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A multiple deficit model of Reading Disability and Attention-Deficit/Hyperactivity Disorder: Searching for shared cognitive deficits

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Abstract

Background—This study tests a multiple cognitive deficit model of Reading Disability (RD), Attention-Deficit/Hyperactivity Disorder (ADHD), and their comorbidity.

Methods—A structural equation model (SEM) of multiple cognitive risk factors and symptom outcome variables was constructed. The model included phonological awareness as a unique predictor of RD and response inhibition as a unique predictor of ADHD. Processing speed, naming speed, and verbal working memory were modeled as potential shared cognitive deficits.

Results—Model fit indices from the SEM indicated satisfactory fit. Closer inspection of the path weights revealed that processing speed was the only cognitive variable with significant unique relationships to RD and ADHD dimensions, particularly inattention. Moreover, the significant correlation between reading and inattention was reduced to nonsignificance when processing speed was included in the model, suggesting that processing speed primarily accounted for the phenotypic correlation (or comorbidity) between reading and inattention.

Conclusions—This study illustrates the power of a multiple deficit approach to complex developmental disorders and psychopathologies, particularly for exploring comorbidities. The

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theoretical role of processing speed in the developmental pathways of RD and ADHD and directions for future research are discussed.

Keywords

Reading Disability; Attention-Deficit/Hyperactivity Disorder; Processing Speed; Comorbidity; Multiple Deficit Model

Reading Disability (RD) and Attention-Deficit/Hyperactivity Disorder (ADHD) are both complex neurobehavioral disorders affecting approximately 5% of children in the population (DSM-IV-TR, APA, 2000). RD and ADHD co-occur more frequently than would be expected by chance (estimates of 25% – 40% in both disorders) (Willcutt & Pennington, 2000). This study presents a multiple cognitive deficit model of RD, ADHD, and their comorbidity.

Multiple deficit models (Pennington, 2006) propose a multifactorial etiology for complex developmental and psychiatric disorders where the constellation of risk and protective factors determines outcome. Comorbidity is to be expected when risk factors are shared between disorders. Despite increasing theoretical and empirical support for multiple deficit models, there has been little research directly evaluating whether such models can account for comorbidity.

Neuropsychological studies of RD, ADHD, and other disorders have primarily focused on identifying cognitive deficits specific to a given disorder. For RD, the deficits identified include phonological awareness (Vellutino, Fletcher, Snowling, & Scanlon, 2004), other aspects of speech and language processing (Bishop & Adams, 1990), naming speed (Compton, Olson, DeFries, & Pennington, 2002; Purvis & Tannock, 2000; Semrud-Clikeman, Guy, Griffin, & Hynd, 2000; Wolf & Bowers, 1999), processing speed (Caravolas, Volin, & Hulme, 2005; Catts, Gillispie, Leonard, Kail, & Miller, 2002; Kail & Hall, 1994; Shanahan et al., 2006; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005), and verbal working memory (Rucklidge & Tannock, 2002; Swanson, Mink, & Bocian, 1999; Willcutt et al., 2001; Willcutt, Pennington et al., 2005).

In the case of ADHD, there is less agreement about neuropsychological deficits. One candidate that has received considerable research attention is executive functioning, most notably response inhibition (Barkley, 1997), but also organization/planning and working memory (Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). In addition to executive functioning impairments, children with ADHD demonstrate cognitive weaknesses in domains such as processing speed (Shanahan et al., 2006) and naming speed (Rucklidge & Tannock, 2002).

Taken together, these studies identify specific cognitive deficits in RD and ADHD as well as potential shared deficits in processing speed, naming speed, and verbal working memory. Of these deficits, processing speed has also emerged as a candidate shared deficit from studies analyzing combined samples of children with RD and ADHD (Shanahan et al., 2006; Willcutt, Pennington et al., 2005).

The current study has two specific aims. First, we test a multiple cognitive deficit model .of RD and ADHD using structural equation modeling (SEM). Secondly, we test the multiple deficit models of RD and ADHD simultaneously to determine if any of the cognitive dimensions are predictive of both RD and ADHD dimensions. If so, we will explore the extent to which the cognitive factor(s) can account for the observed relationship between the RD and ADHD symptom dimensions. We predict that phonological awareness will be a unique predictor of RD, response inhibition will be a unique predictor of ADHD, and processing speed, naming speed and/or verbal working memory will be potential shared cognitive risk factors.

Method

Participants

Participants included a total of 614 children and adolescents (386 males and 228 females), 8–16 years. The participants were recruited as part of the Colorado Learning Disabilities Research Center (CLDRC) twin study, which is an ongoing population-based study of the etiology of RD and ADHD, described elsewhere (DeFries et al., 1997). In brief, permission was sought from parents of all twin pairs between 8–18 years in 22 local school districts to review school records for evidence of reading problems. Parents and teachers were also asked to provide *DSM-IV* ADHD symptom ratings on the Disruptive Behavior Rating Scale (DBRS: Barkley & Murphy, 1998). If either member of a twin pair had a history of reading difficulties or met screening criteria for ADHD, the pair and any siblings were invited to participate in the full study. A comparison group of control twins was selected from the overall sample of pairs who did not meet the screening criteria for RD or ADHD. Inclusion criteria included the following: (1) English-speaking home, (2) no evidence of neurological problems or history of brain injury, (3) no uncorrected visual or auditory deficits, and (4) no known genetic disorders or syndromes. Additional criteria specific to this study were: (1) a Full Scale IQ score of at least 70 on the WISC-R (Wechsler, 1974) and (2) age range between 8–16 years to minimize missing data due to test version differences associated with age. To preserve the statistical assumption of independence, one twin was randomly chosen from the twin pair, regardless of diagnostic status, to be included in the analyses for this study. Further details regarding the sample demographics are provided in the Appendix.

