healthy adult sample. Based on these studies there may be multiple predictors of PS, including focused attention/short-term memory, working memory, motor speed, executive functioning, and, perhaps, naming speed, that may vary depending upon the component(s) of PS assessed. Given the current state of the literature, it is unclear which of these factors may be associated with the perceptual, cognitive, and/or output speed deficits in children with ADHD, which our study will address.

Children with ADHD may experience weaknesses in all of these potential correlates of PS: focused attention/short-term memory, working memory, executive functioning, naming speed, and motor functioning. A deficit that is commonly, but not consistently, found in ADHD is poor focused attention/short-term memory functioning. For example, several studies have demonstrated that visual-spatial short-term memory is impaired in children with ADHD (Aman, Roberts, & Pennington, 1998; Kirk, 2001; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Martinussen & Tannock, 2006; McInnes, Humphries, Hogg-Johnson, & Tannock, 2003;

Sonuga-Barke, Sergeant, Nigg, & Willcutt, 2008). More specifically, visual/non-spatial short-term memory performance may be intact (French, Zentall, & Bennett, 2001; Karatekin, 2004; Kibby & Cohen, 2008; McInnes et al., 2003; Rucklidge & Tannock, 2002; Willcutt et al., 2001), but visual-spatial short-term memory performance is frequently poor (Aman et al., 1998; Kibby & Cohen, 2008; Martinussen et al., 2005; McInnes et al., 2003; Sonuga-Barke et al., 2008). In contrast, verbal short-term memory may be intact in individuals with ADHD when they are focused on the task (Karatekin, 2004; Kibby & Cohen, 2008; McInnes et al., 2003; Rucklidge & Tannock, 2002; Willcutt et al., 2001). Nonetheless, there are studies that have demonstrated impairments in at least some aspects of verbal short-term memory (Pallas, 2003; Quinlan & Brown, 2003).

Some researchers suggest the central executive is the component of working memory that is most impaired in ADHD (Alderson, Hudec, Patros & Kasper, 2013; see Kibby, 2012 and Martinussen et al., 2005 for reviews), perhaps because the central executive component serves as an attention-directing unit that guides attention to the appropriate storage system to aid in memory processing (Karatekin, 2004). Therefore, it would be reasonable to expect that working memory deficits are linked to inattention (Martinussen & Tannock, 2006). Nonetheless, the literature on the central executive in ADHD is disparate, especially for the verbal domain (Kibby & Cohen, 2008; Pallas, 2003; Rucklidge & Tannock, 2002; see Kibby, 2012; Roodenrys, 2006; Willcutt et al., 2005). Given that ADHD is a heterogeneous disorder, it is likely that only a subset has problems with verbal working memory. In contrast, spatial working memory is commonly impaired in children with ADHD (Brocki, Randall, Bohlin, & Kerns, 2008; Gau & Chiang, 2013; Kibby, 2012; Martinussen et al., 2005; Willcutt et al., 2005).

There is a great deal of research assessing executive functioning in ADHD, which often concludes that there are deficits in shift, inhibition, planning, and/or working memory at the group level (Barkley & Biederman, 1997; Nigg et al., 2005; Pennington & Ozonoff, 1996; Sergeant, Geurts, & Oosterlaan, 2002), likely due to poor frontal-striatal functioning (Casey, Castellanos, Giedd, & Marsh, 1997). A meta-analysis by Willcutt and colleagues (2005) calculated that 65% of the studies reviewed showed significant impairment in executive functioning in individuals with ADHD. Hence, there are some researchers who have not found executive functioning weaknesses in ADHD (e.g., Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2005).

Another area that may be affected in ADHD is rapid automatized naming. Rapid automatized naming tasks measure the speed at which an individual can name stimuli (e.g., colors, pictures, symbols). One reason why rapid automatized naming may be affected in ADHD is that slow rapid automatized naming may result from poor white matter integrity, which is also necessary for attentional processes (Arnett et al., 2012). Many studies have demonstrated that children with ADHD have worse performance on rapid automatized naming tasks as a group, including Rapid Automatized Naming (Tannock, Martinussen & Frijters, 2000; Weiler et al., 2000) and other naming measures (Arnett, et al., 2012; Willcutt et al., 2001), than their typically developing counterparts. However, a minority of the studies fail to find significant effects for completion time or errors (e.g., Felton et al., 1987; McGrath, et al., 2011; Raberger & Wimmer, 2003). Various studies utilizing the Rapid Automatized Naming task found that children with ADHD were slower at completing the Color and Object naming conditions than controls, but differences in the Number and Letter conditions are less commonly found (Semrud-Clikeman, Guy & Griffin, 2000; Tannock et al., 2000). Thus, children with ADHD may struggle more with lexical/semantic (i.e., object naming) than phonetic naming (i.e., letter naming; Tannock et al., 2000).

