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Predicting Word Reading and Comprehension with Executive Function and Speed Measures Across Development: A Latent Variable Analysis

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Abstract

The present study explored whether different executive control and speed measures (working memory, inhibition, processing speed, and naming speed) independently predict individual differences in word reading and reading comprehension. Although previous studies suggest these cognitive constructs are important for reading, we analyze the constructs simultaneously to test whether each is a unique predictor. We used latent variables from 483 participants (ages 8 to 16) to portion each cognitive and reading construct into its unique and shared variance. In these models we address two specific issues: (a) given that our wide age range may span the theoretical transition from "learning to read" to "reading to learn," we first test whether the relation between word reading and reading comprehension is stable across two age groups (ages 8 to 10 and 11 to 16); and (b) the main theoretical question of interest: whether what is shared and what is separable

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for word reading and reading comprehension are associated with individual differences in working memory, inhibition, and measures of processing and naming speed. The results indicated that: (a) the relation between word reading and reading comprehension is largely invariant across the age groups; (b) working memory and general processing speed, but not inhibition or the speeded naming of non-alphanumeric stimuli, are unique predictors of both word reading and comprehension, with working memory equally important for both reading abilities and processing speed more important for word reading. These results have implications for understanding why reading comprehension and word reading are highly correlated yet separable.

Keywords

word reading; reading comprehension; listening comprehension; working memory; inhibition; processing speed; naming speed; latent variable analysis; individual differences

Reading is a complex ability requiring the integration of several different cognitive and perceptual processes. To understand this sentence, for example, at a minimum one must be able to visually process the words one sees, match the words to stored phonological, orthographic, and semantic representations, and then combine these representations with context to form an understanding of the underlying meaning of the sentence and the larger passage. As passages get longer and more complicated, the cognitive demands increase. Cognitive abilities, therefore, are important sources for individual differences in reading ability. It is unlikely, however, that all contribute equally to reading ability. Understanding which cognitive abilities play important roles during reading, how cognitive predictors of word reading might be the same or different as the cognitive predictors of reading comprehension, and whether these relations change depending on the age of the reader can offer insight into why people differ in their reading performance.

The current study examines the unique concurrent cognitive predictors of individual differences in reading ability via their relations with word reading and reading comprehension. The cognitive predictors included in our analyses are two executive control (working memory and inhibition) and two speed (processing speed and naming speed) measures. As will be discussed in depth later, previous research has shown that each of these cognitive skills is correlated with reading ability, but their respective predictive powers for reading have not been directly compared within a single study. The current study did just that and in that context first tested whether the relation between the ability to read individual words (word reading) and the ability to understand extended text (reading comprehension) is similar or different across two age groups (ages 8 to 10 and ages 11 to 16). Once we know whether the relations amongst the reading factors are invariant across the two age groups, we can address the main theoretical question of the paper: whether what is shared and what is unique between word reading and reading comprehension are associated with individual differences in any of the four cognitive constructs.

Relation between Word Reading and Reading Comprehension

A common way of conceptualizing the relation between word reading and reading comprehension in experienced readers is that reading comprehension is the product of word reading and listening comprehension (Hoover & Gough, 1990; Hoover & Tunmer, 1993). As such, reading comprehension and word reading abilities share important variance but are separable due to the influence of listening comprehension on reading comprehension, as supported in both phenotypic studies (e.g., de Jong & van der Leij, 2002; Gough, Hoover, & Peterson, 1996) and in behavioral genetic studies (e.g., Harlaar et al., 2010; Keenan, Betjemann, Wadsworth, DeFries, & Olson, 2006).

Most previous studies examining the links between cognitive and reading abilities have used measures of either word reading or reading comprehension (e.g., Denckla, 1972; Shanahan et al., 2006; Swanson, Zheng, & Jerman, 2009; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005). However given that word reading and reading comprehension are correlated yet separable, it is possible that some cognitive abilities will be important for both word reading and reading comprehension, while others could uniquely predict either word reading or reading comprehension. For example, both word reading and reading comprehension could rely on cognitive abilities needed for rapid integration of orthographic and phonological information such as rate of cognitive processing (naming speed and processing speed in our study). Other cognitive abilities could be more strongly linked to reading comprehension than word reading, such as the ability to ignore and suppress irrelevant or outdated information (inhibition) and maintaining input while accessing stored representations (working memory).

Potential Developmental Differences in the Word Reading/Reading Comprehension Relation

The relations between word reading, reading comprehension, and listening comprehension are known to change throughout early reading development (Curtis, 1980; Gough et al., 1996). Near the beginning of reading instruction, individual differences in reading comprehension and word reading are nearly indistinguishable from each other. For example, Byrne et al. (2007) found in a sample of first-grade twins that the genetic and shared-environmental influences on reading comprehension were nearly the same as the genetic and shared-environmental influences on word reading, suggesting nearly complete overlap for genetic and environmental influences on individual differences in these abilities in first graders. If a child is unable to successfully read many of the individual words in a text, she will be unable to understand the meaning of the text.

As word reading skills improve, individual differences in reading comprehension become less influenced by individual differences in word reading ability and more influenced by the child's overall linguistic comprehension abilities (Hoover & Gough, 1990; Joshi, Williams, & Wood, 1998; Rupley, Willson, & Nichols, 1998). Word reading and reading comprehension, therefore, will be strongly related in children who are still mastering phonological and basic word reading skills. As children become more proficient word readers, the relation between word reading and reading comprehension declines and listening comprehension becomes an important source of individual differences in reading ability (Keenan, Betjemann, & Olson, 2008; Vellutino, Tunmer, Jaccard, & Chen, 2007).

Cognitive correlates of word reading and reading comprehension, therefore, could change depending on children's stage of reading development. Given that the large age range of our participants (ages 8 to 16) could span the theoretical transition from "learning to read" to "reading to learn" (Chall, 1983), we split our sample into two age groups (ages 8 to 10 and ages 11 to 16) to test whether the relation between reading comprehension and word reading is invariant across this period in reading development.

Additional evidence for the need to test age invariance comes from a previous study by our group that focused specifically on differences among reading comprehension measures in their relation to word reading across a similar age group (Keenan et al., 2008). Using the same four reading comprehension measures and about half the sample included in the present study, they found that the two reading comprehension measures that used shorter, one- to two-sentence passages had significant age by word reading ability interactions in hierarchical regression analyses, while the other two tests, using longer passages, did not. While Keenan et al. did not include the cognitive variables nor use latent variables, we considered their measure-specific results in setting up our models to test for age differences in relations between word reading and comprehension, as well as their relations to the cognitive variables.

It is important to note that our reading ability model includes listening comprehension. We are not implying that listening comprehension is a direct measure of reading ability; indeed, reading ability typically refers to word reading and decoding, reading comprehension, and, occasionally, reading fluency. We include listening comprehension in our analyses with word reading and reading comprehension because we are interested in whether the relation between reading comprehension and word reading is age invariant, and the relation between reading comprehension and listening comprehension is a critical aspect of this analysis.

Cognitive Correlates Underlying the Relation Between Word Reading and Reading Comprehension

Working memory

The idea that working memory is important for reading has been supported in previous research (e.g., Baddeley, Logie, Nimmo-Smith, & Brereton, 1985; Just & Carpenter, 1992; Kaakinan, Hyona, & Keenan, 2003; Locascio, Mahone, Eason, & Cutting, 2010; Perfetti, Landi, & Oakhill, 2005; Sesma, Mahone, Levine, Eason, & Cutting, 2009; Swanson & Berninger, 1995; Vellutino, Fletcher, Snowling, & Scanlon, 2004; for a recent review, see Swanson et al., 2009). Working memory is typically viewed as more crucial for reading comprehension than word reading. This is because reading comprehension, in addition to reading individual words, requires one to be able to match up, retain, and manipulate words and their meanings to form a coherent gist of what is being read. For example, Seigneuric and Ehrlich (2005) found that working memory became an important predictor of reading comprehension ability in third graders, but was not a predictor in younger students. They interpret their findings as supporting the idea that working memory will only begin to predict reading comprehension after word reading ability has been generally mastered.

While Seigneuric and Ehrlich (2005) downplay the possibility that working memory predicts word reading, an alternative explanation for their results is that working memory only becomes crucial once a general level of reading ability has been met, suggesting there is no reason why working memory would be tied specifically to reading comprehension. This implies a potential reciprocal relation between word reading and reading comprehension that is mediated by working memory, such that the quicker one is able to read individual words and match them up to stored representations, the quicker one can figure out the underlying meaning of the passage. Reading more efficiently can help learn and store more new words, leading to an improved word reading ability that will help for comprehending the next text, etc. Under this argument, working memory should predict word reading as well as reading comprehension; however, the relative contributions of working memory to each might vary. The present study tests the contributions of working memory to both word reading and reading comprehension. If working memory is more critical for reading comprehension than for word reading, that would suggest that the two reading constructs are separable at least partially due to the differential effects of working memory.

Inhibition

The role of inhibition for reading ability may not be as obvious as for working memory. Because the term *inhibition* has many definitions in the literature and also because there are different types of inhibition (e.g., Friedman & Miyake, 2004; Nigg, 2000), it is important to note that, in this study, we are specifically defining inhibition as the ability to suppress or remove outdated information and ignore irrelevant extraneous information to help maintain current goals and relevant stimuli. This form of inhibition has been posited to be crucial for reading comprehension because successful comprehension requires one to limit and suppress potentially misleading representations caused by ambiguity in either words or the overall context (e.g., Gernsbacher & Faust, 1991). Evidence supporting the role of inhibition for reading comprehension comes from studies showing deficits in inhibition can be found in children who struggle with comprehension (Borella, Carretti, & Pelegrina, 2010; Locascio et al., 2010).

Whether or not inhibition predicts word reading is an open question, as few studies have included measures of word reading (e.g., Altemeier, Abbott, & Berninger, 2008; Chiappe, Hasher, & Siegel, 2000). Van der Sluis, de Jong, and van der Leij (2004), found that the children with reading disabilities were not impaired on either inhibition or shifting compared to a control group, while the children with arithmetic disabilities and children with both disabilities showed impairments on some of the shifting, but not inhibition, tasks. In contrast, Altemeier et al. (2008) found that growth in inhibition from first to fourth grade significantly predicted fourth grade word reading and spelling. Altemeier et al. (2008) posit that early readers still learning to read rely upon executive functions to suppress distracting information, which is needed because decoding is effortful at this stage.