Procedures

The study protocol was approved by the Institutional Review Boards at the University of Colorado, Boulder and the University of Denver. After obtaining informed consent at both institutions, two testing sessions were completed at the University of Colorado, and a third testing session was scheduled approximately one month later at the University of Denver. Participants taking psychostimulant medication were asked to withhold medication for 24 hours prior to each testing session.

Measures

Detailed descriptions of the battery of tasks administered have been published in previous reports (Gayán & Olson, 2001; Willcutt, Pennington et al., 2005). As a result, Table 1 is limited to a brief description of the tasks grouped according to construct along with a basic definition of each cognitive construct. All models utilized continuously distributed scores of the cognitive and symptom dimensions. Dimensional Inattention and Hyperactivity-Impulsivity scores were calculated for parent and teacher raters by averaging the ratings on the nine DSM-IV inattention or hyperactivity-impulsivity items on the DBRS.

It is important to highlight a few features of this battery. First, the PIAT Spelling task is listed under the Single Word Reading construct because it is essentially a single word reading task involving spelling recognition, not production. Secondly, the constructs Processing Speed and Naming Speed are defined based on a previous exploratory factor analysis which indicated two separate factors, one composed of rapid naming tests and one composed of perceptual speed and symbolic processing tasks (Shanahan et al., 2006).

Data Cleaning & Analyses

Raw scores from the tasks in Table 1 were used in the analyses and were reflected, when necessary, so that higher scores were associated with better performance. Outliers were winsorized to 4 SD and variables with extreme violations of normality (Kline, 2005) were log transformed. We controlled for possible linear and nonlinear effects of age by regressing the raw scores on age and age squared and saving the unstandardized residuals for further analysis.

SEM analyses were run with AMOS 16.0 using maximum likelihood estimation and imputation of missing data using full information maximum likelihood estimation.

For the cognitive indicators, missing data was minimal (0–10% missing). For the symptom dimensions, missing data was minimal for the indicators of the Single Word Reading factor (<1% missing). For the ADHD symptom dimensions, it was more common to have missing data because information was gathered from multiple raters: mothers (7% missing), fathers (23% missing), and teachers (26% missing).

Results

Measurement Models

For the CFAs of the symptom and cognitive dimensions, we used the following general guidelines for reasonable model fit: χ^2/df <3, Comparative Fit Index (CFI) >.90, Root Mean Square Error of Approximation (RMSEA) <.08 (Kline, 2005).

Symptom Dimensions—Our measurement model for the symptom dimensions of RD and ADHD is displayed in Figure 1. The latent factors represent continuously distributed symptom dimensions underlying the diagnostic categories of RD and ADHD. We allowed the errors to correlate for the same rater across the Inattention and Hyperactivity-Impulsivity dimensions. Our proposed model fit the data well, χ^2 (21, N=614) = 48.69, p <.01, χ^2/df = 2.32, CFI = .99, RMSEA = .046 (90% Confidence Interval [CI] = .029 – .064) and was accepted without further modification.

Cognitive Dimensions—Our measurement model for the continuously distributed cognitive dimensions is displayed in Figure 2. In this model, we allowed errors from subtests of the same measure to correlate in order to allow for test-specific factors (e.g., directions and administration) and/or child factors (e.g., fatigue). For the RAN tasks, only the most strongly associated error terms were allowed to correlate, in this case between RAN numbers and letters, because the other RAN tasks had negligible residual associations. Our proposed model fit the data well, χ^2 (92, N=614) = 242.56, p <.001, χ^2/df = 2.64, CFI = .96, RMSEA = .052 (90% CI = .044 – .060). As can be seen in Figure 2, the strongest correlations among the latent factors were between Naming Speed and Processing Speed (r = .74) and Phonological Awareness and Verbal Working Memory (r = .73). We tested two alternative models in which these two dimensions were collapsed into one factor. However, in both cases, the alternative models resulted in a significant decrease in model fit. As a result, we accepted the model depicted in Figure 2.

Multiple Deficit Model

The combined multiple deficit models for Single Word Reading, Inattention, and Hyperactivity-Impulsivity are shown in Figure 3. The measurement components of these models are not shown in order to simplify the figure. This proposed model fit the data adequately, χ^2 (245, N=614) = 584.32, p <.001, χ^2/df = 2.39, CFI = .96, RMSEA = .048 (90% CI = .043–.052).