Finally, motor functioning may be affected in ADHD as well. In a study of fine motor abilities, children with ADHD (subtype unspecified) performed worse than controls on a task assessing both finger and hand movement, but they had more difficulty using their fingers than their hands in the various motor exercises (Steger et al., 2001). Males with ADHD also performed worse on the Purdue Pegboard than controls (Pitcher, Piek and Hay, 2003). Nevertheless, motor problems are not always demonstrated in ADHD (e.g., Weiler et al., 2000). Taken together, individuals with ADHD tend to display fine motor problems, particularly with dexterity on timed measures.

Due to the dearth of research on the neuropsychological correlates of PS deficits, the present study examined focused attention/short-term memory, working memory, other aspects of executive functioning, naming speed, and fine motor functioning as predictors of perceptual speed, cognitive speed, and psychomotor speed. Initially we used the entire sample to enhance the range of the variables of interest and power for our regression analyses. It was hypothesized that statistical predictors of Symbol Search performance would include visual-spatial focused attention/short-term memory functioning as each item is unique and the figures are novel, potentially decreasing the ease of verbal mediation and necessitating the use of visual short-term memory during the search process. Statistical predictors of Coding performance were hypothesized to include verbal focused attention/short-term memory, verbal working memory, fine motor dexterity, and executive functioning based upon the work of Jacobson and colleagues (2011) and Crowe and colleagues (1999). It was believed that Coding allows for greater verbal mediation than Symbol Search due to its use of the same number-figure pairs throughout the task; hence, greater verbal short-term memory, as well as working memory, skills may be required to respond quickly. Statistical predictors of Decision Speed performance were hypothesized to include verbal focused attention/short-term memory and verbal working memory, as the task measures the ability to quickly assess category membership of common objects. In terms of output speed, fine motor dexterity was expected to be a predictor of psychomotor speed. Simple reaction time was not assessed, as ADHD and controls did not differ on this measure in our prior study. It was expected that inhibition and naming speed would be related to performance on all PS measures assessed, as inhibition is often required for accurate performance, and naming speed may be related to retrieval speed and is timed. These regression analyses were then repeated, using the children with ADHD only to determine whether predictors varied for those with ADHD versus the total sample. ADHD was analyzed as a group instead of by subtypes because both subtypes performed comparably on our PS measures as found in our prior study (manuscript in submission); because both subtypes tend to perform comparably in short-term memory (Cockcroft, 2011), cognitive executive functioning, (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Chhabildas et al., 2001; Nigg et al., 2005; Schmitz et al., 2002; Willcutt et al., 2005), rapid naming (Nigg et al., 2002), and motor speed (Pitcher et al., 2003); and to enhance power. In the analyses focused on ADHD, predictors were not expected to vary from the total sample, except that visual-spatial short-term memory and working memory may not be as strongly related to PS, as many to most in the regression analyses likely would have deficits in these areas, limiting the variability of these variables.

Method

Participants

A more thorough description of participants and how they were diagnosed is presented in a prior paper (manuscript in submission). In brief, all children, ages 8-12 years, participated in grant-funded studies focused on RD and ADHD (see Acknowledgements). Only those with ADHD and controls were included in this project. The sample contained 50 children who had ADHD-PI, 40 who had ADHD-C, and 61 who were typically developing children. The sample was 52% male and 90% Caucasian. Groups were equated on age, gender, race/ethnicity, maternal education and verbal reasoning/intellect. Children with ADHD-PI and C were comparable in inattention but differed in hyperactivity/impulsivity, as is expected based upon DSM-IV criteria, which was the current DSM version at the time of data collection. Overall, the severity of ADHD was mild, with hyperactivity/impulsivity levels being the most mild as some children had ADHD-PI instead of -C. The Verbal Comprehension Index was used as the measure of IQ instead of FSIQ, as FSIQ includes measures of PS and working memory but the VCI does not. See Table 1 for descriptive data on children with ADHD and controls.

Insert Table 1 about here

Children with ADHD were diagnosed according to DSM-IV criteria by a child neuropsychologist. The specific criteria are described in a prior paper (Kibby, Dyer, Vadnais, Jagger, Casher & Stacy, 2015). In brief, the diagnostic process included three components: a clinical interview, a DSM-IV questionnaire covering criteria for ADHD among other disorders, and the Behavior Assessment System for Children, 2nd edition (BASC-2). To be diagnosed with ADHD, DSM-IV criteria had to be met using the three measures. Children were classified as controls if they did not meet diagnostic criteria for ADHD. Exclusionary criteria were applied to both groups and included psychiatric diagnoses other than ADHD (e.g., major depression, generalized anxiety disorder), medical or neurological disorders (e.g., TBI, tics, immune disorders), reading disorders, severe environmental problems (e.g., suspected abuse), or an IQ below 80. The original sample from which this study was drawn included 284 children, but after children meeting these criteria were excluded, the final sample contained 151 children.

All participants were recruited through the greater region which overlapped four States, constituting a community sample. Some children with ADHD were diagnosed with the disorder prior to testing, but diagnosis was confirmed during testing. Corresponding with their earlier diagnosis, some children with ADHD were being treated with mediation, but all participants were off medication during testing.

Measures

According to their respective manuals, all measures utilized have at least adequate or better psychometric properties.