Taken together, Altemeier et al. (2008) and van der Sluis et al. (2004) offer mixed support for the importance of inhibition for word reading. However, the paucity of studies examining this research question suggest the need for additional examination. If our results support that inhibition is an independent predictor of reading comprehension but not word reading, then inhibition might be one reason why reading comprehension and word reading are separable. As with working memory, it is also possible that the contributions of inhibition could vary depending on the age group. Inhibition might be more predictive of word reading ability for the younger age group, given that reading comprehension and word reading will be more closely related if this group is still learning to read.

Processing speed and naming speed

The term *processing speed* typically refers to how quickly a person is able to complete a cognitive task, such as matching up visual stimuli. Successful word reading requires a person to match up words with stored representations, as such processing speed should predict how efficiently and accurately one is able to do this. Processing speed could also be a predictor of reading comprehension, as the more efficiently a person is able to encode words, the more text they will be able to read and the more rapidly the text and meaning can be integrated.

Within the reading literature, however, the role of speed has generally been more focused on the extent to which a person's ability to rapidly name stimuli is important for successful word reading. Many previous studies on reading have found that individuals with word reading disabilities are slower than skilled readers on naming speed tasks (e.g., Denckla, 1972; Wagner, Torgeson, Laughon, Simmons, & Rashotte, 1993; Wolf & Bowers, 1999). Slower naming speed is hypothesized to reflect problems with the processing and production of sounds related to language. Naming speed, therefore, is hypothesized to be an important predictor of word reading. To the extent that naming speed captures the rate at which one can integrate orthography with the context of the passage, naming speed could also be an important predictor of reading comprehension. Naming speed is typically measured via rapid naming tasks that require a participant to serially name as many stimuli as possible within a short, fixed time period (generally less than one minute). Letters and digits are the most common stimuli used in rapid naming tasks, with colors and objects also frequently used.

Other studies have found that lower-ability readers are slower on processing speed tasks that use nonlinguistic stimuli or do not require explicit naming, suggesting that perhaps naming speed is important for word reading only to the extent that it measures general processing speed (e.g., Nicolson & Fawcett, 1994; Willcutt et al., 2005; Wolff, Michel, & Ovrut, 1990). A potential explanation for children with reading disabilities displaying deficits in both naming speed and general processing speed tasks comes from Wolf and Bowers' (1999) dual deficit hypothesis. It proposes that rapid naming performance reflects both the ability to access and bind visual stimuli to their stored phonological representations as well as general timing and speed of processing ability.

Few studies have tested the dual deficit hypothesis by including both general processing speed and naming speed tasks. One of the studies that included both found that, after processing speed variance was accounted for, rapid naming of animals predicted no significant additional variance in reading (Catts, Gillispie, Leonard, Kail, & Miller, 2002). This finding suggests that the explicit act of naming stimuli may not uniquely predict word reading. To test the dual deficit hypothesis across the two age groups, we included measures of both processing speed and naming speed. To test further the theory that the ability to quickly name stimuli is important for reading, we only used naming speed tasks without alphanumeric stimuli. As such, we are able to test whether the ability to quickly name stimuli is an important predictor of word reading or reading comprehension over and above the extent to which general speed of processing is important for word reading, reading comprehension, or both.

Current Study

The four cognitive abilities used in the present study come from largely parallel lines of research regarding the roles of working memory, inhibition, and speed of processing in reading. Given that there is evidence that different types of executive functions show considerable overlap yet are distinct in important ways (e.g., Miyake et al., 2000), including all four constructs allows us to address whether each is a unique predictor of word reading, reading comprehension, or both.

In addition to including measures of both word reading and reading comprehension and testing the extent to which four cognitive constructs uniquely predict independent or overlapping variance in word reading or reading comprehension across the younger and older age groups, the current study extends previous studies of cognitive predictors of reading in two important ways. First, the current study examines a full range of reading abilities. The majority of previous studies looking at the relations between cognitive and reading abilities in children have compared children with reading disabilities to higher-ability readers (e.g., Cain, 2006; Catts et al., 2002; Denckla, 1972; Shanahan et al., 2006; Swanson et al., 2009; Willcutt et al., 2005). Although the focus on lower-ability readers in previous studies is understandable, this sort of group comparison involving the impaired and control groups potentially limits the generalizability of the results to all readers. The current sample approximates the distribution of reading ability across the population, thus increasing the generalizability of our results.

A second strength of the present study is the use of latent variable modeling. Although the use of latent variable models is on the rise, few studies examining cognitive, word reading, and comprehension abilities have utilized latent variable techniques. In latent variable modeling, each latent factor is made up of the variance shared by its observed variables. Any nonshared variance, including measurement error, is extracted as error variance and is not included in the model. Thus, a latent variable represents only what is common amongst the observed variables that define it, creating a more precise and ‘pure’ measure of the construct.

Method

Participants

The present study used data from a total of 483 participants (253 males, 230 females) ranging in age from 8 to 16 years old (*M* = 11.10; *SD* = 2.51). The participants were split into two age groups to address potential developmental changes caused by the transition from “learning to read” to “reading to learn” frequently argued to occur around the fourth grade: the younger group (ages 8 to 10: *n* = 266) and the older group (ages 11 to 16: *n* = 217).

The data came from a large, ongoing twin study being conducted by the Colorado Learning Disabilities Research Center (CLDRC) examining the etiology of reading disability and attention deficit hyperactivity disorder (ADHD; DeFries et al., 1997; Olson, 2006). One twin from each pair was selected at random to be included in the present analyses.

The CLDRC identifies twins ages 8 to 18 years from across the Colorado front range by examining the records of cooperating school districts. Twin pairs are excluded if they are learning to read English as a second language, or if either twin has a documented brain injury, seizures, significant uncorrected hearing or visual impairment, or rare genetic etiology such as Fragile X, Downs Syndrome, or sex chromosome anomalies. All twin pairs with a school history of reading disability and/or ADHD in at least one member of the pair are invited to participate in the study along with a subset of twin pairs with no school history of either disorder.

All individuals included in the present analyses had a WISC-R (Wechsler, 1974) or WISC-III (Wechsler, 1991) Full-scale IQ score of at least 70. While the CLDRC tests participants up to age 18, the age cutoff for the present study was 16 due to the fact that children older than 16 take the adult version of the Wechsler IQ test (Wechsler, 1981). The sample included 128 (26.5%) participants with a school history of reading disability and 93 (19.3%) with a school history for ADHD. Out of those participants, 38 met the criteria for both reading disability and ADHD. The remaining 262 (54.2%) of the participants had no school history of reading disability or ADHD. Although the selection procedure suggests that the sample may not be fully representative of children in Colorado, the distributions on standardized measures were approximately normal with means and standard deviations similar to those for the tests’ norming populations (see Table 1).

Procedure

Participants completed a total of four 2.5 hour testing sessions typically on weekends, two sessions each day at the University of Colorado and two at the University of Denver. The University of Colorado testing occurred approximately one month prior to the University of Denver testing. Trained examiners administered all measures.

Measures

The tests are listed with the constructs they are hypothesized to measure. The data from all measures were coded such that higher numbers indicate better performance. Table 1 displays descriptive statistics for all measures. Low-bound estimates for reliabilities are calculated from monozygotic twin correlations of the measures and are shown in the diagonals in Tables 2 (for all reading and listening variables) and 4 (for all cognitive variables).

Working memory tasks—The following three tasks were used to measure the ability to manipulate and maintain information in memory.

Digit span: This subtest was administered from either the WISC-R (Wechsler, 1974) or the WISC-III (Wechsler, 1991) tests. The larger CLDRC study switched versions of the WISC from the WISC-R to the WISC-III in 2006. One hundred and eighty-eight participants in the present analyses received the WISC-III. In both versions, participants repeated multiple series of numbers either forwards or backwards (e.g., 2, 5, 9, 4). The series began with two numbers and continued to increase in length. Given the differences in standardization between the two versions, raw scores indicating the number of series correctly recalled, combined across forward and backward digit span, were used for the present analyses.

***Sentence span* (Siegel & Ryan, 1989):** Participants generated a word at the end of a simple sentence presented orally (e.g., “I throw the ball up and then it comes….”) and then had to repeat their generated words in blocks ranging from two to six sentence sets. The dependent variable used for the present analyses was the total number of sets recalled correctly.

***Counting span* (Case, Kurland, & Goldberg, 1982):** Participants counted the number of yellow dots presented on a set of cards and then repeated, in order, the number of dots that appeared on each card. The sets ranged in size from two cards per set to six cards per set. The present analyses used the number of sets recalled correctly.

Inhibition tasks—The following three measures were used to assess the ability to suppress outdated or irrelevant information.

Gordon Diagnostic System (GDS) continuous performance test (CPT) vigilance and distractibility: Two different versions of the GDS (Gordon, 1983) were used to index inhibition ability. In the vigilance version, a series of digits flashes on a screen. Participants were instructed to press a button whenever “1” is followed by “9”. The distractibility version was similar to the vigilance test, but with irrelevant digits flashing on the side of the column of target stimuli. The dependent variable used for both tests to index inhibition ability was the number of commission errors (i.e., responding to a nontarget).

Stop-signal reaction time (SSRT): In this computerized task, participants had to press either the “X” or the “O” key on the keyboard when the corresponding letter was flashed on the screen. Participants were instructed to press the button as quickly as possible. On some trials, an auditory tone was presented shortly after the letter was flashed. If the tone occurred, the participant was instructed to not push the button, thus inhibiting their learned response. The dependent measure for the SSRT was the stop-signal reaction time, which basically assessed how long the lag between the letter and tone had to be in order for the response to be successfully inhibited. Fifty-six percent of the participants received a nontracking version (Logan, 1994). Due to improvements in computer programming, the remaining participants received a tracking version wherein the task demands were adjusted based upon an individual’s performance (Logan, Schachar, & Tannock, 1997). Scores were standardized within versions.

Processing speed tasks—The following two tasks were used to assess the ability to quickly match stimuli to targets.

***Colorado perceptual speed (CPS) test 1-2* (DeFries, Singer, Foch, & Lewitter, 1978; Decker, 1989):** Participants had to search a visual display as quickly as possible to find which of the four possible responses matched the target series of letters. In CPS parts 1 and

2, phonetically similar letters and phonetically dissimilar letters were the targets. Each part contained 30 items and participants had 1 minute to complete as many items as possible. The dependent variable used for the following analysis was the number correct for both parts.

***ETS identical pictures* (French, Ekstrom, and Price, 1963):** This test was similar in format to the CPS tests, but used pictures as stimuli rather than letters. There were two parts, each with 48 items. Participants had 90 seconds for each part. Total number correct on both parts was the dependent variable.