Of the three modeled shared cognitive deficits (i.e., Processing Speed, Verbal Working Memory, and Naming Speed), only Processing Speed significantly predicted Single Word Reading, Inattention, and Hyperactivity-Impulsivity. Naming Speed significantly predicted Single Word Reading and Hyperactivity-Impulsivity, but this latter effect was in the unexpected direction (i.e., faster Naming Speed associated with more Hyperactivity-Impulsivity symptoms). Verbal Working Memory did not uniquely predict any of the symptom dimensions. Overall, this model reduced the zero order correlation between Single Word Reading and Inattention from $r = .42$, $p < .001$ to $r = .10$, $p = .11$, a reduction that was attributable to the shared association with Processing Speed. The model also reduced the zero order correlation between Single Word Reading and Hyperactivity-Impulsivity from $r = .22$, $p < .001$ to $r = .08$, $p = .17$, which was attributable to both Processing Speed and Naming Speed.

Hierarchical Regression in SEM

The previous multiple deficit analysis was potentially susceptible to instability in the regression coefficients due to strong correlations between some of the cognitive indicators. To address this problem, we conducted hierarchical SEM analyses, which allowed the latent factors to be entered into the multiple deficit model in pre-specified orders, rather than simultaneously (De Jong, 2009). This analysis tested for the effect of specific cognitive factors after controlling for previously entered variables. We focused on variable orders that would disentangle the common and unique effects of the two most highly correlated pairs of latent variables, Naming Speed-Processing Speed and Phonological Awareness-Verbal Working Memory. In the chosen variable orders, each variable was entered last and the highly correlated pairs were entered first and last with swapped orders (i.e., first and second vs. second and first, fourth and fifth vs. fifth and fourth). Results are presented in Table 2 below. The first line of each order block shows the contribution of each cognitive factor before any of the other factors are controlled, meaning that the beta estimate reflects predictive variance that is both shared with other cognitive indicators and unique to that cognitive factor. The last line of each order block shows the unique effect of each cognitive factor after controlling for all other variables in the model. Looking across variable orders, it is clear that only Processing Speed uniquely and consistently predicts at least two of the symptom dimensions, Single Word Reading and Inattention, in the predicted direction.

These analyses also highlighted some complexities associated with variable order which were not evident from the initial multiple deficit analyses. For example, the relationship of Naming Speed and Processing Speed with Hyperactivity-Impulsivity is complex and changes depending on the order of entry of the variables, suggesting that the unique relationships are not robust. The association of Verbal Working Memory with the symptom dimensions is also complex. Phonological Awareness accounts for a large part of its relationship with Single Word Reading, whereas a combination of overlapping variance with Naming Speed, Processing Speed, and Inhibition accounts for its relationship with Inattention and Hyperactivity-Impulsivity. Thus, when Verbal Working Memory is entered into the equation last, it does not contribute any unique predictive power to the symptom dimensions.

Exploratory Analyses

Developmental differences—Because of the wide age range of the study participants, we compared the fit of the multiple deficit model in participants aged 8–10 (N=358) versus 11–16 (N=256). Raw scores were age residualized within age group for this analysis. Because these were exploratory analyses with multiple tests, an alpha level of $p < .01$ was set. The CFA of the symptom model showed no significant age differences in the path weights or covariance structure. The CFA of the cognitive dimensions showed age differences in a few factor loadings (pig latin, phoneme deletion, SSRT, Gordon distractibility commissions decreased in older group, Colorado perceptual speed increased in older group) and one covariance between Phonological Awareness and Processing Speed (r =.40 in younger group, r =.60 in older group). Allowing for these age differences in the cognitive CFA, there was no further evidence of age differences in the regression weights from the cognitive dimensions to the symptom dimensions in the multiple deficit model.

Alphanumeric Naming speed—A distinction in the naming speed literature is often drawn between alphanumeric and non-alphanumeric naming (van den Bos, Zijlstra, & lutje Spelberg, 2002), with alphanumeric naming often being more strongly associated with reading. We ran a follow-up analysis of the multiple deficit model with naming speed defined by only the alphanumeric indicators RAN letters and RAN numbers. Model fit was comparable to the initial model and the pattern of results remained substantially the same. Alphanumeric Naming Speed predicted Single Word Reading with a similar magnitude as before (β=.10, p <.01), and the paths to Inattention and Hyperactivity-Impulsivity were non-significant. Processing Speed significantly predicted Single Word Reading (β=.27, p <.001) and Inattention (β=.31, p <.001), as before, but not Hyperactivity-Impulsivity, consistent with the findings of the hierarchical models that this latter path weight was unstable.

Reading accuracy: Because the Single Word Reading factor included a timed reading test, we selected the purest untimed single word reading indicator, PIAT Reading Recognition, to test whether Processing Speed remained a significant predictor of untimed reading. Processing Speed continued to predict untimed reading, albeit decreasing from β=.25, p<.001 to β=.18, p <.01, and associations with Inattention and Hyperactivity-Impulsivity were unchanged. The only substantive change in the pattern of results was that Naming Speed was no longer a significant predictor of PIAT Reading Recognition (β=.09, p =.10). This result may reflect the fact that Naming Speed is often more strongly associated with reading fluency than reading accuracy.

Controlling for IQ: To ensure that the overall pattern of results in the multiple deficit model was not due to differences in full-scale IQ between children, we residualized the cognitive factor indicators using a full-scale IQ proxy consisting of the verbal and performance IQ subtests that were not measures of verbal working memory or processing speed (i.e., excluded arithmetic, coding, and digit span). The pattern of results depicted in the multiple deficit model of Figure 3 remained the same, so the association of Processing Speed with Single Word Reading and Inattention is independent of IQ.