Processing Speed. All measures of PS have a predetermined time limit set by their respective test manuals. Hence, they assess the number of items completed correctly within the time limit. Depending upon the time of testing, Wechsler Intelligence Scale for Children – Third Edition (WISC-III; Wechsler, 1991) or Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV; Wechsler, 2003) Symbol Search and Coding subtests were administered to assess perceptual and cognitive processing speed, respectively. Symbol Search requires quickly and accurately examining a set of symbols and deciding whether the target symbols for that item are within the adjacent set. Each item set is unique. Coding requires matching numbers with their corresponding symbols and copying the symbols as quickly as possible in the corresponding blank. As the same set of 9 number-symbol pairs is used throughout the subtest, this subtest measures incidental memory/procedural learning along with psychomotor speed. The stimuli for the subtests were quite similar between the two editions of the WISC.

Coding Copy from the WISC-IV was used as the measure of output speed. Coding Copy uses the same symbols as Coding, but symbols are written above the blanks instead of numbers. Hence, there is no number-symbol pairing in this task; the child only needs to copy the symbol above for each blank. This task minimizes the cognitive demands of Coding, at least in terms of incidental learning, and, thus, may be a purer measure of psychomotor speed.

The Woodcock-Johnson III Test of Cognitive Abilities (WJ-III Cog; Woodcock et al., 2001) Decision Speed subtest was used to assess cognitive PS along with Coding. Decision Speed may be a purer measure of cognitive PS as it minimizes psychomotor demands compared to Coding. It also appears to measure a different aspect of cognitive PS than Coding. This subtest measures quick semantic categorization, as the participant is asked to circle two out of seven pictures that are the most similar conceptually (e.g., a sun and a moon) for each item.

Memory. The Children's Memory Scale (CMS; Cohen, 1997) was used as a measure of verbal focused attention/short-term memory, visual-spatial focused attention/short-term memory, and verbal working memory. The Forward portion of the Numbers subtest measures verbal focused attention/short-term memory by requiring participants to repeat a number series verbatim immediately after it is presented. The Sequences subtest measures verbal working memory by requiring the participant to mentally manipulate common sequences (e.g., say the days of the week backward). The Picture Locations subtest measures visual-spatial focused attention/short-term memory by requiring the child to remember the location of pictures that are presented for two seconds each. It is similar to Numbers Forward in that the number of positions to be recalled gradually increases. Standard scores were obtained using the CMS's software.

Perseveration/Shift. The Wisconsin Card Sorting Test—64 Card Version (WCST-64*;* Kongs, Thompson, Iverson, & Heaton, 2000) is a measure of cognitive flexibility and problem-solving ability. The Perseverative Errors score was used, which is the extent to which the child maintained an incorrect response style despite receiving feedback that he/she was incorrect. Standard scores were calculated based on the norms provided in the manual.

Rapid Naming. Rapid Object Naming is a subtest from the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999). In this subtest, children were asked to name six common objects presented in an array of 36 items as quickly as possible. The standard score was based off the time taken to complete the page using the test's manual.

Planning/Inhibition. The Tower test from the A Developmental Neuropsychological Assessment (Korkman, Kirk & Kemp, 1998) was administered as a measure of planning skills. On this test, children are asked to rearrange three colored balls on three vertical pegs to reach the target positions within a mandatory number of moves, all while following a set of rules. The standard score is based on the construction of the correct positions within the given time limit. Furthermore, the number of rule violations was recorded, and this was transformed into normed units. Rule violations is a separate measure from the Tower standard score, as children are not penalized on their Tower raw score when they make rule violations.

Fine Motor Dexterity. The Grooved Pegboard (Lafayette Instrument Company, 1989) is a timed measure of fine motor dexterity. This task required the individual to manipulate keyed pegs so that they fit into grooved holes, as quickly as possible. The score was calculated based on the total time required to complete the matrix with each hand. Standard scores were calculated based upon the means and standard deviations provided in the manual. The child's dominant hand score was used for the purposes of this study.

Procedure

All children underwent a full day of neuropsychological assessment that included the measures described above as part of NIH-funded projects (see Acknowledgements for grant numbers). Testing was conducted in a day to minimize the amount of time parents and children had to miss work/school, as this was a community sample. Order of test administration was varied systematically, except that the WISC always was administered first and the CMS after a longer break to help reduce mental fatigue on these concentration-intensive measures. Further, scheduled, frequent breaks were provided throughout the testing day to minimize fatigue, and when they were insufficient for a given child, additional breaks were provided. Parent(s) completed questionnaires and a clinical interview on their child. The children's teachers were asked to complete questionnaires as well, which they mailed directly to us. The projects from which these data were drawn were approved by the Southern Illinois University Institutional Review Board's Human Subjects Committee before data collection commenced, as well as during data collection.

Results

Preliminary Analyses

Initially, variables were assessed to determine whether they violated statistical assumptions for multiple regression, and two violated assumptions. Grooved Pegboard's data was able to be transformed adequately. Decision Speed's kurtosis was unable to be corrected through various statistical transformations, and, thus, was left untransformed for ease of interpretation.