Naming speed tasks—The following two measures were used to assess ability to rapidly name visually presented stimuli.

Rapid automatized naming (RAN) colors and objects: The RAN tests were adapted from tasks used by Denckla and Rudel (1976). In the tests, participants were given a display of colors or objects and had to name as many as possible in 15 seconds. We used the number of items named correctly as the dependent variable.

Listening comprehension tests—The following three measures were used to assess ability to understand the meaning of an auditory passage.

***Woodcock-Johnson (WJ) oral comprehension* (Woodcock, McGrew, & Mather, 2001):** Participants listened to a short one or two sentence passage and had to supply the correct last word. Some sentences had only one possible correct answer, while most sentences had between 2 and 5 possible answers. The dependent measure was the number of correct answers.

Qualitative reading inventory 3 (QRI): In this modified version of the original test (Leslie & Caldwell, 2001), participants first answered a question regarding the topic of the upcoming passage to assess domain knowledge. They then listened to one or two passages on audiotape and had to retell the passage as best they could. Finally, participants were asked six additional comprehension questions. An average performance score was made up of the number of items or ideas that the participant mentioned during retelling as well as the number of comprehensions questions answered correctly. Participants received passages of different lengths depending upon their age. All scores were standardized within level to allow for comparisons across different levels of passages.

Barnes KNOW-IT: We administered a shortened version of the original Barnes KNOW-IT from Barnes, Dennis, and Haefele-Kalvaitis (1996) and Barnes and Dennis (1996). Participants first learned approximately 20 facts about an imaginary planet. Then they listened to six episodes describing two children visiting the imaginary planet and answered 18 comprehension questions. The number of comprehension questions answered was the dependent variable.

Reading comprehension tests—We used the following four tests to assess ability to understand the meaning of a written passage.

***Woodcock-Johnson (WJ) passage comprehension* (Woodcock et al., 2001):** Participants read one or two sentences with one word missing and supplied the correct missing word. Some sentences had only one possible correct answer, while most sentences had between 2 and 5 possible answers. Participants were scored on the number of correct answers.

Qualitative reading inventory 3 (QRI): This test was identical in format to the QRI reading inventory for listening comprehension except that participants read the passages aloud rather than listened to them (Leslie & Caldwell, 2001).

Gray oral reading test-3 (GORT) **(Wiederholt & Bryant, 1992):** Participants read passages aloud and answered five multiple-choice questions for each passage. A participant's score was made up of the number of comprehension questions answered correctly.

Peabody individual achievement test (PIAT) comprehension (Markwardt, 1970): Participants read one or two sentences and then selected which of four pictures represented the meaning of the passage. Participants were scored on the number of correct answers.

Word reading tests—We used the following three tasks to measure ability to read words presented without context.

Peabody individual achievement test (PIAT) word recognition (Markwardt, 1970): Participants read increasingly difficult, unrelated words until they reached an error criterion. A participant's score was the number of words read correctly.

Peabody individual achievement test (PIAT) spelling (Markwardt, 1970): Participants answered a series of multiple-choice questions to test their spelling recognition. We included this test as a measure of word reading in this study because its focus was on recognition rather than spelling production. A participant's score was the number correct.

Time-limited oral reading of single words **(Olson, Forsberg, Wise, & Rack, 1994):** Participants read increasingly difficult words from a list of 182 words presented on a computer screen. To be scored as correct, accurate responses had to be initiated within a two-second time limit as measured by a voice key. The dependent measure used was the position in the list the participant reached.

Data Analyses

Preliminary data analyses—Prior to all analyses, variables were examined for skew, kurtosis, and outliers. Outliers falling more than three standard deviations (SDs) beyond the mean for the each age group were trimmed to three SDs. Outliers were minimal and accounted for less than 1% of all scores. The three inhibition tasks and the Barnes comprehension test showed significant skew, which was corrected via log-transformations prior to the data analyses.

Following checks and corrections for outliers, skew, and kurtosis, possible linear and nonlinear effects of age were controlled by regressing the dependent variables on age, age squared, and age cubed. The residuals from these regressions were standardized within each age group. The resulting values were used in all subsequent analyses.

Five variables had missing data that was replaced with the variable's mean. The three PIAT subtests were each missing seven scores, the WJ passage comprehension test was missing one score, and the SSRT had 13 missing scores.

Multivariate analyses—We used a combination of latent variable techniques: confirmatory factor analyses (CFA) and full structural equation modeling (SEM; Bollen, 1989). All CFA and SEM analyses were carried out using AMOS 17.0.0 (Arbuckle, 2008). To assess how well the models tested fit the original data, four different fit indices will be reported for each model: chi-square (χ^2), chi-square difference test ($\Delta\chi^2$), Bentler's (1990) comparative fit index (CFI), and Steiger and Lind's (1980; see also Steiger, 1998) root mean square error of approximation (RMSEA). Chi-square tests how well the model's expected variances and covariances fit the sample's observed variances and covariances. When comparing nested models, if the difference between the two models' chi-square values is not significant, the two models fit the data equally well and hence that the less complex model (i.e., the one with greater degrees of freedom) should be preferred. CFI compares the current model to a null model. CFI values range between zero and one with values close to .95 considered a good fit (Hu & Bentler, 1999). Finally, RMSEA is a population-based index that estimates the discrepancy in fit between the model and data taking into account degrees of freedom. RMSEA values range from zero to one with values less than .10 representing good fit (Loehlin, 1998). A benefit of RMSEA is that it is possible to obtain 90% confidence intervals (90% CI) to test a null hypothesis of poor fit.

Results

The current study addressed: (a) to what extent the relation between word reading and reading comprehension is similar across two age groups; and (b), the main theoretical question, whether what is shared and what is separable for word reading and reading comprehension are associated with individual differences in the four cognitive constructs. To address the first part, we report results from the CFA models that focused on the three reading ability factors (word reading, listening comprehension, and reading comprehension) and examined their interrelationships across the two age groups. The second question is addressed in two parts: (a) using CFA models that focused on the four cognitive ability factors (working memory, inhibition, processing speed, and naming speed) and examining the relations and age invariance among those factors and (b) using SEM models that included the paths connecting the cognitive and reading factors to each other and testing the age invariance across the two age groups (ages 8 to 10 and ages 11 to 16).

Testing the Relation Between Word Reading and Reading Comprehension Across the Two Age-Groups

Correlations between reading and listening variables—Table 2 displays the zero-order correlations between all observed measures of word reading, reading comprehension, and listening comprehension. Both age groups are presented on the table with younger participants located below the diagonal and older participants located above the diagonal. All variables are significantly correlated with each other. For both age groups, variables measuring listening comprehension and reading comprehension tended to have slightly higher correlations with each other than with the word reading variables.

Modeling the relation between word reading and reading comprehension— Before testing a CFA with both age groups, we first tested models for the groups separately to validate that the model was appropriate for each group. The three-factor reading model is shown in Figure 1. Numbers on straight, single-headed arrows are standardized factor loadings and are equivalent to standardized regression coefficients. Numbers next to curved, double-headed arrows are correlations. Numbers above the observed measures (in rectangles) represent error in each measure not captured by the model. The loadings before the slash are for the younger age group while loadings after the slash are for the older age group. The error correlation for the two QRI tests was significant and is included in all subsequent models.[1] As Figure 1 indicates, for both age groups, the correlations among the three reading-related latent variables were substantial, but the correlations were particularly

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[1] As part of model testing we let errors correlate if their measures were subtests or versions of the same test. If the error correlation was not significant, it was dropped and is not shown in the model.

high for the reading and listening comprehension factors (.88 for the younger group and .95 for the older group). The fit of this model for each age group was only moderately good (ages 8 to 10: $\chi^2[31] = 95.81$, CFI = .96, and RMSEA = .09, 90% CI [.07, .11]; ages 11 to 16: $\chi^2[31] = 63.31$, CFI = .97, and RMSEA = .07, 90% CI [.05, .09]).

Keenan et al.'s (2008) earlier analysis of the four reading comprehension tests used in the current study showed that the PIAT, which assessed reading comprehension for single sentences, and the WJ passage comprehension, which used only one- or two-sentence passages, had large amounts of their variance explained by word reading ability in addition to reading comprehension ability. We therefore allowed these two reading comprehension variables to load onto both the reading comprehension latent factor and the word reading latent factor (see Keenan et al., 2008 for additional details and discussion regarding this issue). The inclusion of the cross-loadings resulted in significant improvement of model fit over the previous model where the PIAT and WJ passage comprehension tests only loaded onto reading comprehension (ages 8 to 10: $\Delta\chi^2[2] = 50.46$, $p < .01$; ages 11 to 16: $\Delta\chi^2[2] = 25.02$, $p < .01$). All subsequent models, therefore, include the cross-loadings.[2]

Having established a three-factor CFA for word reading, reading comprehension, and listening comprehension that fit both age groups, we tested the invariance of this model across the two age groups. In line with recommendations by Tabachnick and Fidell (2007) and Byrne (2001), the process of testing invariance across two groups involved testing nested models comprising increasingly stringent constraints. First, the baseline model with no equality constraints across the two age groups imposed was tested. Next, the factor loadings were constrained equal across groups. If this model was found to be not significantly different from the baseline model, the next step was to constrain the latent covariances. Finally, all remaining parameters (i.e., the factor variances, observed variable error variances, intercepts, and error covariances) were constrained equal. The model with all parameters constrained equal fit significantly worse than the baseline model with no parameters constrained across the age groups, $\Delta\chi^2(26) = 55.67$, $p < .01$. Examination of the baseline model loadings showed that the loadings and variances for the two QRI tests were significantly different for the two age groups. When we tested a model that did not constrain these loadings and variances equal across age groups but constrained all other parameters, the fit of this model was not significantly different from the baseline model, $\Delta\chi^2(21) = 31.53$, $p = .07$.

In line with Byrne, Shavelson, and Muthén (1989) and Steenkamp and Baumgartner (1998), that we could constrain the loadings and variances of three of the four reading comprehension tests and two of the three listening comprehension tests equal across the two age groups shows that our data fit the assumptions of partial measurement invariance.[3] This suggests that the pattern of relations between reading comprehension, listening comprehension, and word reading is fairly stable across the two age groups even if two individual measures load onto the latent factors differently for the younger and older participants.

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[2] To ensure that our results were not primarily due to the inclusion of two reading comprehension tests that shared variance with both the word reading tests and the reading comprehension tests, we ran our final structural equation model without the PIAT and WJ Passage Comprehension tests included. All standardized factor loadings were within +/- .02 of the loadings shown in Figure 4 and all levels and patterns of significance were maintained. As such, the presence of the cross-loadings is important if the PIAT and WJ passage comprehension tests are included, but our overall findings and conclusions do not hinge upon the inclusion of those two tasks.