Rapid Symbolic Processing: To investigate the role of letter strings in the Processing Speed construct, we dropped the Colorado Perceptual Speed indicator and reran the multiple deficit analyses. We found that Processing Speed no longer significantly predicted Single Word Reading (β=.008, p =*ns*) and Naming Speed became a stronger predictor of Single Word Reading (β=.25, p <.001). So, without this indicator, the shared variance defining the latent Processing Speed trait apparently shifted away from what we call rapid symbol processing, and the new Processing Speed latent trait no longer accounted for the relation between Single Word Reading and Inattention.

Overall, these results provide evidence that processing speed, particularly symbolic processing speed, is associated with reading and inattention symptom dimensions and accounts for their correlation, a result that was robust to various analytic approaches, including hierarchical analysis, age group modeling, and control of full-scale IQ.

Discussion

This study tested a multiple cognitive deficit model of RD, ADHD, and their comorbidity. The model included phonological awareness as a unique predictor of RD, response inhibition as a unique predictor of ADHD, and processing speed, naming speed, and verbal working memory as potential shared cognitive deficits.

Consistent with the multiple deficit model (Pennington, 2006), each symptom dimension had multiple predictors, some specific and some shared. The multiple deficit model of the RD symptom dimension included two unique predictors, phonological awareness and naming speed, and one shared predictor with the ADHD dimensions, processing speed. Together, these three predictors accounted for 75% of the variance in the RD symptom dimension. The multiple deficit model of the ADHD symptom dimensions included one unique predictor, response inhibition, and one shared predictor, processing speed. Together, these two predictors accounted for 35% of the variance in Inattention and 16% in Hyperactivity-Impulsivity.

From the description above, it is clear that the shared predictor in the multiple deficit models of RD and ADHD symptom dimensions was processing speed. Among the three cognitive variables modeled as potential shared predictors (i.e., naming speed, verbal working memory, and processing speed), only processing speed demonstrated unique and consistent relations with RD and ADHD symptom dimensions, in this case primarily Inattention. Importantly, the residual correlation between RD and Inattention was reduced to non-significance in the multiple deficit model, meaning that the only shared predictor, processing speed, accounted for their correlation (or comorbidity.) This is the most novel and important result of the current study because it supports the key prediction of the multiple deficit model (Pennington, 2006) for explaining comorbidity, namely that comorbidity is attributable to a shared cognitive deficit (or deficits). The fact that processing speed was more strongly associated with reading and inattention, compared to hyperactivity-impulsivity is consistent with the finding that reading and inattention are more closely related both phenotypically (Willcutt & Pennington, 2000) and genetically (Willcutt, Pennington, Olson, & DeFries, 2007).

Theoretically, the role of processing speed in both RD and ADHD is currently not well understood, although speed variables have featured in theoretical conceptualizations of both disorders. Focusing on RD, Wolf & Bowers' (1999) proposal of a second non-phonological factor contributing to reading skill that involves automaticity or efficiency of processing does fit with the results of the current study, with the qualification that it remains unclear whether this factor is better tapped by symbol processing speed, naming speed, or both. Our results showing that processing speed accounts for unique variance in reading are consistent with those of Catts et al. (2002), but not Bonifacci & Snowling (2008). The differences between these two studies may be due to either the processing speed measures utilized or the IQ levels of the RD groups. In Catts et al. (2002), there was a significant group difference in mean full-scale IQ favoring controls, whereas in Bonifacci & Snowling (2008), the groups did not differ significantly on IQ. In terms of tasks, Catts et al. (2002) used a battery of 10 tasks across content domains, including linguistic content, whereas Bonifacci & Snowling (2008) used a battery of four tasks that included simple reaction time, choice reaction time, and number and symbol scanning. In the current study, we found a unique relation between processing speed and reading accuracy, even after controlling for IQ, but this relation depended on the inclusion of symbol processing tasks.

Clearly, more work is needed to define what aspects of processing speed uniquely relate to the development of reading skill (for a recent example see Vaessen, Gerretsen, & Blomert, 2009). What should be noted here is that a simple phonological model of reading skill does not provide a straightforward account of how reading automaticity is attained or what cognitive factors contribute to it. More work is needed to define the distinctions between naming speed and symbolic processing speed and the role of each in reading acquisition and fluency.

Theoretical conceptualizations of ADHD have also implicated processing speed, for instance, by way of energetic and activation factors (e.g., Sergeant, 2000; Sergeant, 2005). In this formulation, processing speed may be overly fast or overly slow in ADHD because the child is unable to appropriately regulate their energetic state. Another ADHD theoretical conceptualization links processing speed to “sluggish cognitive tempo” (Hartman, Willcutt, Rhee, & Pennington, 2004), but the specific mechanisms through which processing speed may increase risk for ADHD or specific ADHD subtypes remains under-specified and deserves further inquiry.

One surprising finding from the multiple deficit model was that Verbal Working Memory did not uniquely predict Single Word Reading or ADHD dimensions, which is likely attributable to the broad constellation of cognitive risk factors for RD and ADHD that were included in the model. The hierarchical regression analyses highlighted that Verbal Working Memory was a significant predictor of RD and ADHD dimensions, consistent with previous literature, but only because of shared variance with other cognitive indicators (i.e., it was a predictor when entered first in the model, but not when entered last). These results highlight the need to include a comprehensive battery of cognitive indicators when examining multiple deficit models of disorders. Otherwise, variance that is shared with an omitted third variable may be misattributed to a specific cognitive indicator.