Pearson correlations were conducted between the variables used in the study to assist the reader in interpreting the regression results. As anticipated, the four processing speed variables were only moderately correlated with each other (other than Coding and Coding Copy), representing at least partially distinct aspects of the greater concept of PS. Independent variables tended to have small correlations with each other, so composite scores were not created. See Table 2.

Insert Table 2 about here

Statistical Predictors of Processing Speed Performance in the Total Sample

This study utilized multiple regression for the main analyses. The four PS measures were the dependent variables. Independent variables for each analysis included Numbers Forward, Sequences, Picture Locations, Tower, Tower Rule Violations, WCST Perseverative Errors, Rapid Object Naming, and transformed Grooved Pegboard.

The overall equation predicting Symbol Search was significant, adjusted $R^2 = .19$, $F(8, 142) = 5.26$, $p < .001$. Picture Locations, Tower Rule Violations, and Rapid Object Naming were significant predictors of Symbol Search performance. See Table 3 for descriptive data.

Insert Table 3 about here

With regard to Coding, the overall model was significant, adjusted $R^2 = .27$, $F(8, 142) = 7.74$, $p < .001$. Sequences, Numbers Forward, Tower Rule Violations, and Rapid Object Naming were significant predictors. See Table 4 for descriptive data.

Insert Table 4 about here

The overall model predicting Decision Speed performance was significant, adjusted $R^2 = .08$, $F(8, 142) = 2.67$, $p = .009$. Grooved Pegboard and Rapid Object Naming were significant predictors. See Table 5 for descriptive data.

Insert Table 5 about here

Coding Copy data was only collected on a subset of the sample because this measure was added to data collection during the second grant which funded this project. The overall equation was significant, adjusted $R^2 = .38$, $F(8, 48) = 5.36$, $p < .001$. Sequences and Tower rule violations were significant predictors of Coding Copy. Rapid Naming and Perseverative Errors displayed trends. See Table 6 for descriptive data.

Insert Table 6 about here

Comparison of ADHD versus Controls on the Predictor Variables

A MANOVA was run to compare the groups on the predictor variables to determine whether the ADHD group differed from the controls as would be expected from the literature.

Results indicated that there was a significant difference between groups overall, Wilks' *Lambda* = .83, $F(8, 126) = 3.16$, $p = .003$. At the univariate level, groups differed at the $p < .05$ level for Tower rule violations, Sequences, and Picture Locations. They differed at the $p < .10$ level on Perseverative Errors and Rapid Object Naming, displaying a trend. The groups were comparable on Tower, Numbers Forward, and Grooved Pegboard (ps > .10).

Statistical Predictors of Processing Speed Performance in the ADHD Group

Regression analyses then were run exclusively on those with ADHD to determine whether the same predictors would be significant when only using this group. This analysis was not performed on Coding Copy, however, due to the already small N. With regard to Symbol Search, the overall model was significant, adjusted $R^2 = .12$, $F(8, 81) = 2.55$, $p = .016$. Picture Locations was a significant predictor, $\beta = 0.24$, $t(81) = 2.14$, $p = .035$, 95% CI [0.003, 0.08]. Rapid Object Naming ($p = .103$), Perseverative Errors ($p = .136$), Tower rule violations ($p = .547$), Grooved Pegboard ($p = .312$), Sequences ($p = .952$) and Numbers Forward ($p = .242$) were not significant.

In the Coding analysis, the overall model was significant, adjusted $R^2 = .24$, $F(8, 81) = 4.43$, $p < .001$. Regarding the individual predictors, Rapid Object Naming, $\beta = 0.43$, $t(81) = 4.45$, $p < .001$, 95% CI [0.05, 0.12], and Numbers Forward, $\beta = -0.20$, $t(81) = -2.03$, $p = .046$, 95% CI [-0.07, -0.001], were significant; Tower rule violations displayed a trend, $\beta = 0.18$, $t(81) = 1.80$, $p = .075$, 95% CI [-0.05, 0.97]. Tower ($p = .832$), Perseverative Errors ($p = .862$), Grooved Pegboard ($p = .805$), Picture Locations ($p = .406$), and Sequences ($p = .182$) were not significant.

For Decision Speed, the overall model displayed a trend, adjusted $R^2 = .09$, $F(8, 81) = 2.03$, $p = .053$. Regarding the individual predictors, Picture Locations was significant, $\beta = .23$, $t(81) = 2.02$, $p = .047$, 95% CI [0.003, 0.41], but Rapid Object Naming ($p = .139$), Numbers Forward ($p = .895$), Tower rule violations ($p = .195$), Tower ($p = .742$), Perseverative Errors ($p = .613$), Grooved Pegboard ($p = .613$), and Sequences ($p = .182$) were not.