[3] As an additional check of invariance across the two age groups, in line with recommendations from Vandenberg and Lance (2000), we compared the CFI and RMSEA values for the fully constrained model to the baseline model with no constraints imposed. The CFI value for the fully constrained model was .98, only .01 less than the baseline model (.99). The RMSEA values were also very similar at .04 (90% CI [.03, .05]) for the fully constrained model and .03 (90% CI [.03, .05] for the baseline model. Per Vandenberg and Lance (2000), these values suggest the hypothesis of invariance across the two groups should not be rejected and provide support for the conclusion that the tests measure similar constructs across the two age groups.

The fit indices for the three-factor model with two of the reading comprehension measures cross-loaded are displayed in Table 3. The high CFI (.99), low RMSEA (.03), and low χ^2 ([79] = 115.16, $p = .01$) show that this model fits the data well. Also reported in Table 3 are model comparisons we conducted to ensure that the three-factor model indeed provided a better fit to the data than a model with one general reading factor or a two-factor model that collapsed two of the reading factors into one factor. These alternative models were specified by fixing some or all of the factor correlations to 1.0. For example, the one-factor model testing the unity of the reading constructs was made by fixing all factor correlations to 1.0. As Table 3 shows, the fit indices for a two-factor model with cross-loadings did not fit the data worse than the three-factor model. In the interest of parsimony, therefore, we chose to use one comprehension factor that combined the listening and reading comprehension measures. The final two-factor model is shown in Figure 2.

Summary—There are three main findings from the word reading and comprehension models. First, reading comprehension and listening comprehension could be collapsed into one general comprehension factor once two of the reading comprehension tests cross-loaded onto the word reading and reading comprehension factors. Second, we found that word reading and comprehension form distinct factors supporting the idea that reading comprehension and word reading are separable constructs that potentially have different cognitive predictors. Third, the relation between word reading and comprehension is relatively invariant across the two age groups.

Cognitive Correlates of Word Reading and Reading Comprehension

Correlations between cognitive variables—Table 4 displays the zero-order correlations between all observed measures of working memory, inhibition, naming speed, and processing speed. Nearly every measure was significantly correlated with the other measures, and the pattern of correlations was similar for both age groups (the correlations for the age 8 to 10 group are presented below diagonal and those for the age 11 to 16 group above diagonal). Importantly correlations were generally higher for measures hypothesized to underlie similar constructs. This finding demonstrated convergent validity of the measures and provided support to use CFA to assess whether our variables of cognitive ability support a four-factor model.

Modeling the relations between the cognitive constructs—As with the CFA models for reading ability, we first established separate models for each age group. The baseline model for each age group had the observed cognitive variables loading onto the latent factors they were hypothesized to measure. The resulting CFA model for each age group is presented in Figure 3 with standardized factor loadings on straight single-headed arrow, correlations on curved, double-headed arrows, and error leftover in observed measures represented by numbers above the observed measures. The loadings before the slash are for the younger age group while loadings after the slash are for the older age group. The error correlation for the two CPT subtests was significant and is included in all subsequent models. The fit of this baseline model for both age groups was good (ages 8 to 10: $\chi^2[28] = 39.24$, CFI = .98, and RMSEA = .04, 90% CI [.00, .07]; ages 11 to 16: $\chi^2[28] = 30.78$, CFI = 1.00, and RMSEA = .02, 90% CI [.00, .06]).

We then tested for invariance across the two age groups to see if the relations amongst the cognitive variables were consistent for the younger and older age groups. As with the CFA models for reading ability, we tested a series of nested models with parameters constrained equal across the two age groups. The chi-square difference between the baseline model and the model with all parameters constrained equal was not significant, $\Delta\chi^2(15) = 17.75$, $p = .28$. This suggests that the relations between the cognitive factors do not vary across the two age groups and that our measures assessed similar constructs in younger and older participants.

The fit indices for the four-factor model are displayed in Table 5. The high CFI value (.99), low RMSEA value (.02), and nonsignificant χ^2 ([83] = 94.24, $p = .18$) show that the four-factor model fit the data well. The four factors were significantly correlated with each other ranging from $r = .47$ for the correlation between inhibition and naming speed to $r = .69$ for the correlation between working memory and inhibition. Table 5 also displays the results from model comparisons we conducted to ensure that the four-factor model depicted in Figure 3, but collapsed across age groups, indeed provided a better fit to the data than various simpler models. Specifically, we compared the fit of the four-factor model with models that assume either that all factors were really measuring the same underlying construct (a model with only one latent factor) or that some of the factors were measuring the same underlying construct (a model with two or three latent factors). The fit indices in Table 5 show that the model with the best fit was the four-factor model.

The results of the CFA using our cognitive measures indicated that the measures formed four distinct but significantly correlated latent factors and that the relations amongst the cognitive factors are stable across the two age groups.

Modeling the cognitive predictors of word reading and comprehension—The SEM included all six factors established in the previous models (working memory, inhibition, processing speed, naming speed, comprehension, and word reading). One side of the model contained reading CFA (Figure 2) and the other side contained cognitive CFA (Figure 3 but constrained equal across the age groups). We added structural paths such that each cognitive factor predicted each reading factor (see Figure 4).

It is important to keep in mind that SEM modeling is correlational in nature and essentially is a complex multiple regression analysis with that can include either latent variables, as in this study, or individual variables. Unidirectional arrows leading from one factor to another factor denote which factor is the independent variable and which is the dependent variable. Loadings on these lines, therefore, are estimates of how much change in the independent variable (after controlling for the other factors it is correlated with) predicts change in the dependent variable. These loadings should not be interpreted as suggesting that a change in the independent variable *causes* change in the dependent variable.

The fit of the SEM with all structural loadings constrained across the two age groups was not significantly different from a model with no constraints imposed, $\Delta\chi^2(8) = 5.71$, $p = .68$. Examination of fit indices for the constrained model showed that it was a good fit to the data, $\chi^2(356) = 463.52$, CFI = .98, RMSEA = .03, 90% CI [.02, .03]. Thus the direct effects of the cognitive factors onto the reading and listening factors are similar for the older and younger participants. As Figure 4 shows, comprehension was significantly predicted by working memory ($p < .01$) and marginally so by processing speed ($p = .08$). Word reading was significantly predicted by both working memory and processing speed ($p < .01$ for both). Inhibition and naming speed did not independently predict comprehension or word reading ($p = .52$ for inhibition to comprehension, $p = .72$ for naming speed to comprehension, $p = .12$ for inhibition to word reading, and $p = .25$ for naming speed and word reading).

In summary, comprehension and word reading scores increased as working memory and processing speed increased, with processing speed more strongly predictive of word reading than comprehension. Performance on inhibition and naming speed tasks, however, had no significant direct effect on either word reading or comprehension after controlling for the other cognitive factors. This pattern of results held across the two age groups, suggesting that these relations are relatively stable between the ages of 8 and 16.

To what extent is the relation between word reading and reading comprehension being driven by IQ?—To test for the possibility that our results were actually reflecting individual differences in general intelligence rather than the specific contributions of the four cognitive factors, we tested our model with IQ predicting both word reading and comprehension. For IQ, we used the participants' Full-scale IQ scores from the either the WISC-R or WISC-III. Because the WISC Full-scale IQ measure includes the digit span subtest, we deleted digit span from the working memory factor leaving counting span and sentence span as the two variables for working memory. The fit of this model was good, $\chi^2(346) = 441.23$, CFI = .98, and RMSEA = .02, 90% CI [.02, .03]. Figure 5 shows the structural portion and latent variable correlations of this model (for simplicity and clarity, all the loadings for individual tasks are omitted). Full-scale IQ significantly predicted both word reading and comprehension ($p < .01$ for both) over and above the other four cognitive factors. It is important to note, however, that Full-scale IQ was more predictive of reading comprehension (standardized loading = .78) than word reading (standardized loading = .27). This suggests that part of what differentiates word reading and reading comprehension is the extent to which general intelligence is needed. Finally, working memory continued to predict both word reading and comprehension ($p < .01$ for both) and processing speed continued to predict word reading ($p < .01$) even after Full-scale IQ was controlled for. Therefore, the contributions of working memory and processing speed to reading are not completely redundant with IQ.

Alternative Models Tested

Do contributions of naming speed change when alphanumeric naming speed tests are included?—Other studies looking at the relations between naming speed and reading ability have reported naming speed deficits in children with reading disabilities (e.g., Denckla, 1972; Wagner et al., 1993; Wolf, Bally, & Morris, 1986). Our decision to use naming speed measures that only used non-alphanumeric stimuli (RAN colors and objects) contrasted with previous research that tested naming speed with alphanumeric stimuli (RAN digits and letters). We tested an additional SEM to see whether our results would change if the alphanumeric naming speed measures were included. The model was identical to the original model shown in Figure 4 but included RAN digits and RAN letters loaded onto the naming speed latent factor. This new model fit the data well, $\chi^2(438) = 635.20$, CFI = .96, and RMSEA = .03, 90% CI [.03, .04]. Figure 6 shows the structural loadings and the correlations between latent factors for this model. Processing speed continued to predict word reading ($p < .01$) and comprehension ($p = .03$). Working memory also continued to significantly predict both comprehension and word reading ($p < .01$ for both). Importantly the inclusion of naming digits and letters produced a significant path from naming speed to word reading (standardized loading = .23, $p < .01$). The independent link between word reading ability and naming speed tasks, therefore, appears to partly rely upon the use of alphanumeric stimuli in the speeded tasks.

Are the results driven by the participants with ADHD?—To ensure that the results are not being biased due to the high percentage of participants with a school history of ADHD, we tested the final SEM model omitting participants who had a school history of ADHD. The sample with no ADHD participants had 215 younger age-group participants and 174 older age-group participants. The model fit well, $\chi^2(350) = 451.28$, CFI = .97, and RMSEA = .03, 90% CI [.02, .03]. Compared to the final SEM model shown in Figure 4, the loadings from working memory to comprehension and word reading increased ($p < .01$ for both) while the loadings from inhibition to comprehension and word reading decreased (p

= .59 and $p = .31$ respectively). These changes did not affect the patterns of significance, the loadings from naming speed and processing speed, nor our overall conclusions.