The results of this study should be interpreted in the context of its limitations. With regard to the multiple deficit model, the cognitive constructs included were not all-inclusive of previously identified predictors of RD and ADHD. Future analyses might include measures of speech and language processing and additional executive functions. Similarly, the symptom dimensions did not include measures of reading fluency, only a timed measure of reading accuracy. This focus on reading accuracy may limit the generalizability of the findings to more transparent orthographies than English. Replication of these results in an independent sample will be crucial because this sample is partially overlapping with samples from previous papers documenting processing speed as a potential shared cognitive deficit (Shanahan et al., 2006; Willcutt, Pennington et al., 2005). In terms of interpretation of the results, these analyses are ultimately ambiguous regarding whether Processing Speed plays a causal role in both RD and ADHD. It could be that processing speed deficits are a result of having RD or ADHD, rather than a cause. Or, processing speed may play a causal role in one disorder but be a correlate in the other disorder. Further studies with longitudinal samples will be necessary to address this issue. Such longitudinal studies should also extend into younger age ranges than covered by this study to assess the early developmental processes unfolding in RD and ADHD.

Despite these limitations, the novel contribution of these analyses is the explicit testing of a multiple deficit model of RD and ADHD that identified processing speed as a candidate shared cognitive deficit that explains their comorbidity. A recent multivariate behavioral genetic study in this sample showed that processing speed accounts for the genetic correlation between RD and ADHD (Willcutt et al., in press), so processing speed may be a useful phenotype for identifying specific genetic risk factors shared by RD and ADHD. Further exploration of the role of this cognitive skill in the etiology of both disorders and their comorbidity is warranted.

Key Points

- A multiple deficit model of neurodevelopmental disorders holds that a given disorder is produced by a combination of specific and shared deficits, with shared deficits accounting for the comorbidity between disorders.
- We tested a multiple deficit model of RD and ADHD and found that phonological awareness and naming speed were specific predictors of single word reading, inhibition was a specific predictor of ADHD dimensions (inattention and hyperactivity-impulsivity), and processing speed was a shared predictor of both reading and inattention.
- The association of processing speed with reading and inattention primarily accounted for the correlation (or comorbidity) between these dimensions.
- This study illustrates the power of a multiple deficit approach for understanding comorbidities among neurodevelopmental disorders.

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Abbreviations

RD	Reading Disability
ADHD	Attention-Deficit/Hyperactivity Disorder
CFA	Confirmatory Factor Analysis
SEM	Structural Equation Model

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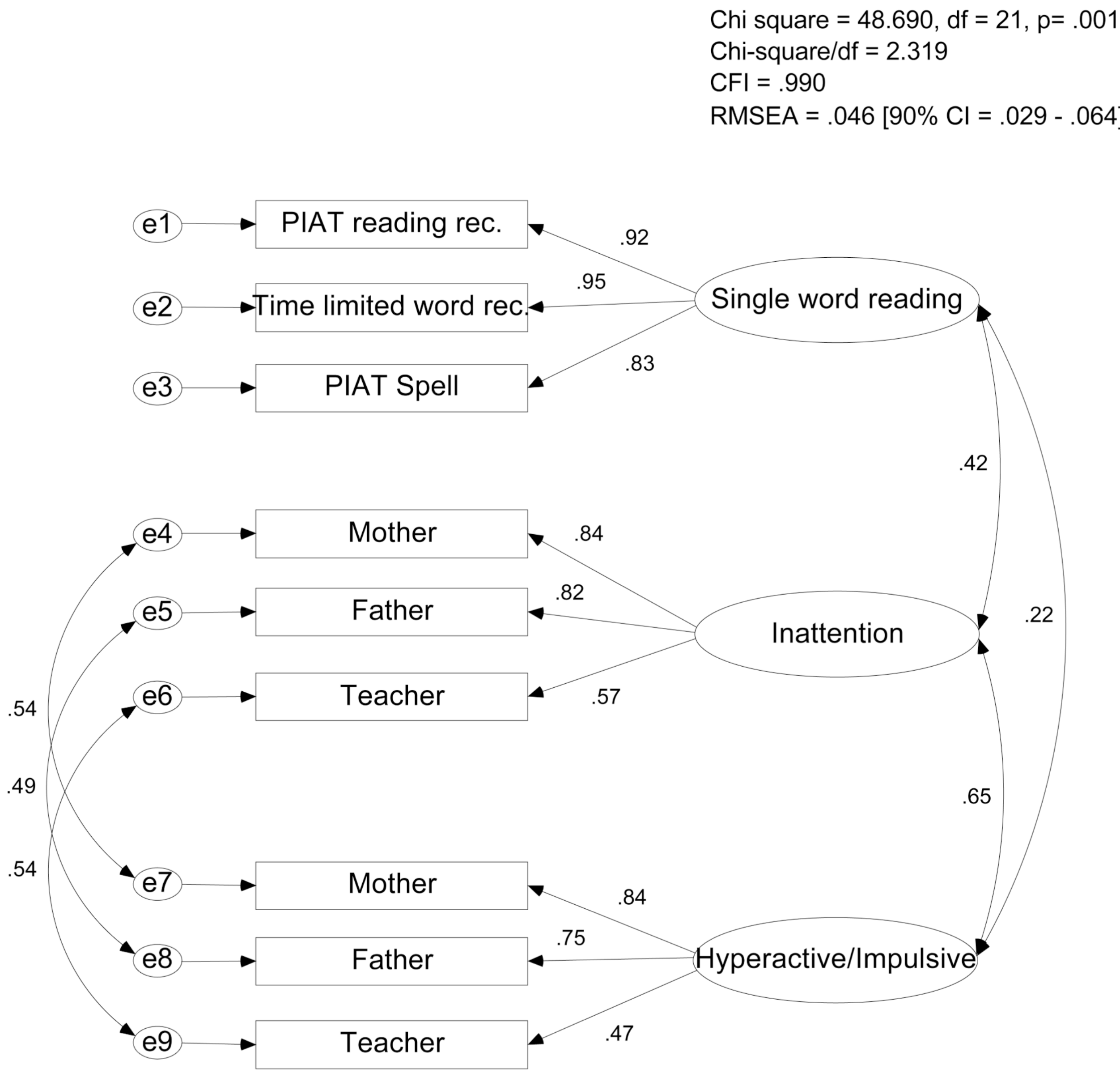