Discussion

Slow processing speed (PS) is a common problem in children with ADHD. Nonetheless, neuropsychological correlates of these deficits are largely unknown. Only two studies were found in this area, and they assessed statistical predictors of PS: Jacobson and colleagues (2011) and Crowe and colleagues (1999). Using their total sample comprised of children with ADHD and controls, Jacobson and colleagues found focused auditory attention/verbal short-term memory, verbal working memory, and spatial working memory predicted Coding performance. Using a healthy adult sample, Crowe and colleagues found graphomotor speed and executive functioning predicted Digit Symbol-Coding, whereas graphomotor speed and incidental learning predicted Symbol Search. Based on these studies, there may be multiple statistical predictors of PS, including focused attention/short-term memory, working memory, motor speed, executive functioning, and, perhaps, naming speed based upon the work of Shanahan and colleagues (2006), that may vary depending upon the component(s) of PS assessed. Given the current state of the literature, we sought to determine the neuropsychological correlates of perceptual, cognitive, and output speed deficits in children with and without ADHD.

In terms of perceptual speed, it was hypothesized that the predictors of Symbol Search would include visual focused attention/short-term memory, inhibition, and naming speed. Analyses supported this hypothesis. During this task, the child is presented with novel visual stimuli that must be stored in visual short-term memory until the item is completed to ensure efficient performance. Inhibition was expected in order for the child to inhibit impulsive responses and draw a line through the yes/no boxes only after ensuring the correct response. Rapid object naming also was expected, given its visual identification and retrieval speed demands. While the zero-order correlation between verbal working memory (Sequences) and Symbol Search was significant, Sequences' slope was not, suggesting Picture Locations was the better predictor of the two short-term/working memory variables when used in combination with other variables. Limited prior research has assessed predictors of Symbol Search performance.

Only one study was found, that by Crowe and colleagues noted above. They did not use the same measures as our study, but they did assess verbal working memory, visual-spatial focused attention/short-term memory, graphomotor speed, and executive functioning, along with incidental learning. They found only graphomotor speed and incidental learning to be predictive of Symbol Search performance, whereas we found visual-spatial focused attention/short-term memory to be predictive, along with other measures they did not utilize. The differences in findings may be related to variations in the measures used, the populations studied (they did not have an ADHD group), as well as the age differences between the samples (adults versus children). Further research in this area is warranted.

In the analysis that was run with only the children with ADHD, visual focused attention/short-term memory remained significant, and rapid naming showed a slight trend, but inhibition lost its significance. Nonetheless, inhibition differed significantly between groups, with ADHD performing worse than controls, and rapid naming showed a trend in this direction. Hence, when only children with ADHD were used, many of those with better functioning on inhibition and rapid naming (i.e., controls) were removed from the analysis, and the resulting score range may have been insufficiently variable to detect effects. In general, poor visual short-term memory/focused attention, and perhaps poor rapid retrieval, may be contributing to/corresponding with the perceptual speed deficits in ADHD. Poor impulse control may affect performance as well given results from the total sample.

It was hypothesized that the predictors of incidental learning/psychomotor speed (Coding) would be verbal focused attention/short-term memory, verbal working memory, fine motor dexterity, executive functioning, and naming speed based upon the work of Jacobson and colleagues (2011) and Crowe and colleagues (1999). Analyses revealed that verbal focused attention/short-term memory, verbal working memory, inhibition, and rapid naming were significant predictors of Coding. While the zero-order correlation between visual-spatial short-term memory (Picture Locations) and Coding was significant, Picture Locations' slope was not, suggesting Sequences was the better predictor of the two short-term/working memory variables when used in combination with other variables. Further, although the zero-order correlation between verbal short-term memory (Numbers Forward) and Coding was not significant, when used in combination with other variables, it does help predict Coding performance. Finding both verbal short-term and working memory to be predictive of Coding performance is consistent with the work of Jacobson et al., 2011, although forward digit span demonstrated a negative relationship whereas verbal working memory (Sequences) demonstrated a positive one in our study. Children with efficient performance may have labeled the symbols, along with the numbers, and held them in working memory while fluidly switching between the number-symbol pairs. Sequences requires some switching, along with working memory, in that one has to say known sequences in reverse order, mentally manipulating the order. The link between working memory and PS is demonstrated across a number of methods, including studies illustrating the importance of working memory in PS performance (Conway, Cowan, Bunting, Therriault & Minkoff, 2002; Jacobson et al., 2011; Woodcock et al., 2001), the impact of PS on working memory capacity (Salthouse, 1996), and the interactions of working memory and attention on PS performance (Nikolas & Nigg, 2013). Rapid object naming may have been predictive of Coding because of its measuring labeling and retrieval speed. Inhibition was predicted to be significant in order for the child to inhibit impulsive responses and to draw the symbol only after ensuring the correct response. Fine motor dexterity, however, was not significant. A measure of graphomotor speed may have been a more fitting predictor of writing the symbols quickly than fine motor dexterity, and such measures have been shown to be predictive of Coding in other studies (Jacobson et al., 2011; Crowe et al.,1999). Greater inclusion of those with dexterity problems may have yielded different results as well, as our ADHD sample had comparable dexterity to controls. Although our short-term and working memory results are similar to the findings of Jacobsen and colleagues, our findings are dissimilar from the work of Crowe and colleagues (1999). They found executive functioning to be a significant predictor in their healthy adult sample, along with graphomotor skill. We did not find all executive functioning to be predictive of Coding when using WCST Perseverative Errors (shift) and Tower (planning), only working memory and inhibition were. Similar to the Symbol Search results, it is possible that differences in cognitive and motor development across age and diagnostic groups impacted the strategies participants used while completing Coding, along with dissimilarities in the measures used across the two projects.