General Discussion

The present study examined the extent to which the shared and independent variance in word reading and comprehension can be accounted for by their relations to four different cognitive abilities. To do this, we first explored the potential for age differences in the relations between word reading and reading comprehension. We then explored the extent to which variance in word reading and reading comprehension either overlaps or is independent is associated with the four cognitive abilities. Overall, the results of the current study offer new insights into these issues. In this General Discussion section, we revisit the questions, draw conclusions on the basis of the reported data, and discuss their implications.

The Relation between Word Reading and Reading Comprehension Across the Two Age Groups

We tested for the potential for developmental changes in the relations between word reading and reading comprehension across the age range of our participants. Because our age-range spanned the theoretical fourth grade transition from “learning to read” to “reading to learn” (Chall, 1983; Leach, Scarborough, & Rescorla, 2003; Sanacore & Palumbo, 2009), we split our sample into two age groups: 8 to 10 year olds and 11 to 16 year olds. Overall, we found that the patterns of correlations between the reading latent variables were similar across the age groups. This suggests that the relation between word reading and reading comprehension is similar across our two age groups and that previous findings suggesting an increased reliance on reading comprehension ability in the fourth grade (e.g., Catts, Hogan, & Adlof, 2005; Leach et al., 2003; Scarborough, 2005; Sanacore & Palumbo, 2009) may reflect changes in academic instruction rather than changes in the underlying reading relations.

The finding of invariance across the age groups might first appear to be in conflict with the previous work from our group that found significant age by word reading ability interactions for two of our four measures of reading comprehension (Keenan et al., 2008). However the current study is modeling the variance common amongst all four reading comprehension measures rather than each measure on its own. This suggests that how one measures reading comprehension could change the results regarding the relation between word reading and reading comprehension across the two age groups.

To test this idea we reran our reading CFA twice: first, modeling the reading comprehension factor using only the two measures that showed significant age effects in the Keenan et al. study (the tests with one- and two-sentence passages: WJ passage comprehension and PIAT reading comprehension) and second, modeling the reading comprehension factor with the two measures that used longer passages and did not have significant age effects (the GORT and QRI). In the first model we were no longer able to collapse listening and reading comprehension into one factor ($\Delta\chi^2[17] = 344.92$, $p < .01$), but we were able to in the second model ($\Delta\chi^2[17] = 20.42$, $p = .25$). Analyses that include reading comprehension tests with shorter passages only might conclude that reading comprehension is more strongly tied to word reading ability for younger participants while analyses with longer passages may find that reading comprehension ability is not significantly independent from listening comprehension for both age groups.

It is also important to note that our results are limited in that our youngest participants were eight years old. While we were able to test for differences between children typically described as “learning to read” or “reading to learn,” it is likely that children in the earlier stages of “learning to read” may require different cognitive processes or have different patterns of relations between the cognitive and reading constructs. Byrne et al. (2007), for example, found that word reading and reading comprehension abilities were almost completely unitary for first graders. It is possible that a reading ability latent variable model for first graders might collapse reading comprehension with word reading while maintaining a separate listening comprehension factor. Word reading and reading comprehension might share the same cognitive predictors in very early reading development, therefore, while listening comprehension could have its own independent predictors.

Cognitive Correlates of Word Reading and Comprehension

The main theoretical question addressed in our study, whether the shared and independent variance between word reading and reading comprehension can be accounted for by their relations to the different cognitive measures, was tested in the SEM. After controlling for working memory, inhibition, processing speed, and naming speed, the correlation between the comprehension and word reading latent factors dropped from $r = .59$ (Figure 2) to $r = .28$ (Figure 4). The significant drop in correlation ($p < .01$ as assessed by nonoverlapping 99% confidence intervals) suggests that the four cognitive abilities together substantially mediate the relation between comprehension and word reading. A large part of what is shared between word reading and comprehension, therefore, are these cognitive processes. We discuss the results for each of the cognitive variables in the following subsections.

Working memory accounts for part of the overlap in word reading and reading comprehension

Previous studies interested in the role of working memory for reading have largely focused on the relation between working memory and reading comprehension (e.g., Just & Carpenter, 1992; Swanson et al., 2009). We initially hypothesized that working memory would be more closely related to reading comprehension performance because successful comprehension depends upon the ability to remember and integrate information across the text to build appropriate situation models (Kintsch & Rawson, 2008). The finding that working memory uniquely predicted both comprehension and word reading even after controlling for the other cognitive constructs was surprising, therefore, and provides important new evidence that successful reading of both individual words and longer passages requires active maintenance of what is being read, manipulating the information into a coherent form, and accessing stored orthographic representations.

In addition, the finding that working memory predicts both word reading and comprehension at similar levels may reflect a potential reciprocal relation amongst the reading factors. As a child’s word reading ability improves, overall comprehension ability increases, which in turn can further aid in improving word reading. The loadings from working memory to word reading and reading comprehension could capture, therefore, either the extent to which working memory capacity constrains a person’s comprehension and word reading ability (e.g., Just & Carpenter, 1992) or the extent to which working memory improves via experience with language, both word reading and comprehension (e.g., MacDonald & Christiansen, 2002). Given that our methodology is correlational, we are unable to provide support for either causal view. Instead the present findings demonstrate that working memory is an independent predictor of both reading factors and support the idea that working memory is part of what is shared between word reading and comprehension.

Processing speed accounts for part of the distinction between word reading and reading comprehension

The finding that processing speed was a significant predictor of word reading after controlling for naming speed, working memory, and inhibition, and even though the time-constraints on the three word reading tasks were minimal, supports the role for efficient and automatic cognitive processing during word reading. Learning the associations between visual stimuli and speech sounds is thought to be an important part of learning to read (e.g., Ehri, 2005). Recent findings from Blau et al. (2010) and Byrne et al. (2011) suggest that individuals with reading disabilities struggle with the automatic mapping between graphemes and phonemes supporting the importance of this type of associative learning for successful reading. We propose that the significant loading from processing speed to word reading is capturing part of the process of quickly making visual-verbal associations.

While processing speed was a significant independent predictor of word reading, it was only a marginally significant independent predictor of comprehension. We argue that the lower contributions of processing speed to the comprehension factor are driven by the tasks that make up both the processing speed and comprehension factors. First, the two processing speed tasks used visual stimuli; thus, how quickly a participant was able to process visual stimuli was crucial. Second, our comprehension factor consisted of both reading comprehension and listening comprehension tasks. If processing speed is important for reading because it taps visual-verbal associative learning, there should be minimal contributions of processing speed to listening comprehension. In addition, in comprehension tasks a participant is aided by a larger semantic context potentially reducing the need to accurately identify individual words. Part of why word reading and reading comprehension are separable, therefore, may be that context can aid word recognition in extended text while isolated word reading does not have that support.[4]

Neither inhibition nor naming speed are unique predictors of word reading or reading comprehension

Inhibition is thought to be important for reading, specifically reading comprehension, because it limits potentially distracting ambiguous, outdated, or irrelevant information (e.g., Gernsbacher & Faust, 1991; Cain, 2006). In contrast to these findings, inhibition did not uniquely predict word reading or comprehension in our study. We can think of two possible interpretations for our findings. First, that previous research was modeling what was common between working memory and inhibition rather than the unique variance in inhibition. The second, and more radical, interpretation is that general cognitive ability completely subsumes inhibition leaving no additional variance.

To test the idea that the role of inhibition found in previous studies was reflecting general cognitive ability or working memory rather than something specific about inhibition, we ran the SEM with inhibition as the only cognitive factor. The results of this model indicated that inhibition predicted both word reading (standardized loading = .32, $p < .05$) and comprehension (standardized loading = .37, $p < .05$). By controlling for processing speed, working memory, and naming speed, we extracted a large amount of general cognitive ability from inhibition leaving little variance to predict either word reading or comprehension.

In addition to demonstrating that inhibition is not a unique predictor of either reading ability, this finding has implications for understanding the relation between inhibition and working memory. While some theories of working memory have argued that variations in inhibitory

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[4] One of our word reading tasks, time-limited oral reading of single words, has a small speeded component to it, as children must start to read each word within two seconds of it appearing on the screen. It is possible that processing speed would be more highly related to this measure than the other two word reading measures without time constraints. However the time constraint for time-limited oral reading of single words is relatively lax compared to other timed measures of word reading. In addition, our model looks at the relation between processing speed and word reading as latent factors. Thus the word reading factor is what is shared between time-limited oral reading and the other two word reading measures, minimizing the possibility that the processing speed-word reading relation is being biased by the inclusion of time-limited oral reading.

control are the source of individual differences on working memory tasks (e.g., Lustig, Hasher, & Zacks, 2007; Lustig, May, & Hasher, 2001), the fact our model showed that working memory predicted significant independent variance in both word reading and comprehension while inhibition did not argues against a unique causal role of inhibition for variance in working memory ability. Our results also provide evidence contrary to theories such as the one put forward by Kane, Conway, Hambrick, and Engle (2007) that a third factor, made up of general attention-control ability, could be the cause of individual differences in both inhibition and working memory. Our working memory factor continued to predict both word reading and reading comprehension even after controlling for processing speed, naming speed, and Full-scale IQ, all abilities that should rely upon general attention-control. Taken together, our results suggest that general cognitive ability largely subsumes the role of inhibition in reading ability even though there is a uniquely predictive role for working memory.

Support for the idea that inhibition is largely subsumed by general cognitive ability comes from another study modeling executive functions as latent variables (Friedman et al., 2008). The authors included measures of inhibition in addition to two other executive functions, updating and shifting. After modeling the common variance amongst the three latent constructs as "Common Executive Function," the authors found unique variance in both updating and shifting, but no additional variance in inhibition. These results, even though the inhibition used in the study was about prepotent responses rather than separating out irrelevant information, are consistent with our results and provide support for the idea that inhibition may not be separable from general cognitive ability.

The finding that processing speed, but not naming speed, independently predicted both word reading and reading comprehension helps to clarify the role of naming speed. While some previous research has tied naming speed to word reading (e.g., Compton, 2003; Denckla & Rudel, 1974; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wolf & Bowers, 1999), our analyses support that the rapid naming of non-alphanumeric does not predict either word reading or reading comprehension once variance in general processing speed is accounted for (e.g., Catts et al., 2002; McGrath et al., 2011).

An important caveat to this conclusion, however, is that naming speed with digits and letters independently predicted word reading even after processing speed was controlled for. When we reran the main SEM model (Figure 4) with alphanumeric naming speed added (Figure 6), the link between naming speed and word reading became significant. We conclude, therefore, that the link between naming speed and word reading after controlling for processing speed and other cognitive abilities is not the ability to overtly name stimuli, but instead reflects the participant's overall ability to recognize and use alphanumeric stimuli.[5] This interpretation is supported by other studies that found stronger links of rapid naming to word reading with alphanumeric stimuli versus nonalphanumeric stimuli (Schatschneider, Carlson, Francis, Foorman, & Fletcher, 2002; van den Bos, Zijlstra, & Spelberg, 2002).