Figure 1.

Measurement model for the continuously distributed symptom dimensions underlying RD and ADHD. Standardized path estimates and correlation coefficients are depicted by single-headed and double-headed arrows, respectively.

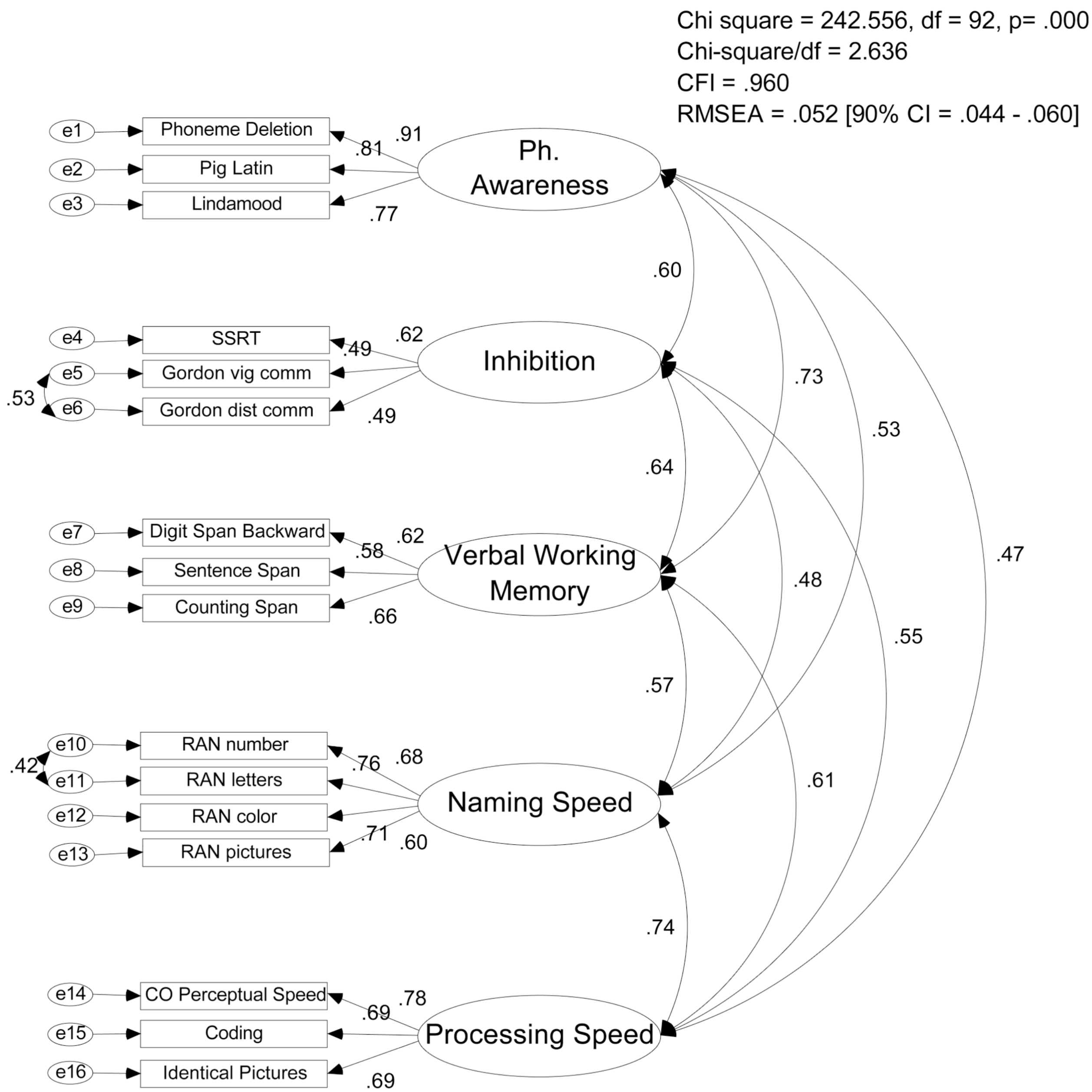

Figure 2.
Measurement model for the continuously distributed cognitive dimensions of RD and ADHD. Standardized path estimates and correlation coefficients are depicted by single-headed and double-headed arrows, respectively.