In the analyses that were run only with children with ADHD, verbal focused attention/short-term memory and rapid naming were significant predictors of Coding, and inhibition displayed a trend, but verbal working memory lost significance. Of the predictor variables, inhibition (rule violations) and verbal working memory (Sequences) differed significantly between groups. When only children with ADHD were used, many children with better functioning on these measures (controls) were removed from the analysis, limiting the measures' ability to predict Coding functioning. Verbal focused attention/short-term memory and rapid naming remained significant predictors across the two analyses, suggesting their importance in Coding performance across those with and without attention problems. Therefore, poor verbal short-term memory/focused attention and slow rapid retrieval may correspond with the deficits found in Coding in ADHD. Poor impulse control and verbal working memory may as well given our results from the total sample. Although Coding is often thought of as a visual task, it is clear that verbal processes may contribute to/correspond with performance on this task.

It was hypothesized that the predictors of cognitive speed (Decision Speed) would include verbal focused attention/short-term memory, verbal working memory, inhibition, and naming speed based upon face valid task demands, as literature on this measure in ADHD was not found. Analyses revealed that only fine motor dexterity and rapid naming were significant predictors of decision speed. Given the largely unexpected nature of these findings, it is possible that the independent variables used were not as appropriate for Decision Speed as they were for Symbol Search and Coding. More specifically, although the overall model was significant, the fit was better for the Symbol Search and Coding models than the Decision Speed model. With regard to rapid naming, it seems clear that the ability to rapidly retrieve information is an important predictor across a variety of PS tasks. The relationship between naming and PS also may be due to both types of measures being timed. Fine motor dexterity (Grooved Pegboard) is more difficult to justify, however, given that it seemingly would be more important for the fine motor demands of Coding than Decision Speed, which only requires slashes. Nevertheless, Grooved Pegboard is a timed measure, and the speeded nature of the task might have yielded its relation to Decision Speed in the face of few better predictors being available. In addition, executive functioning measures were not significant, suggesting that these variables are not predictive of semantic decision speed in a mixed sample of children, but there may better predictors than what were included in this study. There was no known published research on the predictors of Decision Speed to draw upon, so our findings may help springboard future research in this area. As Decision Speed had significant zero-order correlations with visual-spatial short-term memory and verbal working memory, further investigation of these variables, along with rapid naming, is warranted in a future study.

Within the ADHD sample, visual attention/short-term memory was significant, and rapid naming and fine motor dexterity were no longer significant. As groups did not differ in dexterity, range issues likely are an insufficient explanation for this effect. What may be the case is that controls and ADHD groups rely on differing processes to make category decisions quickly. Children with ADHD may rely on simple visual attention/short-term memory more heavily to perform Decision Speed, along with other processes that were not assessed. As Decision Speed was not related to either the inattention or hyperactive/impulsive dimension in our subtype study (manuscript submitted for publication), more work on this measure in ADHD is warranted to understand its determinants.

In terms of the predictors of output speed, inhibition and verbal working memory were significant in the total sample, and rapid naming, perseverative errors, and fine motor dexterity displayed a trend. Impulse control and working memory/shift may be important for speeded psychomotor performance (Coding Copy). A child who struggles with executive functioning may respond in a haphazard manner, pay poor attention to detail, and not self-regulate performance well (e.g., have poor pacing and not switch well between symbols), leading to slow and/or inaccurate performance. These results are consistent with past findings on psychomotor slowing in ADHD in that it may be specific to neurodevelopmental impulsivity and less commonly found when comparing other psychiatric groups (i.e., mood, anxiety and oppositional defiant disorders) to controls (Mayes & Calhoun, 2007; Sabri et al., 2016; Walker, Shores, Trollor, Lee & Sachdev, 2000). Alternatively, given that Coding always was administered prior to Coding Copy following the WISC Integrated manual's procedures, it is possible that children with more efficient working memory were able to encode the symbols better during Coding and, thus, perform better on Coding Copy. This hypothesis could be tested in future research by counterbalancing Coding and Coding Copy to negate possible order effects. Furthermore, more research with a larger, more impaired sample is needed to determine whether fine motor dexterity is related to psychomotor speed in ADHD.