The role of IQ

To help clarify the relations between word reading and comprehension and between the cognitive variables, we ran an additional SEM with Full-scale IQ included as a fifth

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[5] One of our processing speed tasks, the CPS 1-2, used letters as stimuli possibly inflating the contribution of processing speed to our word reading and comprehension factors. For the following reasons, however, we suspect that replacing the CPS 1-2 with another task that does not use letters would not change our results greatly. First, our processing speed latent factor modeled the shared variance between the CPS 1-2 and the identical pictures test, which does not use alphanumeric stimuli. Second, we also found that processing speed was a significant independent predictor of word reading and comprehension even with alphanumeric rapid naming tasks included in the model. These findings suggest that reading utilizes general processing speed ability, as measured by tasks requiring matching of visual stimuli to targets, in addition to efficient explicit processing of alphanumeric stimuli.

cognitive predictor (see Figure 5). Importantly, after controlling for Full-scale IQ, working memory continued to equally predict both word reading and comprehension, strengthening our conclusion that working memory is an independent predictor of both aspects of reading and the results are not an artifact of general intelligence effects. However, while Full-scale IQ was a significant independent predictor of both word reading and comprehension, including Full-scale IQ did not significantly decrease the correlation between word reading and comprehension from $r = .28$ (Figure 4) to $r = .19$ (Figure 5; drop in correlation $p > .05$ as assessed by overlapping 95% confidence intervals). These results suggest that Full-scale IQ is not a significant mediator of the word reading and comprehension relation once the other four cognitive factors are controlled for.

In addition, the results showed that Full-scale IQ is more strongly tied to the comprehension factor than the word reading factor. This finding potentially reflects the fact that our Full-scale IQ scores from the WISC include verbal comprehension subtests, including vocabulary. De Jong and van der Leij (2002) found that verbal IQ was a significant predictor of reading comprehension in elementary school, even after controlling for prior reading ability. This supports the idea that Full-scale IQ scores will be more strongly tied to comprehension than isolated word reading.

Directionality of loadings does not equal causation

While we have mentioned this fact before, it is important to re-emphasize that the significant loadings on the unidirectional arrows from working memory and processing speed to comprehension and word reading factors are not proof of causal relations. As in multiple regression analyses, these loadings reflect how performance on the word reading or comprehension factor changes depending upon performance on a cognitive factor. They do not prove, for example, that increases in working memory are the cause of increased performance in comprehension. It is possible that children who are better comprehenders seek out activities that utilize and increase their working memory capacity.

Conclusion

Successful reading is a complex skill requiring the integration of several cognitive processes. The overarching goal of the present study was to test whether different cognitive abilities are unique sources of individual differences in word reading and comprehension. Understanding which cognitive abilities predict either word reading or comprehension can provide insight into how these two reading constructs overlap yet are separable. Although neither naming speed nor inhibition predicted reading ability over and above general cognitive ability, working memory and processing speed do appear to be important independent sources of variance for both word reading and reading comprehension, with processing speed more crucial for word reading than reading comprehension. Overall we found that how well a child is able to manipulate and keep information active in their working memory and how quickly they are able to process visual information are important for both comprehension and word reading.

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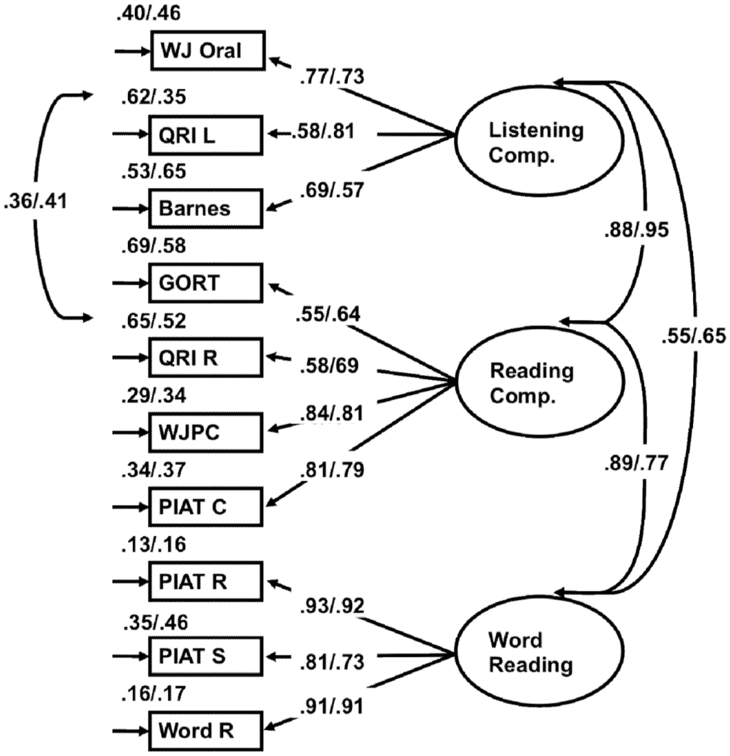

Figure 1.
Three factor model for reading ability variables. All factor loadings are standardized maximum likelihood estimates. Double-headed arrows show correlations. Small arrows pointing to observed variables represent residual variance components (error variances). Parameters with two numbers show loadings for the younger group before the slash and older group after the slash. All parameters significant ($p < .05$). WJ Oral = Woodcock-Johnson Oral Comprehension; QRI L = Qualitative Reading Inventory-Mean Listening Question Score; Barnes = Barnes KNOW-IT Average of Coherence Inference, Elaborative Inference, and Literal Proportions; WJ PC = Woodcock-Johnson Passage Comprehension; QRI R = Qualitative Reading Inventory-Mean Reading Question Score; GORT = Gray Oral Reading Test 3; PIAT C = PIAT Comprehension; PIAT R = PIAT Reading Recognition; PIAT S = PIAT Spelling; Word R = Time-limited Oral Reading of Single Words.

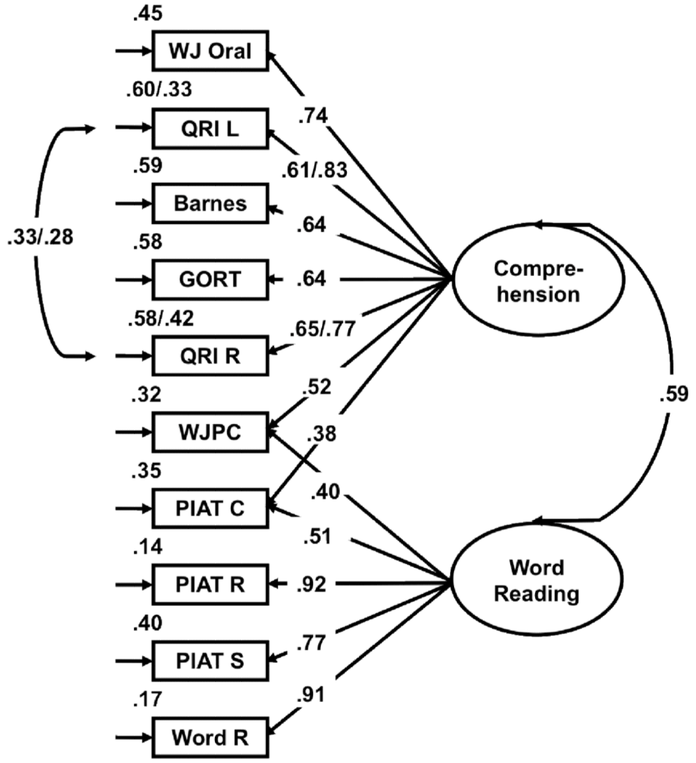

Figure 2.

Final confirmatory factor analysis model for reading ability variables. All factor loadings are standardized maximum likelihood estimates. Double-headed arrows show correlations. Small arrows pointing to observed variables represent residual variance components (error variances). Parameters with one number were constrained equal across age groups. Parameters with two numbers show loadings for the young group before the slash and old group after the slash. All parameters significant ($p < .05$). WJ Oral = Woodcock-Johnson Oral Comprehension; QRI L = Qualitative Reading Inventory-Mean Listening Question Score; Barnes = Barnes KNOW-IT Average of Coherence Inference, Elaborative Inference, and Literal Proportions; WJ PC = Woodcock-Johnson Passage Comprehension; QRI R = Qualitative Reading Inventory-Mean Reading Question Score; GORT = Gray Oral Reading Test 3; PIAT C = PIAT Comprehension; PIAT R = PIAT Reading Recognition; PIAT S = PIAT Spelling; Word R = Time-limited Oral Reading of Single Words.

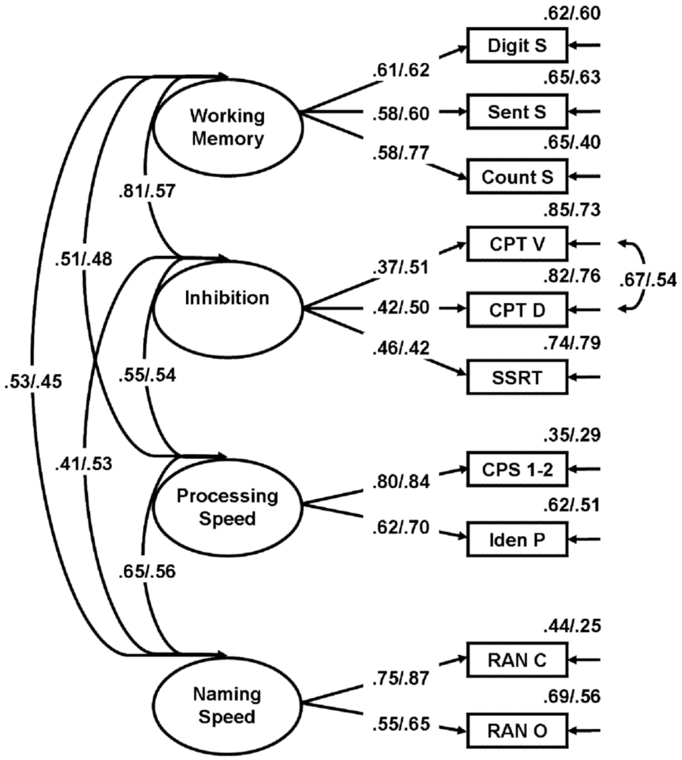

Figure 3.