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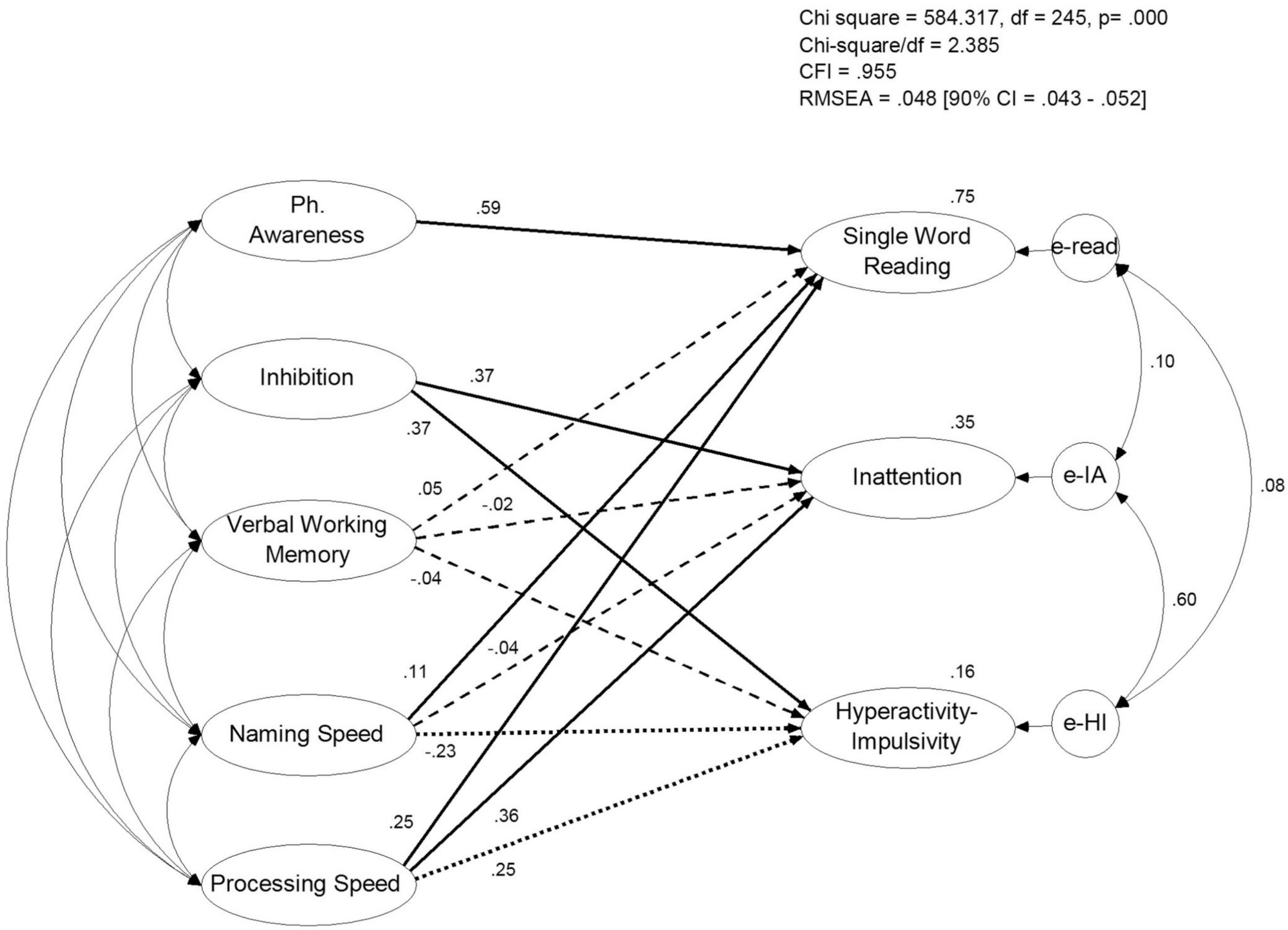

Figure 3.
SEM model predicting continuously distributed RD and ADHD symptom dimensions from cognitive dimensions. The measurement components of the model are not depicted for simplification of the figure. Standardized path estimates and correlation coefficients are depicted by single-headed and double-headed arrows, respectively. Numbers above the endogenous latent variables indicate the percent of variance accounted for in each latent variable. Solid lines indicate paths significant at *p*<.05. Dashed lines indicate nonsignificant paths. Dotted lines indicate paths that were significant in this model, but showed inconsistent statistical evidence across different analytic strategies.

Table 1

Indicators for the symptom and cognitive dimensions. Basic definitions of the cognitive dimensions are provided for reference.