Taken together, for perceptual and cognitive PS it is apparent that having faster naming skill correlates with better PS performance. The extent to which a child can visually identify, verbally label, and/or rapidly retrieve stimuli may impact his or her ability to efficiently complete these PS tasks, and/or slow PS may impact rapid lexical retrieval. Inhibition is important for perceptual, psychomotor and incidental learning PS so as to not provide a response prematurely and impulsively. In contrast to these measures which predicted both SS and Coding, visual attention/short-term memory only significantly predicted SS, whereas verbal working memory only significantly predicted Coding, when used in combination with other measures in the total sample. This is consistent with the demands of the tasks, as SS uses novel, non-linguistic stimuli for each item, whereas Coding uses the same stimuli throughout paired with numbers, allowing for verbal mediation. The finding that some of the predictors were lost when only the ADHD group was used suggests the impact that attention control, along with impulse control, may have on PS performance, possibly through its effects on rapid automatized naming and verbal working memory skills. For semantic decision speed, future research should work to identify the relevant skills predictive of this task, as predictors may differ from the other measures of PS assessed. Schrank (2011) theorized the importance of semantic processing (i.e., speed of mental manipulation of stimulus content and making symbolic comparisons), including semantic acquired knowledge, object recognition, and semantic comparisons, for Decision Speed performance, as well as loadings onto short-term memory and cognitive efficiency. This information may help inform a better future model, as we did not utilize measures of semantic acquired knowledge and semantic comparisons, and timed object recognition was significant in our study.

A strength of our study is that it is one of the few experiments to assess the neuropsychological functions that correspond with PS performance, and this differentiation will help the field better understand the ways in which cognitive functioning is related to PS deficits in ADHD. It also is one of the first to show that the various components of PS have distinct as well as shared contributors in children, supporting their characterization as separable aspects of the greater concept of PS. With regard to the study’s limitations, more work is needed to determine whether the identified cognitions are causes or ramifications of PS functioning, or whether the relationships are more indirect and due to unidentified third variables. Although this study can serve as a guide, subsequent research should use a longitudinal design, as ours was correlational in nature. Further, future replication studies should use a larger sample size of ADHD-PI and -C of greater severity to tease out potential subtype effects. Ours was a community sample with milder severity than a clinic sample, which may have contributed to some of our semi-partial correlations being small although significant. In addition, it is clear that the Decision Speed model is insufficient: model fit was worse than the Symbol Search and Coding models (8% of the variance explained versus 19% and 27%, respectively), and the significant predictors were not as expected. Future work should aim to better identify the skills that underlie performance on more complex PS measures. Furthermore, our ADHD sample was comparable to controls in planning (Tower), verbal short-term memory (Numbers Forward), and dexterity (Grooved Pegboard). Although not all children with ADHD are affected in these areas, this may have affected our regression results due to the limited variability for these variables.

The study also did not have orally presented PS measures. Given that individuals with ADHD are more often impaired on visually presented tasks (Brocki et al., 2008; Gau & Chiang, 2013; Martinussen et al., 2005; Martinussen & Tannock, 2006; Sonuga-Barke et al., 2008; Willcutt et al., 2005) than orally presented ones, it would be interesting to compare predictors of visual versus oral PS tasks to better understand how they may differ. Future research should counterbalance administration of Coding and Coding Copy as well, using a larger sample for Coding Copy, as noted above. Future research also should test the participants across multiple, shorter sessions as mental fatigue may have occurred during some of our measures, and we were unable to test its affects due to study design limitations. We were unable to test across multiple sessions as this was a community sample and participants were not paid. They were provided with a free neuropsychological report instead for their participation. Asking parents to take off work repeatedly would have been too much of a burden for no paid compensation.

In conclusion, when predicting PS performance, visual attention/short-term memory may contribute to perceptual speed (Symbol Search), and verbal working memory may contribute to incidental learning/psychomotor processing speed (Coding). Rapid automatized naming and inhibition helped predict both PS tasks, as well as psychomotor speed (Coding Copy), suggesting rapidly visually identifying and retrieving stimuli, as well as inhibiting incorrect responses, are important for efficient task completion in general. Rapid naming also predicted semantic decision speed (Decision Speed), although more work is needed on predictors of this aspect of cognitive PS. Thus, PS deficits in children with ADHD may be related to their rapid automatized naming, impulse control, and short-term memory/working memory deficits.

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Table 1

Participant Demographic Variables

Variables	Controls	ADHD	*df*	X^2	*p*-values
Gender (% Male)	44.26	56.70	1	2.24	.13
Race (% Caucasian)	90.16	90.00	4	1.66	.80
	M(SD)	*M(SD)*	*df*	*F*	*p*-values
Age	9.74(1.38)	9.62(1.38)	1, 149	0.26	.61
	[9.39 - 10.09]	[9.33 - 9.91]			
Maternal Education	5.61(1.02)	5.46 (1.41)	1, 140	0.50	.49
	[5.34 - 5.88]	[5.15 – 5.77]			
VCI	104.87(11.60)	100.21(14.00)	1, 149	4.60	.034
	[101.90 - 107.84]	[97.28 - 103.14]			
BASC-2 PRS	48.66(9.39)	67.02(6.48)	1, 149	202.33	<.001
Attention Problems	[46.25 - 51.06]	[65.66 - 68.38]			
BASC-2 PRS	45.36(8.47)	61.09(13.14)	1, 149	68.11	<.001
Hyperactivity	[43.19 - 47.53]	[58.34 – 63.84]			
BASC-2 TRS	46.30(8.70)	61.28(9.40)	1, 141	91.64	<.001
Attention Problems	[43.97 - 48.63]	[59.27 – 63.28]			
BASC-2 TRS	45.50(7.32)	57.82(13.23)	1, 141	39.56	<.001
Hyperactivity	[43.54 - 47.60]	[55.00 – 60.64]			

Note. Maternal Education: 5 = some college; VCI: Verbal Comprehension Index; BASC-2 PRS/TRS: Behavior Assessment System for Children, 2nd ed. Parent or Teacher Rating Scales; *** $p < .001$; 95% confidence intervals for the means are presented in brackets.