Confirmatory factor analysis model for cognitive ability variables split by age groups. All factor loadings are standardized maximum likelihood estimates. Double-headed arrows show correlations. Small arrows pointing to observed variables represent residual variance components (error variances). Parameters with two numbers show loadings for the young group before the slash and old group after the slash. All parameters significant ($p < .05$). Digit S = Wechsler Intelligence Scale for Children Digit Span; Sent S = Sentence Span; Count S = Counting Span; CPT Vigil = Gordon Continuous Performance Test Vigilance Commission Errors; CPT Distract = Gordon Continuous Performance Test Distractibility Commission Errors; SSRT = Stop-Signal Reaction Time; CPS 1 and 2 = Colorado Perceptual Speed Tests 1 and 2; RAN C = Rapid Automatized Naming Colors; RAN O = Rapid Automatized Naming Objects.

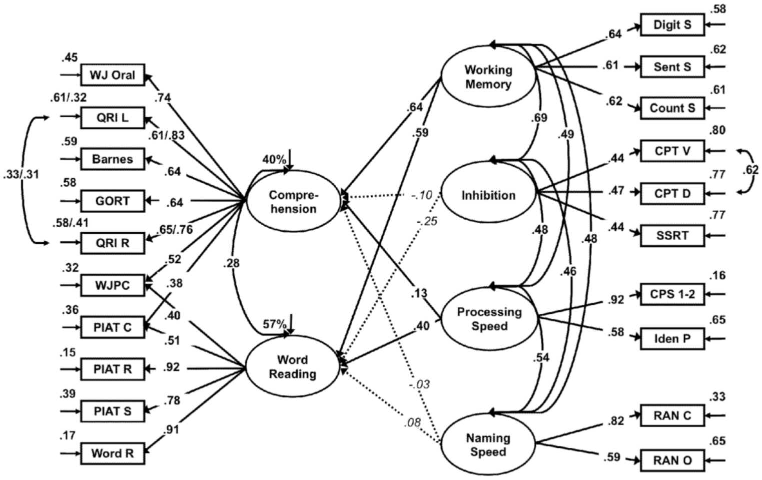

Figure 4.

Final structural equation model. All loadings are standardized maximum likelihood estimates. Percentages above endogenous latent variables represent R^2 (percentage of variance explained). Small arrows pointing to observed variables and reading latent factors represent residual variance components (error variances). Parameters with one number were constrained equal across age groups. For parameters that were not constrained, the younger group (Ages 8 to 10) is denoted first and older group (Ages 11 to 16) is denoted after. All significant parameters are shown on a solid line and equal $p < .05$ with the exception of Processing Speed to Comprehension ($p = .08$). Non-significant parameters denoted by dotted line and are in italics. WJ Oral = Woodcock-Johnson Oral Comprehension; QRI L = Qualitative Reading Inventory-Listening; Barnes = Barnes KNOW-IT; WJPC = Woodcock-Johnson Passage Comprehension; QRI R = Qualitative Reading Inventory-Reading; GORT = Gray Oral Reading; PIAT C = PIAT Comprehension; PIAT R = PIAT Reading Recognition; PIAT S = PIAT Spelling; Word R = Time-limited Oral Reading of Single Words; Digit S = Digit Span; Count S = Counting Span; Sent S = Sentence Span; CPT Vigil = Gordon Continuous Performance Test-Vigilance Commission Errors; CPT Distract = Gordon Continuous Performance Test-Distractibility Commission Errors; SSRT = Stop-Signal Reaction Time; CPS 1 and 2 = Colorado Perceptual Speed Tests 1 and 2; RAN C = Rapid Automatized Naming Colors; RAN O = Rapid Automatized Naming Objects.

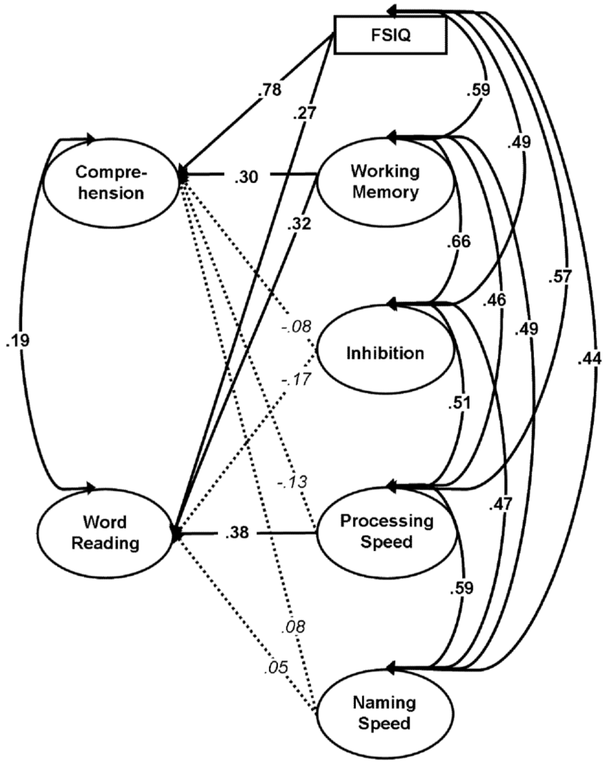

Figure 5.

Structural portion of model with Full-scale IQ. Working memory factor is composed of sentence span and counting span measures only. All other factors are composed of the same measures as in Figure 4. All factor loadings are standardized maximum likelihood estimates. Double-headed arrows show correlations. Parameters on solid lines are significant ($p < .05$). Loadings on dotted lines are not significant and are in italics. FSIQ = WISC-R or WISC-III Full-scale IQ score.

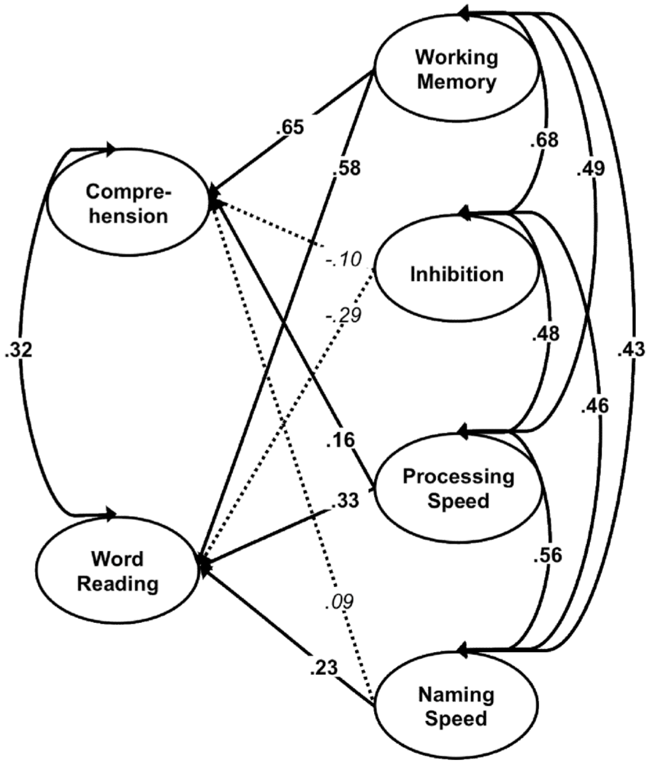

Figure 6.

Structural portion and latent variable correlations for model when naming speed latent factor is composed of RAN letter, digit, color, and object. With the exception of naming speed, factors are composed of the same measures as in Figure 4. All factor loadings are standardized maximum likelihood estimates. Double-headed arrows show correlations. Parameters on solid lines are significant ($p < .05$). Loadings on dotted lines are not significant and are in italics.

Table 1

Range, Mean, Standard Deviation, Skewness, and Kurtosis for All Measures Split by Age Group

	Ages 8 to 10					Ages 11 to 16				
Measure	***n***	**Range**	**M (SD)**	**Skew**	**Kurt**	***n***	**Range**	**M (SD)**	**Skew**	**Kurt**
Age	265	8.01 - 10.99	9.15 (.87)			217	11.04 - 16.96	13.39 (1.71)		
GORT	265	4 - 20	10.57 (2.94)	.23	−.44	217	4 - 20	12.14 (3.08)	.17	−.42
WJPC	264	69 - 130	101.47 (9.97)	−.08	.42	217	65 - 140	103.89 (9.64)	.05	1.27
PIAT C	262	75 - 135	110.45 (12.18)	−.39	.02	212	77 - 128	105.08 (11.63)	−.27	−.51
QRI R Rec[a]	265	0 - .78	.36 (.15)	−.53	.22	217	.07 - .81	.29 (.14)	−.18[a]	−.07[a]
QRI R Qu[a]	265	0 - 6	4.45 (1.18)	−.53	.22	217	1.5 - 6	4.62 (.98)	−.18[a]	−.07[a]
QRI L Rec[a]	265	0 - .84	.34 (.17)	−.38	−.25	217	.04 - .67	.30 (.12)	−.49[a]	.37[a]
QRI L Qu[a]	265	0 - 6	4.37 (1.47)	−.38	−.25	217	.50 - 6	4.5 (1.12)	−.49[a]	.37[a]
WJ Oral	265	77 - 139	108.11 (11.45)	−.09	−.08	217	66 - 130	105.08 (10.05)	−.49	.93
Barnes CI[ab]	265	.07 - 1	.72 (.19)	.12	−.49	217	0 - 1	.83 (.16)	−.72[a]	.75[a]
Barnes EI[ab]	265	.11 - 1	.74 (.18)	.12	−.49	217	.17 - 1	.80 (.16)	−.72[a]	.75[a]
Barnes L[ab]	265	.11 - 1	.76 (.21)	.12	−.49	217	0 - 1	.84 (.19)	−.72[a]	.75[a]
Word R	265	13 - 177	89.67 (35.15)	.05	−.60	217	54 - 192	149.62 (31.01)	−.60	−.04
PIAT R	262	77 - 135	107.49 (10.96)	.01	.04	213	77 - 135	104.40 (11.54)	−.14	−.23
PIAT S	262	78 - 135	105.36 (11.74)	.13	−.18	213	69 - 135	101.08 (12.90)	.11	−.19
Digit S	265	2 - 18	10.03 (2.93)	.14	−.59	217	4 - 19	10.05 (2.80)	.29	.12
Sent S	265	0 - 11	4.35 (1.73)	.72	1.07	217	1 - 14	6.56 (2.28)	.36	.17
Count S	265	1 - 13	5.85 (2.02)	.48	.40	217	3 - 14	7.97 (2.25)	.32	−.34
CPT D[b]	265	0 - 177	16.41 (25.54)	.37	−.50	217	0 - 93	4.02 (9.20)	.92	1.21
CPT V[b]	265	0 - 121	11.78 (19.83)	.55	.31	217	0 - 45	2.83 (4.88)	.67	−.03
SSRT 1[bc]	110	132 - 695	326.91 (112.37)	.60	−.03	122	148 - 552	268.99 (81.63)	.98	1.34
SSRT 2[bc]	142	112 - 843	390.40 (146.30)	.60	−.03	95	122 - 611	271.05 (105.31)	.98	1.34
CPS 1-2	265	3 - 34	13.60 (5.41)	.68	.45	217	8 - 57	26.83 (8.58)	.65	.42
Iden P	265	20 - 96	47.19 (11.12)	.46	1.05	217	35 - 96	70.71 (14.16)	.10	−.69