Measure	Reliability	Reference	Brief Description
Symptom Dimensions			
Single Word Reading			
PIAT Reading Recognition	.89	(Dunn & Markwardt, 1970)	Read single words that increase in semantic and phonetic difficulty.
PIAT Spelling	.65	(Dunn & Markwardt, 1970)	Select the correct spelling of a spoken word from 4 phonologically similar options.
Timed Oral Reading	.89	(Olson, Wise, Conners, Rack, & Fulker, 1989)	Read aloud single words within 2 seconds of their presentation.
ADHD Inattentive symptoms			
Disruptive Behavior Rating Scale	.71 – .94[a]	(Barkley & Murphy, 1998)	Mother, father, teacher ratings of DSM-IV inattention symptoms on a 0–3 scale with anchors *not at all*, *sometimes*, *often*, and *very often*.
ADHD Hyperactive/Impulsive symptoms			
Disruptive Behavior Rating Scale	.66 – .93[a]	(Barkley & Murphy, 1998)	Mother, father, teacher ratings of DSM-IV hyperactivity - impulsivity symptoms on a 0–3 scale with anchors *not at all, sometimes, often,* and *very often*.
Cognitive Dimensions			
Phonological Awareness	-Oral language skill characterized by the ability to dissect a spoken word into smaller sound units, the smallest of which are phonemes.		
Phoneme Deletion	.80	(Olson, Forsberg, Wise, & Rack, 1994)	Remove a phoneme from a word or nonword and say the resulting word.
Lindamood Auditory Conceptualization Test	.67	(Lindamood & Lindamood, 1971)	Use colored blocks to represent phonemes in sound sequences and nonwords.
Pig Latin	.78	(Olson et al., 1989)	Move first phoneme of a spoken word to the end of the word, then add “ay.”
Inhibition	-The ability to stop a prepotent motor response when specific conditions are present.		
Gordon Commission errors	.72 – .85	(Gordon, 1983)	Total responses to incorrect targets during a continuous performance test (press a button every time you see a 1 followed by a 9) with and without distracters.
Stop Signal Reaction Time (SSRT)	.90 – .96	(Logan, Schachar, & Tannock, 1997)	Computerized measure of stop signal reaction time, a measure of inhibitory control.
Verbal Working Memory	-The ability to hold verbal information in mind while simultaneously performing a manipulation or a separate cognitive task.		
WISC-R Digit Span Backward	.78	(Wechsler, 1974)	Repeat strings of numbers of increasing length in reverse order.
Sentence Span	.65 –.71	(Kuntsi, Stevenson, Oosterlaan, & Sonuga-Barke, 2001; Siegel & Ryan, 1989)	Provide the last word for a set of simple sentences read by the examiner, then reproduce these words in order after the set is completed.
Counting Span	.55 –.67	(Case, Kurland, & Goldberg, 1982; Kuntsi et al., 2001)	Count aloud the number of yellow dots on a series of cards. At the end of each set state in order the number of yellow dots that appeared on each card in the set.
Naming Speed	-The ability to rapidly recognize and name a restricted set of well-known visual items presented in a series.		
RAN Colors	.82	(Denckla & Rudel, 1974, 1976)	Name colors as quickly as possible for 15 seconds.

Measure	Reliability	Reference	Brief Description
RAN Numbers	.86	(Denckla & Rudel, 1974, 1976)	Name numbers as quickly as possible for 15 seconds.
RAN Letters	.86	(Denckla & Rudel, 1974, 1976)	Name letters as quickly as possible for 15 seconds.
RAN Pictures	.80	(Denckla & Rudel, 1974, 1976)	Name pictures as quickly as possible for 15 seconds.
Processing Speed	-Mental efficiency of processing and matching symbols, such as letter, numbers, and pictures.		
WISC-R Coding	.72	(Wechsler, 1974)	Rapidly copy symbols associated with numbers based on a key
Colorado Perceptual Speed Test Part 1 & 2	.81	(Decker, 1989)	Identify a target string of letters or letters and numbers among three foils. Letter strings are not pronounceable (see Appendix).
Identical Pictures Test	.82	(French, Ekstrom, & Price, 1963)	Identify a target picture among an array of pictures with four foils (see Appendix).

Note: Estimated reliability of the primary dependent measure obtained from the original citation for the measure unless otherwise noted.

[a]Range includes estimates of 1-year test-retest reliability (Willcutt et al., 2001) and Cronbach's α

Table 2

Standardized path estimates from hierarchical regression analysis in SEM.

Variable Order	Single Word Reading	Inattention	Hyperactivity-Impulsivity
1. Phonological Awareness	.81*	.34*	.19*
2. Verbal Working Memory	.17*	.25*	.11
3. Inhibition	−.05	.32*	.28*
4. Naming Speed	.21*	.14*	−.07
5. Processing Speed	.17*	.21*	.15*
1. Verbal Working Memory	.71*	.42*	.22*
2. Phonological Awareness	.42*	.05	.05
3. Inhibition	−.05	.32*	.28*
4. Processing Speed	.26*	.25*	.08
5. Naming Speed	.07*	−.01	−.15*
1. Naming Speed	.64*	.39*	.10
2. Processing Speed	.27*	.32*	.25*
3. Inhibition	.15*	.29*	.29*
4. Verbal Working Memory	.31*	.00	−.02
5. Phonological Awareness	.40*	−.03	.00
1. Processing Speed	.66*	.51*	.25*
2. Naming Speed	.23*	.02	−.12
3. Inhibition	.15*	.29*	.29*
4. Phonological Awareness	.50*	−.03	−.01
5. Verbal Working Memory	.07	.02	−.02
1. Processing Speed	.66*	.51*	.25*
2. Naming Speed	.23*	.02	−.12
3. Verbal Working Memory	.35*	.13*	.11
4. Phonological Awareness	.38*	.03	.07
5. Inhibition	−.10*	.26*	.26*

* $p < .05$