Table 2

Correlations Between Dependent and Independent Variables

	Variables	1	2	3	4	5	6	7	8	9	10
1.	Coding	---									
2.	Symbol Search	.46**	---								
3.	Decision Speed	.43**	.39**	---							
4.	Coding Copy	.73**	.16	.31*	---						
5.	Grooved Pegboard	<.01	.10	.22**	.12	---					
6.	Numbers Forward	-.05	.02	<.01	.12	-.01	---				
7.	Picture Locations	.21*	.32**	.22**	.12	.11	-.01	---			
8.	Sequences	.27**	.25**	.19*	.37**	.01	.22**	.30**	---		
9.	Tower	.06	-.05	<.01	-.05	.08	.12	.04	.03	---	
10.	Rapid Obj Naming	.45**	.27**	.21**	.38**	-.03	.09	.20*	.18*	.07	---
11.	Tower RV	.27**	.01	.06	.51**	.03	.13	.13	.16	.34**	.23

Note. Rapid Obj Naming = Rapid Object Naming; Tower RV = Tower Rule Violations; $*p < .05$; $**p < .01$.

Table 3

Multiple Linear Regression Predicting Symbol Search Performance

Predictor	*β*	*t-values*	*p-values*	Semi-partial Correlations^2	95% CI
Sequences	0.11	1.39	.170	0.01	[-0.01 - 0.05]
Numbers Forward	-0.05	-0.65	.510	0.00	[-0.04 - 0.02]
Tower rule violations	0.20	2.50	.013	0.04	[0.12 - 0.97]
Rapid Object Naming	0.19	2.51	.013	0.04	[-0.01 - 0.07]
Picture Locations	0.18	2.23	.027	0.03	[0.004 - 0.06]
Grooved Pegboard	0.06	0.76	.450	0.01	[0.00 - 0.00]
Tower	-0.14	-1.81	.073	0.02	[-0.07 - 0.003]
Perseverative Errors	0.13	1.69	.094	0.02	[-0.003 - 0.04]

Table 4

Multiple Linear Regression Predicting Coding Performance

Predictor	β	*t-values*	*p-values*	Semi-partial Correlations^2	95% CI
Sequences	0.19	2.43	.016	0.04	[0.01 - 0.06]
Numbers Forward	-0.15	-2.04	.043	0.03	[-0.06 - 0.001]
Tower rule violations	0.22	2.93	.004	0.06	[0.19 - 0.98]
Rapid Object Naming	0.40	5.52	<.001	0.18	[0.05 - 0.11]
Picture Locations	0.04	0.49	.624	0.00	[-0.02 - 0.03]
Grooved Pegboard	0.02	0.30	.770	0.00	[0.000 - 0.000]
Tower	-0.04	-0.48	.630	0.00	[-0.04 - 0.02]
Perseverative Errors	-0.001	-0.02	.990	0.00	[-0.02 - 0.02]

Table 5

Multiple Linear Regression Predicting Decision Speed Performance

Predictor	*β*	*t-values*	*p-values*	Semi-partial Correlations^2	95% CI
Sequences	0.12	1.43	.154	0.01	[-0.04 - 0.28]
Numbers Forward	-0.03	-0.41	.681	0.00	[-0.18 - 0.12]
Tower rule violations	0.02	0.23	.819	0.00	[-1.97 - 2.28]
Rapid Object Naming	0.18	2.16	.033	0.03	[0.02 - 0.35]
Picture Locations	0.12	1.41	.160	0.01	[-0.04 - 0.25]
Grooved Pegboard	0.19	2.37	.019	0.04	[0.000 - 0.001]
Tower	-0.04	-0.48	.635	0.00	[-0.22 - 0.13]
Perseverative Errors	0.02	0.28	.777	0.00	[-0.10 - 0.13]

Table 6

Multiple Linear Regression Predicting Coding Copy Performance

Predictor	*β*	*t-values*	*p-values*	Semi-partial Correlations^2	95% CI
Sequences	0.31	2.07	.044	0.12	[0.001 - 0.078]
Numbers Forward	0.05	0.43	.666	0.00	[-0.031 - 0.048]
Tower rule violations	0.41	3.42	.001	0.25	[0.40 – 1.53]
Rapid Object Naming	0.23	1.96	.056	0.04	[-0.01 – 0.08]
Picture Locations	-0.06	-0.46	.651	0.00	[-0.042 – 0.027]
Grooved Pegboard	0.19	1.72	.092	0.04	[0.003 - 0.041]
Tower	-0.16	-1.46	.150	0.07	[-0.071 – 0.011]
Perseverative Errors	-0.24	-1.96	.054	0.07	[-0.061 - 0.001]