	Ages 8 to 10					Ages 11 to 16				
Measure	***n***	**Range**	**M (SD)**	**Skew**	**Kurt**	***n***	**Range**	**M (SD)**	**Skew**	**Kurt**
RAN C	265	7 - 34	19.87 (4.08)	.25	1.00	217	12 - 43	26.38 (4.90)	.16	.34
RAN O	265	8 - 27	17.73 (3.10)	−.07	.09	217	13 - 34	21.97 (3.42)	.16	.84

Note. Age = Age tested at CU Boulder; GORT = Gray Oral Reading Test Scaled Score; WJ PC = Woodcock-Johnson Passage Comprehension Standard Score; PIAT C = PIAT Comprehension Standard Score; QRI R Rec = QRI Reading Comprehension Recall Proportion; QRI R Qu = QRI Reading Comprehension Questions Raw Score; QRI L Rec = QRI Listening Comprehension Recall Proportion; QRI L Qu = QRI Listening Comprehension Questions Raw Score; WJ Oral = Woodcock-Johnson Oral Comprehension Standard Score; Barnes CI = Barnes Comprehension Coherence Inference Questions Proportion; Barnes EI = Barnes Comprehension Elaborative Inference Questions Proportion; Barnes L = Barnes Literal Questions Proportion; Word R = Time-limited Oral Reading of Single Words Raw Score; PIAT R = PIAT Reading Recognition Standard Score; PIAT S = PIAT Spelling Standard Score; Digit S = Digit Span Scaled Score; Count S = Counting Span Raw Score; Sent S = Sentence Span Raw Score; CPT Distract = Gordon Continuous Performance Test- Raw Distractibility Commission Errors; CPT Vigil = Gordon Continuous Performance Test- Raw Vigilance Commission Errors; SSRT 1 = Non-Tracking Version of Stop-Signal Reaction Time Raw Score; SSRT 2 = Tracking Version of Stop-Signal Reaction Time Raw Score; CPS 1 - 2 = Colorado Perceptual Speed Tests 1 and 2 Raw Score; RAN C = Rapid Automatized Naming Colors Raw Score; RAN O = Rapid Automatized Naming Objects Raw Score.

[a] Subtests were combined together to form a final composite varible used in analyses. Skew and kurtosis reported are for the composite variable.

[b] Variable was log-transformed. Skew and kurtosis reported are from after transformation.

[c] Two different versions of the SSRT were given. Results were standardized within measure before forming a composite. Skew and kurtosis reported are for the composite variable.

Table 2

Summary of Zero-order Correlations for Scores on the Reading and Listening Variables by Age Group with Estimates of Reliability on Diagonal

	1	2	3	4	5	6	7	8	9	10
1. WJ Oral	**.62**[1]	.58	.40	.59	.56	.46	.56	.43	.32	.47
2. QRI L	.44	**.67**[1]	.56	.62	.74	.52	.61	.47	.35	.47
3. Barnes	.54	.44	**.59**[1]	.42	.49	.35	.36	.24	.15	.29
4. WJ PC	.58	.47	.45	**.71**[1]	.57	.52	.63	.59	.51	.57
5. QRI R	.44	.60	.48	.52	**.59**[1]	.53	.50	.39	.26	.38
6. GORT	.48	.40	.45	.47	.34	**.48**[1]	.50	.44	.30	.39
7. PIAT C	.49	.40	.39	.66	.51	.42	**.79**[1]	.63	.50	.62
8. PIAT R	.42	.32	.27	.68	.42	.34	.74	**.82**[1]	.66	.83
9. PIAT S	.36	.27	.17	.61	.36	.33	.66	.75	**.67**[1]	.67
10. Word R	.42	.33	.25	.72	.40	.33	.69	.85	.73	**.85**[1]

Note: All correlations signficant at $p < .05$, with correlations greater than .15 significant at $p < .01$. Variables standardized within age groups; Ages 8 to 10 located below diagonal; Ages 11 to 16 above diagonal; WJ Oral = Woodcock-Johnson Oral Comprehension; QRI L = Qualitative Reading Inventory- Mean Listening Question Score (standardized within QRI level); Barnes = Barnes KNOW-IT Average of Coherence Inference, Elaborative Inference, and Literal Proportions; WJ PC = Woodcock-Johnson Passage Comprehension; QRI R = Qualitative Reading Inventory- Mean Reading Question Score (standardized within QRI level); GORT = Gray Oral Reading Test 3; PIAT C = PIAT Comprehension; PIAT R = PIAT Reading Recognition; PIAT S = PIAT Spelling; Word R = Time-limited Oral Reading of Single Words.

[1] Reliabilties estimated from monozygotic twin partial correlations (n = 144 twin pairs, controlling for age). Monozygotic twin correlations can be used as low-bound estimates of reliablitiy. The twins share their genes and their family environment, meaning any within-pair differences in performance are due to nonshared environmental influences including measurement error.

Table 3

Fit Indices for the Reading and Listening Confirmatory Factor Analysis Model and Reduced Models

Model[a]	**df**	**χ^2**	**$\Delta\chi^{2\,b}$**	**CFI**	**RMSEA**	**RMSEA 90% CI**
1. Full three-factor	70	115.16	-	.99	.03	[.01, .04]
2. One-factor	84	543.98	<.01	.84	.11	[.10, .12]
Two-factor models						
3. LC = RC, WR	**81**	**116.19**	**.99**	**.99**	**.03**	**[.02, .04]**
4. LC = WR, RC	81	523.66	<.01	.85	.11	[.10, .12]
5. LC, RC = WR	84	543.98	<.01	.86	.10	[.09, .11]

*Note:*The endorsed model is indicated in bold. LC = Listening Comprehension Factor, RC = Reading Comprehension Factor, WR = Word Reading Factor.

[a] All models shown include cross-loadings from Woodcock Johnson Passage Comprehension and PIAT Comprehension measures onto WR and RC.

[b] p value for χ^2. difference tests comparing Models 2 - 5 to Model 1. The χ^2 difference tests indicated that Model 3 and Model 1 fit the data the best. Model 3 was chosen as the final model due to parsimony.

Table 4

Summary of Zero-order Correlations for Scores on the Cognitive Variables by Age Group with Estimates for Reliabilities on Diagonal

	1	2	3	4	5	6	7	8	9	10
1. Digit S	**.53**[1]	.36	.48	.21	.26	.06	.33	.21	.23	.19
2. Sent S	.38	**.38**[1]	.47	.14	.10	.17	.26	.24	.19	.17
3. Count S	.33	.34	**.36**[1]	.24	.28	.15	.29	.17	.31	.25
4. CPT V	.18	.17	.21	**.45**[1]	.66	.22	.15	.21	.21	.18
5. CPT D	.25	.23	.19	.70	**.53**[1]	.20	.17	.20	.19	.19
6. SSRT	.23	.15	.23	.30	.39	**.34**[1]	.17	.22	.23	.18
7. CPS 1-2	.34	.22	.24	.25	.31	.32	**.68**[1]	.58	.42	.27
8. Iden P	.06	.18	.15	.17*	.22	.30	.49	**.70**[1]	.34	.28
9. RAN C	.20	.23	.28	.19	.28	.22	.38	.34	**.56**[1]	.57
10. RAN O	.19	.17	.17	.09	.25	.33	.28	.24	.41	**.55**[1]

Note: All correlations greater than .10 significant at $p < .05$, with correlations greater than .15 significant at $p < .01$. Variables standardized within age groups; Ages 8 to 10 located below diagonal; Ages 11 to 16 above diagonal; Digit S = Wechsler Intelligence Scale for Children Digit Span; Sent S = Sentence Span; Count S = Counting Span; CPT Vigil = Gordon Continuous Performance Test Vigilance Commission Errors; CPT Distract = Gordon Continuous Performance Test Distractibility Commission Errors; SSRT = Stop-Signal Reaction Time; CPS 1 and 2 = Colorado Perceptual Speed Tests 1 and 2; CPS RAN C = Rapid Automatized Naming Colors; RAN O = Rapid Automatized Naming Objects.

[1] Reliabilties estimated from monozygotic twin partial correlations (n = 144 twin pairs, controlling for age). Monozygotic twin correlations can be used as low-bound estimates of reliablitiy. The twins share their genes and their family environment, so any within-pair differences in performance are due to nonshared environmental influences including measurement error.

Table 5

Fit Indices for the Cognitive Abilities Confirmatory Factor Analysis Model and Reduced Models

Model	df	χ^2	$\Delta\chi^2$ [a]	CFI	RMSEA	RMSEA 90% CI
1. Full four-factor	**83**	**94.24**	-	**.99**	**.02**	**[.00, .03]**
2. One-factor	89	256.10	<.01	.85	.06	[.05, .07]
Two- and Three- factor models[b]						
3. WM = IN, PS = NS	88	164.30	<.01	.93	.04	[.03, .05]
4. WM, IN = NS = PS	82	175.14	<.01	.91	.05	[.04, .06]
5. IN, WM = NS = PS	82	248.87	<.01	.85	.07	[.06, .07]
6. NS, WM = IN = PS	82	205.58	<.01	.89	.06	[.05, .07]
7. PS, WM = IN = NS	82	192.38	<.01	.90	.05	[.04, .06]

Note: The endorsed model is indicated in bold. WM = Working Memory Factor, IN = Inhibition Factor, NS = Naming Speed Factor, PS = Processing Speed Factor.

[a] p value for χ^2 difference tests comparing Models 2 - 7 to Model 1.

[b] We tested all permutations of two-factor and three-factor models. The results for all permutations showed any model with less than four factors did not fit as well as the full four-factor model. In the interest of space, we are only reporting a subset of the models.